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The Phonetics and Phonology of the Timing of Oral and Glottal Events

By

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The Phonetics and Phonology of the Timing of Oral and Glottal Events

By
John Clayton Kingston

Abstract

During voiced stops, the larynx is lowered to expand the oral cavity — to facilitate voicing --, while during voiceless stops the larynx remains relatively high in the neck. Hombert, Ohala, and Ewan (1979) argue that lowering the larynx during a voiced stop reduces the vertical tension on the vocal folds and thereby lowers the fundamental frequency of the following vowel. This work examines the contribution of vertical movement of the larynx to the manipulation of intraoral air pressure during the articulation of ejectives and to the perturbation of the fundamental frequency of neighboring vowels.

I show that the amount of larynx movement which occurs during ejectives is too small to account for the extreme elevation of intraoral air pressure which is characteristic of this class of stop. Furthermore, larynx raising during an ejective does not always increase the rate of vocal fold vibration of a following vowel. It appears, in fact, that the fundamental frequency of a vowel following a stop of any kind is not predictable from the height of the larynx during the stop or its direction of movement.

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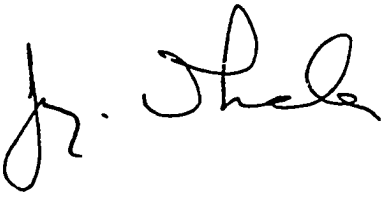
Finally, phonetic and phonological evidence is presented which shows that glottal articulations are "bound" to the stop release, though in continuants, where no audible release occurs, no binding takes place.



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from it. But Steve's contribution goes far beyond instruments and software. Much of my thinking about what the data means and what can or cannot be said about it is the fruit of many long conversations with Steve, where most often I would have come to him with some technical problem or another, and he would make sure I didn't go away until I thoroughly understood both the problem and its solution.

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exploration of the formal properties of glottalized consonants in the fourth chapter is a direct product of many long conversations with her and many of its insights are properly hers. Finally, from the beginning of my graduate career at Berkeley, John Ohala has been the kind of mentor that I needed. When I first started out I had little more than a collection of enthusiasms to work with. Through John's gentle but persistant guidance, I gradually acquired some knowledge to go with them. As a model of how a phonologist should practice his craft, John is without peer.

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Chapter 1

The coordination of oral and glottal events

1.1 Introduction

While certain oral articulations -- a brief but complete obstruction of air flow out of the mouth and an elevation of the soft palate, which prevents air from flowing out through the nose[1] -- are constant features of stops, the various kinds of stops found in the world's languages are distinguished by the glottal articulations which accompany the oral and velopharyngeal occlusions and by when these glottal articulations occur.

The voicing contrast in prevocalic stops is a product of variation in the timing of the opening and closing of the glottis which is realized as a difference in when voicing begins relative to the stop release, the voice onset time (Lisker & Abramson 1964). During phonetically voiced stops, the vocal folds are brought (or remain) together before the stop is released, so the stop is 'prevoiced'. The vocal folds are pulled apart, opening the glottis at about the

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time the oral closure is complete, during phonetically voiceless stops. Voiceless unaspirated stops are produced with a relatively small opening of the glottis during the closure and the vocal folds are pulled back together very close to the release. As a result, voicing begins nearly immediately. To produce an aspirated stop, on the other hand, where voicing does not begin until well after the stop is released, the glottis is opened wide during the closure and the vocal folds reach their greatest separation at the release. The onset of voicing is therefore delayed until the folds are brought back close enough together to vibrate. Glottal articulations are carefully coordinated with oral ones in the production of these three kinds of stops, though the two are not synchronized with one another.

After vowels, voiced and voiceless stops are not necessarily distinguished by the kind of differential timing of glottal and oral articulations that is observed prevocalically. First of all, the opposition is usually reduced from three members to two, the voiceless aspirated and unaspirated stops collapsing into a single voiceless series, contrasting with voiced stops. Second, though phonologically voiced stops can be produced with vocal fold vibration during the stop closure, they often are not phonetically

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voiced. The voicing contrast does not, however, collapse since the preceding vowel is usually noticeably longer before phonologically voiced stops than voiceless ones. (Bannert 1976, Chen 1970, Elert 1976, Fujimura & Miller 1979, Javkin 1977, Kohler, van Dommelen, & Timmerman 1981, Kozhevnikov & Chistovich 1966, Port, Al-Ani, & Maeda 1980, Slis & Cohen 1969, Slis 1970, 1971, cf. Port, Al-Ani & Maeda 1980 who show that that vowel lengthening is not universal before phonologically voiced stops). This difference in vowel duration can carry the distinction when actual vocal fold vibration during the stop closure is minimal or absent (for review see Umeda 1975, Javkin 1976, Klatt 1976), but the presence or absence of vocal fold vibration during the stop is a stronger cue to the voicing contrast than the duration of the preceding vowel.

It is possible, though not entirely certain, that the lengthening of the vowel before a voiced stop is accompanied by a complementary shortening of the stop closure, which contrasts with a relatively longer closure during voiceless stops. In other words, the vowel-stop sequence may appraoch a nearly constant duration, where if the vowel is lengthened, the stop is shortened and vice versa (Fujimura & Miller 1979).

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Intervocalically, there is a similar contrast in closure duration between voiced and voiceless stops, with the voiced stops having shorter closures than the voiceless ones (Lisker 1957) and the preceding vowels showing a complementary difference in duration. It should be noted, however, that there is only a partial tradeoff between vowel and consonant duration (cf. Denes 1955), so strict isochrony for the vowel-stop sequences is not actually achieved.

Clearly, the phonological contrast between voiced and voiceless stops has at least two different phonetic realizations. Prevocalically, it is a difference in the timing of glottal abduction and adduction relative to the stop release, resulting in contrasts in voice onset time, which distinguishes the various classes of stops from one another. After vowels, the situation is more complex. The contrast is always expressible by the presence or absence of voicing during the stop closure itself, but the differences in the duration of the vowel preceding the stop are a sufficiently strong secondary cue to maintain the contrast when it is unclear whether the stop is voiced or not. Though this secondary cue is described here in terms of the duration of the preceding vowel, because of the partial complementarity of vowel and stop durations it might better be expressed as

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a difference in the ratio of their durations. Simplifying a bit, the ratio of vowel to stop duration is greater than one when the stop is phonologically voiced, but less than one when it is voiceless. The results of Fujimura and Miller (1979) suggest that this difference is a result of a difference in the velocity of the closing gestures in the two classes of the stops, with the closure being much slower for the voiced than voiceless stops. Faster closures during voiceless stops will obviously cut the vowel off sooner in the latter case.

The stops examined in this study were nearly all word-initial and prevocalic, so the focus will be on when glottal events occur relative to the oral gestures which produce the stop, particularly the stop release.

The larynx and vocal folds have at least two other degrees of freedom besides abduction/adduction, whose coordination with oral articulations is not nearly so well-understood as is the opening and closing of the glottis. First of all, the entire larynx can be raised or lowered in the neck, and, second, the length and stiffness of the folds themselves can be manipulated. Both vertical movement of the larynx and changes in vocal fold length and stiffness

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have been implicated in the control of vocal fold vibration in the production of stop consonants. Larynx movement changes the volume of the oral cavity and thereby the pressure of the air inside it and changes in the state of the vocal folds affect the resistance to the flow of air through the glottis.

The bulk of the research done on the control of vocal fold vibration during stops has focussed on voiced stops because getting the vocal folds to vibrate behind a stop closure poses a challenge to the speaker. This is because the vibration of the folds is a product of the air flowing between them and will continue only so long as the air flow does. Obstructing the flow of air out of the mouth by producing a stop closure, however, causes air pressure to build up rapidly inside the oral cavity. This increase is rapid enough that intraoral air presseure quickly approaches subglottal air pressure. Once the intraoral air pressure gets close enough to subglottal air pressure -- within about 1 to 2 cm H_2O -- vocal fold vibration ceases, though a low rate of air flow through the glottis can continue until the air pressure above and below the glottis is equalized. If the oral cavity is expanded by lowering the larynx, the rate of increase in intraoral air pressure will be slowed.

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Furthermore, slack folds will vibrate more easily with low rates of air flow between them than tense folds, since the amount of elastic recoil keeping the folds together is less. However, since the volume of air passed into the oral cavity will, therefore, be greater with slack folds than tense ones, intraoral air pressure will increase more rapidly and the moment when supraglottal air pressure gets too close to subglottal air pressure for voicing to continue any longer will arrive sooner. This aerodynamic threat to voicing can be minimized by tensing the folds, since less air will flow between tense than slack folds. However, since tense folds are less likely to vibrate in response to low rates of air flow, it remains unclear which extreme of vocal fold tension is most likely to result in voicing continuing throughout the stop closure. Perhaps a balance could be struck with a moderate amount of tension between partial control over the rate of air folw into the oral cavity and the vibratory responsiveness of the folds. It is certainly possible that the tension of the folds may change during the course of the stop closure, with the folds tense at the outset to prevent too rapid a buildup in pressure in the cavity above the glottis followed by a progressive slackening of the folds to maintain vibration as the transglottal air flow declines.

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The larynx is pulled down during voiced stops and the fact that the fundamental frequency of the following vowel is low indicates that the folds are relaxed. During voiceless stops, on the other hand, where the object is to have no vocal fold vibration during the closure, the larynx remains relatively high in the neck and elevation of fundamental frequency occurs on the following vowel, pointing to a stretching or stiffening of the folds.

The first goal of the research reported here is to assess the effects of larynx movement on the pressure of the air inside the oral cavity. The second goal is to test a hypotheis offered by Hombert, Ohala, and Ewan (1979) that the lower fundamental frequency following voiced stops is an indirect result of the lowering of the larynx which occurs during these stops. Both assessments will be made by examining ejectives, a variety of stop during whose closure very high intraoral air pressure occurs, and comparing them to voiced and voiceless stops. It has been assumed that the extreme elevation of air pressure during ejectives is a result of raising the larynx during the stop closure (Ladefoged 1971). If the larynx moves dramatically during ejectives, they also provide a means of testing the hypothesis that larynx movement is the mechanism whereby the

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fundamental frequency of following vowels is perturbed.

Previous research which shows that larynx movement may change intraoral air pressure and perturb the fundamental frequency of following vowels is discussed in sections 1.2 and 1.3 and the results of new research are presented in chapters 2 and 3, respectively. The data presented in chapter 2 shows that the amount of contraction of the oral cavity which can be accomplished by raising the larynx is too small to account for much of the increase in intraoral air pressure that occurs in an ejective. In chapter 3, it is shown that the fundamental frequency of a vowel following a stop is not predictable from the height of the larynx during that stop, disconfirming Hombert, Ohala, and Ewan's hypothesis, at least as it applies to ejectives.

1.2 Manipulation of intraoral air pressure

In articulatory terms, a stop is a brief but complete contact between two articulators; in aerodynamic terms, it is a period during which air is trapped in the oral cavity, resulting in a buildup of intraoral air pressure, followed by a sudden release of that air to the outside; and,

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finally, in acoustic terms, it is a period of silence or severely reduced energy followed by a burst of noise. I do not propose to argue here for any of these three ways of thinking about stops as the best way of describing the goals speakers pursue in articulating them; instead I am going to consider what effects the increase in oral air pressure during the stop closure has on the other articulations, especially vocal fold vibration, that the speaker is trying to accomplish and what is done about this increase in intraoral air pressure to reverse or encourage these effects. A detailed discussion of the aerodynamics of stops is given in Chapter 2, so I will only lay out the essentials here.

The buildup of air pressure in the oral cavity depends on the following parameters:

(1.1)

a. Size of the oral cavity behind the obstruction: the larger the cavity the slower air pressure will build up.

b. The rate at which air flows through the glottis: the slower the flow the slower the pressure buildup. Rate of flow through the glottis is a function of how close the vocal folds are to one another, how tense they are,

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and the amount by which the air pressure below the glottis exceeds that above (from now on subglottal air pressure will be represented as Ps and supraglottal (intraoral) air pressure as Po).

c. The tenseness of the walls of the cavity: the more relaxed the walls are the slower the pressure will build up, since the walls will expand passively, absorbing some of the potential energy in the air mass. As already noted in (a), the size of the oral cavity significantly affects the amount of compression which takes place as well. If there is a constant volume velocity through the glottis, the buildup in intraoral air pressure will be inversely proportional by Boyle's law to the size of the cavity into which the air is flowing.

d. The extent to which the cavity is actively enlarged: any active expansion will significantly retard the buildup of intraoral air pressure.

The effects of choosing different values for each of these parameters are summarized below:

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(1.2)

Oral Pressure Buildup	SLOW	FAST
a. Size of oral cavity behind the closure	LARGE	SMALL
b. Rate of air flow through the glottis		
i. Glottal aperture	SMALL	LARGE
ii. Vocal fold tension	STIFF	SLACK[2]
iii. Magnitude of difference between Ps and Po	SMALL	LARGE
c. Stiffness of the vocal tract walls	SLACK	STIFF
d. Magnitude of active expansion	LARGE	SMALL

From this table it is clear that the increase in Po will be slowest during a bilabial stop, produced with the vocal folds together and relatively stiff and with a weak respiratory force, while relaxing the cheeks and lips and doing whatever one can -- advancing the tongue root, raising the soft palate, lowering the jaw, lowering the larynx -- to expand the oral cavity. The quickest elevation would be accomplished with a velar stop articulated with the vocal folds wide apart and with a forceful respiratory push, while tensing the walls of the pharynx and pulling the tongue root back and raising the larynx. In short, the stops [b] and

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[k] represent aerodynamic extremes for stops initiated[3] by the flow of air from the lungs.

Stops such as [b] or [k], where the lungs are the initiator have been called "pulmonic" stops (Catford 1977), but I will use Ladefoged's (1971) terminology and refer to them as "oral" stops. They will be distinguished from classes of stops initiated by vertical larynx movement, which will be called "glottalic" stops; these are also known as "ejectives" and "implosives".[4]

Vertical movement downward of the larynx during the articulation of voiced stops and implosives expands the oral cavity and reduces intraoral air pressure, while vertical movement upward during ejectives and if it occurs in their articulation voiceless stops contracts the cavity and raises the air pressure inside it. Most descriptions of the glottalic stops (e.g. Ladefoged 1971, Catford 1977) treat the effect of vertical movement of the larynx on the air on the oral cavity as like that of a piston in a cylinder of an internal combustion engine: when it is raised it compresses the air in the cavity, while lowering the larynx rarefies the air. These descriptions have also noted that the laryngeal piston is usually made airtight by closing the

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glottis tightly during the larynx raising which takes place for an ejective. During implosives, on the other hand, the piston is allowed to leak. The vocal folds are brought close enough together to vibrate as air passes between them, but air flow through the glottis is not stopped entirely. (Air is usually allowed to continue to pass into the oral cavity through the glottis during both voiced and voiceless oral stops, or at least it will so long as subglottal pressure remains sufficiently higher than supraglottal pressure.) An implicit assumption of these descriptions is that the larynx moves more vertically during the articulation of glottalic than oral stops. These facts lead to the following ranking of oral and glottalic stops with respect to their effect on intraoral air pressure. The zero line in this scale represents atmospheric pressure. All stops, except implosives, elevate intraoral air pressure above atmosphere to some extent,

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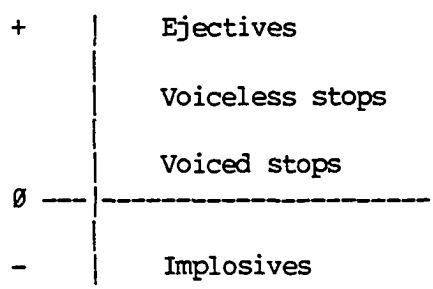
(1.3)



Though Pinkerton (1980) and Nihilani (1974) have shown that intraoral air pressure is negative during implosives in Quiche and Sindhi, respectively, it is probably the case that in casual speech rather than the citation forms collected by these investigators intraoral air pressure instead hovers around zero (cf. Ladefoged 1964 and Ladefoged, Williamson, Elugbe, and Uwakaka 1976 for such evidence in West African languages; also the discussion of ejectives in chapter 2).

If the larynx is lowered further during an implosive than a voiced oral stop, then more facilitation of voicing should be obtained. Larynx raising during an ejective is supposed to elevate intraoral air pressure to higher levels than is observed during voiceless stops, but raising the larynx is not what inhibits voicing during ejectives. This is accomplished instead by the considerable medial compres-

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sion of the folds employed in articulating this class of stops to tightly seal the glottis. The larynx may be raised slightly during voiceless stops as well, but since the glottis is open rather than closed, no compression of the oral air mass can be obtained from this gesture. The first question that needs to be answered then is: does the larynx, in fact, move higher during ejectives than it does during voiceless oral stops and does it move lower during implosives than it does during voiced oral stops? Only ejectives, i.e. the elevation of Po as a result of larynx raising, is investigated experimentally in this work. The second question is: how is larynx movement coordinated with oral articulations; specifically is it timed so that the larynx reaches its highest or lowest point at or near the oral release of the stop?

Is the timing of larynx movement during ejectives and implosives, like the timing of glottal abduction/ adduction in voice onset time contrasts, varied to create phonological contrasts? No clear evidence is available for such a contrast within a single language, but there is abundant evidence that ejectives and implosives are not phonetically the same in all the languages they occur in. For ejectives, the most frequently encountered variation is in the relative

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timing of the glottal and oral releases: the glottal closure may be released together with or soon after the oral one or it may be significantly delayed (Kingston 1982). Corresponding to this difference in the timing of the glottal release relative to the oral one is an impression that ejectives with simultaneous release of glottal and oral closures are less forceful than those where the glottal release is delayed.

It is not yet known whether the difference in timing of the glottal release relative to the oral one in ejectives corresponds to a difference in the timing of larynx raising but one might ask whether the larynx reaches its highest point earlier in the closure in the ejectives with simultaneous oral and glottal releases than it does in those where the glottal release is delayed. If this kind of contrast was encountered, it would provide a parallel to the contrast in the timing of the opening and closing of glottis between unaspirated and aspirated stops.

I expect that larynx movement during glottalic consonants will be timed so that the larynx is at its highest or lowest point near the oral release, since maneuvers which change the volume of the oral cavity have more profound

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effects on Po if they are initiated after the oral closure is made; i.e. simply starting out with an expanded or contracted cavity does not affect Po as much. Unlike a voiceless stop where the glottis remains open during the oral closure, ejectives are articulated with a closed glottis. Closing the glottis prevents further air from flowing into the oral cavity from the lungs, so after the glottal and oral closures are made, increasing intraoral air pressure can only be accomplished by contracting the cavity. Raising the larynx before the oral closure is made, during the preceding vowel, would reduce the amount of compression of air possible once the oral and glottal closures are made, because it would reduce the the amount of cavity contraction which could take place subsequently. It is also not known if the larynx moves as high for an ejective where the glottal release coincides with the oral one as it does during an ejective with a later glottal release.

Implosives also clearly come in a number of kinds (Lindau 1982) but none of the variation observed depends on differences in timing; instead there seem to be crosslinguistic (and occasionally language-internal) variations in the amount of cavity expansion which occurs and in the tension of the vocal folds.

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Two more general questions are implicit in the discussion of both glottalic and oral stops above: is it the oral articulations to which the glottal articulations are tied or vice versa and if it is the oral articulations, is it the oral release, as suggested above, or some other event, such as the oral closure? I argue in section 1.4 and chapter 4 that it is the release of an oral closure which is the reference point for this coordination.

1.3 Perturbation of fundamental frequency after stops

A distinct kind of timing issue comes up in trying to explain the perturbation of the fundamental frequency of vowels (from now on Fo) following stops. Some aspect of the state of the glottis during a stop articulation only reverts slowly to a state appropriate to a vowel, more slowly at any rate than the movement of the oral articulators from stop to vowel. As a consequence, Fo at the beginning of a vowel is perturbed upward after voiceless stops, the ejectives of some languages, and implosives and downward after voiced stops, sonorants, and the ejectives of other languages.

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Larynx height during vowels correlates directly with Fo, and since the larynx and Fo at the beginning of the vowel following the stop are both higher after voiceless stops than voiced ones, it has been suggested that raising the larynx during the stop raises Fo of the following vowel (Hombert, Ohala, & Ewan 1979). If the perturbation of Fo by voiced and voiceless stops is not a byproduct of vertical movement of the larynx during the preceding stop, then it is possible that changes in vocal fold tension would have to be induced through changes in the level of activity of the vocalis, the lateral cricoarytenoid, or perhaps the cricothyroid, since the activity of these muscles changes the stiffness or length of the vocal folds and thereby the rate at which they will vibrate. The cricothyroid is an unlikely source for the perturbations, however (see below). Stiffening or stretching the vocal folds will inhibit voicing (but see footnote 2), while relaxing them will facilitate it (Halle & Stevens 1971). Elevation of Fo would be expected after voiceless stops and depression after voiced ones.

Lowering the larynx during voiced stops is presumably intended to reduce intraoral air pressure by expanding the oral cavity. Larynx lowering would encourage voicing, but as noted above, larynx raising should have no noticeable

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effect on intraoral air pressure if the glottis is open as it typically is during voiceless stops. From this point of view, the perturbation of Fo is an consequence of a maneuver whose primary purpose is a change in oral cavity volume. If, on the other hand, the perturbation of Fo is caused by direct adjustments of the stiffness or length of the vocal folds themselves, which like larynx movement are intended to make voicing easier or more difficult, then the Fo perturbations are clearly not induced by the action of another articulator, though they are still ancillary to the primary purpose of the articulatory adjeustment: encouraging or inhibiting voicing. In both explanations, the perturbation of Fo occurs because whatever laryngeal mechanism changes vocal fold tension during the stop is slower to revert to the state required for the following vowel than are the oral articulators.

If larynx height or movement in the neck during the articulation of a stop is the mechanism that perturbs Fo of neighboring vowels, then significant perturbations should be observed next to ejectives and implosives. Ejectives should elevate Fo, and implosives should depress it. Furthermore, since the movement up and down of the larynx is presumably greater for ejectives and implosives than for voiceless and

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voiced stops, respectively, the glottalic consonants should raise and lower Fo even more than the corresponding oral stops do. Data presented in chapter 3 do not bear out the expectation that ejectives should raise Fo more than voiceless oral stops do. Ejectives do not elevate Fo in all languages; in some they in fact depress it, and in one language where they do elevate Fo, they elevate it no more than a voiceless stop does. Implosives are even more problematic since phonological evidence (presented in chapter 3) suggests that they actually elevate rather than depress Fo in a number of languages, though it is not clear that they do so in all languages they occur in.

Chapter 3 below contains an elaboration of the question of Fo perturbation by oral and glottalic stops. The phonological consequences of these perturbations are discussed in detail, together with an evaluation of the two principal mechanisms which have been proposed to explain the Fo perturbations by oral stops and a discussion of their applicability to glottalic consonants. Resolving the paradox presented by the glottalic stops would appear to require rejection of vertical larynx movement as the mechanism for perturbing Fo, at least for ejective and implosives and perhaps also for oral stops, in favor of direct manipulation

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of vocal fold stiffness. This hypothesis is considered in some detail in that chapter.

1.4 Articulatory binding

In the last chapter of this thesis, phonological evidence illustrating the coordination of glottal and oral aritculations, primarily in glottalic and glottalized consonants, is considered. The bulk of the data presented in that chapter concerns the distribution of this sort of consonant in a number of American Indian languages. It is suggested that there is a fundamental difference in how oral and glottal articulations are coordinated in glottalic stops, i.e. noncontinuants, vs. glottalized fricatives and sonorants, i.e. continuants. The essential difference between stops and continuants is that in producing the former, the release of the oral closure is a prominent acoustic event, while for the latter, because their articulation does not completely obstruct the air flow out of the oral cavity, the release is not acoustically salient. In the terms proposed in chapter 4, I suggest that glottal articulations in stops are "bound" to the stop release, but in continuants where no comparable acoustic anchor is

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available, no binding need take place.

The essential phonological consequence of this difference between stops and continuants is that the occurrence of glottal contrasts in stops is constrained to occur on a stop which is audibly released. In stops which are unreleased, such as those which occur syllable-finally in many languages, glottal contrasts are often not maintained. In continuants, on the other hand, the absence of any oral anchor for the glottal articulations results in a considerable variability in when the glottal articulations occur relative to the oral ones. Furthermore, it is shown that in a number of languages, glottal articulations are detached from oral ones in continuants, while remaining firmly bound in the same language to stops.

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Notes.

1. Though air is allowed to pass out through the nose in both pre- and postnasalized stops such as $\underline{{}^{m}b}$ and $\underline{b^{m}}$, air flow through the nose is shut off by raising the soft palate for part of their duration. As is the cases with other kinds of complex segments such as affricates, the pre- and postnasalized stops present little difficulty once it is recognized that the onset and offset of activity of the various articulators need not be coterminous.

2. The fact that fundamental frequency is low both during and after a voiced stop suggests that the folds are probably slack rather than stiff at the end of the stop.

3. The initiator of a sound is the source of its energy: for the stops [b] and [k], the energy comes from the air pressure which has built up in the oral cavity during the closure as a result of the continuing flow of air into that cavity caused by the uninterrupted contraction of the lungs. The burst produced when a stop is released is an acoustic consequence of the

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transformation of the energy stored as elevated intraoral air pressure to rapid flow of air out of the mouth. Since the change in oral air pressure during the articulation of these stops can be traced back to lung contraction, the lungs are considered the initiator in their case.

4. The term "glottalized" will be used in two senses in this work, both different from that of the term "glottalic" defined above. First, in connection with sonorants and occasionally stops, glottalization means a modification of phonation during or adjacent to the segment ranging from a full-fledged glottal stop to a tense or creaky phonation. This sense corresponds to that of the term "laryngealized" found in some discussions of such modifications of this sort of segment, as, for example, in the UCLA Phonological Segment Inventory Database (Maddieson 1980). The other sense is meant in what I call "contact glottalization" in section 4 (and chapter 4) below. This refers to a phonological process whereby a segment which has come into contact with a glottal stop acquires the kind of glottal coarticulation that is appropriate to its manner: an oral stop which is glottalized in this sense becomes

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an implosive or ejective, depending on whether it was originally voiced or voiceless, respectively, while a sonorant is glottalized in the first sense discussed above. Context will always make clear which sense of the term is meant.

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Chapter 2

The effect of larynx movement on Po

2.1 Introduction

Moving the larynx up and down contracts or expands the oral cavity. If the vocal folds are adducted, this movement will elevate or reduce the pressure of the air inside the cavity if a closure is made somewhere above the glottis. As noted in the preceding chapter, larynx movement does influence Po in voiced oral stops, ejectives, and implosives, because the closed glottis creates a separate cavity of air on which the movement of the larynx can work, while in the voiceless oral stops, where an open glottis aerodynamically couples the subglottal and supraglottal cavities, no change in intraoral air pressure can be accomplished by larynx movement.

The larynx is lowered during the closure interval of a voiced stop retarding the buildup of intraoral air pressure. In voiceless stops, the larynx remains relatively high in the neck and may even be raised slightly (Kent & Moll 1969,

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Perkell 1969, Ewan & Krones 1974, Riordan 1980, Westbury 1979, 1983). Reducing intraoral air pressure by lowering the larynx makes voicing more likely and diminishes burst and noise intensity. Elevating intraoral air pressure diminishes the transglottal pressure drop and thereby reduces the likelihood of vocal fold vibration.

Since air initially continues to flow up through the glottis from the lungs, obstructing the channel through which air passes out of the mouth causes intraoral air pressure to build up behind the obstruction. If the closure is held long enough, intraoral air pressure (Po) will eventually equal subglottal air pressure (Ps) and the flow of air through the glottis will stop. After an interval of voicing, a phonologically voiced stop will devoice, if the closure is held long enough for Po to come close to Ps.

2.1.2 The utility of larynx movment as a mechanism for changing Po

The results of aerodynamic modelling show that the pressure difference across the glottis will fall below the minimum necessary to sustain voicing soon after the oral

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closure is made, unless some active or passive expansion of the supraglottal cavity occurs to delay the moment when the pressure threshold is reached and voicing stops.

In 1968, Rothenberg reported on the behavior of a circuit which electrically mimicked the movement and control of air masses up from the lungs, through the glottis into the oral cavity, and finally escaping out into the atmosphere. The principal inputs to this circuit are a voltage representing the expiratory pressure produced by lung contraction, capacitances representing the compliances of the various volumes of air and the walls of the vocal tract, and resistances representing constrictions at the glottis, velopharyngeal port, and in the oral cavity. Finally, the expansion or contraction of the oral cavity is represented as a current source. The principal outputs of the circuit can be translated into subglottal and supraglottal pressures and the volume velocity through the glottis and past any oral constriction. These parameters can then be used in making inferences about whether voicing is possible or not given a particular set of inputs.

Perhaps the most important prediction of Rothenberg's model is that voicing could not be maintained for as long as

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it typically is in voiced stops unless some adjustment is made to slow the increase in Po. Rothenberg's model itself includes three mechanisms for controlling Po. First, it is theoretically possible though so far undemonstrated by experiment that reducing the size of the glottis will increase the resistance to the flow of air at that point and will thereby slow the increase in Po. Since voicing will only occur when the vocal folds are relatively close together, the activity whose continuation is desired actually contributes to its own maintenance. However, increases in glottal resistance ultimately work against the continuation of vocal fold vibration, especially when Po is approaching Ps rapidly, bringing about a reduction in volume velocity between the folds, as it does behind a stop closure. This is because it is progressively more difficult to get stiff folds to vibrate as the volume velocity through the glottis declines. Slack folds appear to make voicing easier to maintain than tense ones, but the fact that slack folds allow a higher volume velocity through the glottis will result in a faster elevation of Po, reducing the advantage the speaker would obtain by this adjustment. Second, the walls of the oral cavity, particularly the soft palate and the anterior cheeks and lips can be relaxed sufficiently

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that they could respond compliantly to an increase in Po. Finally, the oral cavity could be actively expanded by a number of mechanisms during the production of stops. Both passive enlargement and active expansion will retard the elevation of Po and thereby prolong voicing. Considerable evidence has accumulated since Rothenberg's initial demonstration of the properties of his model which shows that each of these three mechanisms contributes to the initiation and maintenance of voicing.

John Ohala (p.c.) has noted that an oral constriction which will produce a fricative such as [ɹ̊] when the glottis is open will only produce a sonorant, i.e. [l], without noticeable frication when the vocal folds are close enough together to vibrate. The high rate of air flow through the open glottis evidently elevates Po enough to create audible turbulence in the flow of air past the oral constriction, while the slower rate of flow through a closed glottis is insufficient to raise Po enough to create turbulence at the constriction downstream.

Passive compliance of the vocal tract walls was demonstrated by Ohala and Riordan (1980). They had subjects sustain voiced stops between identical vowels with an open-

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ended catheter inserted through the nose into the pharynx. The catheter bled off the air in the oral cavity and thereby kept Po sufficiently below Ps that voicing could be maintained for the entire duration of the exhalation. Randomly, at times unknown to the subject, the catheter was quickly plugged by closing a solenoid-activated valve. Voicing continued for an average of 72 +/- 32 ms (median: 64 ms) after the catheter was plugged. Because the subjects were unaware of when the catheter had been plugged and because the vowels on either side of the stop involved the same degree of constriction of the vocal tract, the continuation of voicing after the catheter was plugged is most likely a product of a considerable passive expansion of the oral cavity rather than active expansion (cf. Müller & Brown 1980). This inference is supported by the fact that voicing ended earlier for stops articulated further back in the cavity: after the catheter was plugged, voicing lasted only 54 +/- 17 ms (median: 52 ms) when the closure was at the velum, 69 +/- 27 ms (median: 63 ms) for stops articulated at the alveolar ridge, and 93 +/- 37 ms (median: 82 ms) for bilabial stops. The longer continuation of voicing for more anterior stops is made possible by the larger compliant surface area which Po has to work on.

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Despite the obvious utility of the two mechanisms just discussed, active expansion of the oral cavity has received the most attention (Kent & Moll 1969, Perkell 1969, Westbury 1979,1983, Riordan 1980).

The oral cavity will expand passively in response to an increase in Po if its walls, especially the anterior cheeks and lips and the soft palate, are relaxed. The means by which the oral cavity can be expanded actively include lowering the larynx, advancing the the tongue root, lowering the jaw, and raising the soft palate. These active mechanisms will be maximally effective only if they are coordinated so that the cavity is expanded after the oral closure is made. This kind of coordination cannot be obtained directly from the mechanical properties of the tract itself, nor are they in any obvious way a simple product of the stop articulation itself.

The difficulty is exacerbated by the fact that certain maneuvers necessary to producing the oral closure, particularly raising the tongue blade and dorsum, actually reduce the volume of the cavity. Furthermore, since the tongue blade and dorsum are raised in different ways for different places of articulation, movement of these anterior parts of

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the tongue cannot be used in any consistent way to enlarge the cavity. On the other hand, lowering the jaw and tongue body in anticipation of the release of the stop expands the cavity. The changes in cavity size which takes place as a result of the stop articulation itself are therefore symmetric, first a contraction and then an expansion. Note further that the expansion that takes place before the release comes at a time when it would be most useful in mainitaining voicing, since it occurs when Po is getting close to the critical 1 to 2 cm H_2O transglottal pressure drop necessary for the continuation of voicing. In this context, it also worth noting that Müller and Brown (1980) found that the shape of the air pressure waveform for voiced stops in English typically either flattens out after an initial steep rise or even dips. This reduction in the rate of air pressure buildup suggests that some cavity expansion takes place in the middle of the stop closure. Expansion may only be implemented if the difference between subglottal and supraglottal air pressures gets small enough to threaten voicing.

Since the back wall of the pharynx is relatively stationary, there only four articulators whose manipulation would expand (or contract) the oral cavity at any place of

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articulation: the larynx, the tongue root, the jaw, and the soft palate. In addition, contracting the muscles of the anterior cheeks and lips might reduce the size of the oral cavity slightly in bilabial stops (John Ohala p.c.). Since this study is concerned principally with larynx movement, only the changes observed for this articulator will be discussed here.

In a cineflourographic study of single stops and clusters of stops, Westbury (1979, 1983) showed that the larynx was generally lower for prevocalic voiced stops than voiceless ones, confirming results reported by Kent and Moll (1969) and Perkell (1969). The amount of vertical movement of the larynx observed by Westbury was small, however. At the oral occlusion, the larynx was between 4 and 6 mm lower for word-initial voiced stops at a given place of articulation than it was for the corresponding voiceless stops. By the time of the oral release, the larynx had dropped to between 8 and 13 mm lower for voiced than voiceless stops. The larynx tended to remain level or rise slightly and then fall during word-initial voiceless stops. Intervocalically, the larynx started out in nearly the same position at the oral occlusion for both voiced and voiceless stops and had only dropped 2 to 3 mm by the oral release in voiced stops.

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Again the larynx remained more or less level or rose slightly during intervocalic voiceless stops.

Riordan's (1980) thyroumbrometer measurements showed an even smaller downward movement, between 1 and 2 mm, for intervocalic voiced stops in the speech of two speakers. She estimated that this amount of cavity expansion would only add 6 ms to the duration of voicing, yet even English speakers who rarely prevoice word-initial voiced stops usually voice intervocalic ones (Caisse 1982).

In the measurements of larynx movement during stops reported below, it was found that the larynx is raised considerably above its rest position shortly before speech begins and that the range of movement which occurs during speech is much smaller than that observed in the transition between not speaking and speaking. This suggests that the relatively extensive movement of the larynx observed by Westbury in utterance-initial stops is simply the tail end of the preparatory larynx raising which occurs before speaking starts. Therefore, the much less extensive movement he and Riordan separately observed inside utterances better represents the range which should be considered in assessing the effect of larynx movement on Po. The fact that Westbury

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still observed a substantially lower larynx position for utterance-initial voiced stops than voiceless ones does, however, show that raising the larynx in preparation for speech is modifiable by the need for a larger oral cavity if phonologically voiced stops are to be phonetically voiced.

Using Rothenberg's model, Westbury and Keating (1980) predicted that voicing should continue throughout an intervocalic stop, while in a word-initial stop voicing should not begin until after the oral release. This prediction, taken together with the negligible amount of larynx lowering during intervocalic voiced stops, suggests that maintaining voicing between vowels is somehow physiologically different than initiating it at the beginning a word or alternatively that some other cavity expanding gesture, such as advancing the tongue root, replaces larynx lowering for intervocalic stops.

2.2 Po measurements during Tigrinya stops

2.2.1 Methods

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2.2.1.1 Instrumentation and data sampling

The data on larynx height and movement reported below were obtained using a new version of the thyroumbrometer (Ewan & Krones 1974, Riordan 1980). This device consists of a bank of photocells arranged in an array of 18 rows by 16 columns. The subject lies on his/her back on an inclined board between a dc light source and the bank of photocells. The bank is aligned so that the vertical movement of the subject's larynx is parallel to the rows of photocells; larynx height is therefore indicated by which columns the shadow of the thyroid prominence covers. The light is placed approximately 10 cm from the subject's neck, which is approximately 70 cm from the photocell bank. The subject's head is tilted back slightly and stabilized by placing a notched wooden block under the neck and padding it with foam rubber. The head is tilted to expose the thyroid prominence a bit more and to move the shadow of the chin off the bank of photocells as much as possible. However, the subject's head is not tilted so far back that the muscles by which the larynx is suspended in the neck are noticeably stretched.

The output of the photocells is sampled digitally every 5 ms (a 200 Hz sample rate), starting with the lowest column

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of cells and moving successively to the highest. All 16 columns are sampled within a 2.3 ms interval at the end of each 5 ms data frame. Up to three other channels can be sampled at 200 Hz at the same time as the thyroumbrometer output. In this study, Po was sampled by having the subject hold a glass tube attached to a pressure transducer in the corner of the mouth, along with one channel of audio at 10 kHz.

The recording of larynx movement was calibrated by placing a notched piece of stiff cardboard immediately above the subject's thyroid prominence parallel to its line of movement. The notches were 1 cm apart, so their shadow could be used to determine the actual range of movement of the larynx.

2.2.1.2 Data reduction

The output of the photocells is represented as a string of 16 numbers, one for each column. The value for each column represents the height of the shadow, i.e. the row, cast on the column and, as mentioned above, the position of the shadow with respect to the columns represents the height

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of the larynx. The analysis procedure described next was designed to reduce this string of 16 numbers to a single number representing the height of the larynx.

After a recording session is complete, data analysis is carried out using a interactive procedure which allows the user to look at a reconstrucion of the outline or contour of the shadow of the thyroid prominence on a high-resolution graphics terminal. The user then selects a point along this contour as representing the vertical position of the larynx for that data frame. A portion of the contour spanning five columns centered on the point selected is stored in a template table for comparison with subsequent contours. If the next contour matches any contour which has already been evaluated and stored in the template table, within adjustable tolerances, then the present data frame is assigned the same value for larynx height as the template whose contour it matched. If instead no template in the table matches the present data frame, then the user is forced to evaluate it and a new template is stored in the table.

During the early part of the analysis of any subject's data, the user has to evaluate most of the data frames, since the number of templates in the table is small, but as

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the analysis proceeds and the template table starts to fill up, analysis becomes more and more automatic.

Presently, up to 200 templates can be stored in the table. Some or all of the templates, starting with those entered first and progressing to more recent ones, can be deleted if the table is filled and more data frames remain to be evaluated. The template table can also be reduced by coarsening the tolerances for assessing a match between the present data frame and the templates in the table. These procedures allow the user to keep the template table current, which is useful given the tendency of subjects to shift or settle slightly during the course of a recording session. Individual differences between subjects also resulted in the need to renew the table periodically. For subjects who have relatively low and prominent larynges, an entire recording session could be analyzed without having to empty the template table. On the other hand, if the subject's larynx has rather high, such that it tended to disappear into the chin, it was often necessary to renew the table more than once during the analysis of a single recording session. This was particularly true for the second subject (T2).

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The procedure described above was used in place of some entirely automatic curve-fitting approach for three reasons: first and probably foremost, it could be implemented quickly; second, subjects' tendency to shift or settle could throw off any automatic procedure; and third, it seems unlikely that any reliable procedure could be devised to track the thyroid prominence through its entire range of movement. When the larynx is low, the thyroid prominence has the appearance of a hump or hillock on the neck, and the first derivative or center of gravity of the contour would accurately indicate the vertical position of the larynx, but when the larynx is high in the neck and the upper half of the thyroid prominence disappears into the chin, neither feature is is a reliable indicator of where the larynx is.

2.2.1.3 Establishing a reference point for larynx height

In the next section, data are presented illustrating the relationship between larynx movement and Po in Tigrinya. Before presenting these data, I will outline the general principles applied to its analysis. Since all the speakers examined raised their larynges considerably (at least 5mm) before beginning to speak, the minimum larynx height within

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the utterance is taken as the reference, i.e. zero, point for assessing the movement of this structure, rather than its rest position. Actually, the zero point is the minimum within a portion of the utterance, beginning in the last word of the part of the frame sentence preceding the word of interest and ending in the following word of the frame. Both the beginning and ending points of this interval are within the vowels of the preceding and following frame words. Taking a value from inside the utterance as the zero point means that larynx movement is assessed within the smaller range it covers during speech rather than within the much larger range the larynx moves across in making the transition from not speaking to speaking and back to not speaking again. Furthermore, the effect of larynx movement on Po (or Fo) during or adjacent to a segment embedded in an utterance can only be with respect to the larynx's position in the immediate vicinity of that segment. In other words, the preparatory elevation of the larynx before speaking or its fall after speaking ends cannot significantly influence the more microscopic changes in Po (or Fo) produced by stops in the middle of the utterance. Note also that the range of movement is not changed by taking an utterance-internal value as a reference point since doing so only shifts the

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endpoints by adding a constant to all values.

2.2.1.4 Format of data presentation

Both the larynx movement and Po curves presented in the figures in the following section are averages, taken from between 4 and 6 tokens of each word. The individual tokens were linearly time-warped before averaging so that the points representing the following aerodynamic events were aligned: the beginning of the pressure rise, which occurs near and usually slightly before the oral closure; the point where pressure starts to drop precipitously, which usually follows the oral release by a few milliseconds; and the point where pressure returns to zero, also soon after the oral release. The principle reason for averaging the data before analysis was to smooth out irrelevant fluctuations in the larynx height and pressure curves, especially the AC modulation of the pressure curve due to voicing. The effect of voicing during flanking vowels on the pressure curves was not entirely eliminated by averaging, however. This effect shows up as a positive shift in the entire Po curve. All measurements of Po were made taking this shift into account, i.e. Po during flanking vowels was considered to represent

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zero air pressure and the elevation which occurred during the stop was measured relative to that zero value.

In the figures in the following sections, averaged larynx height (LH: in millimeters (mm)) and pressure (Po: in centimeters of water (cm H_2O)) curves are displayed over the averaged half-wave rectified rms amplitude curve. The important aerodynamic events are marked with labelled vertical lines: PC = pressure at the oral closure; PD = the pressure drop following the oral release; PZ = the point where pressure returns to zero after the release.

2.2.1.5 The speakers

Three young male speakers of Tigrinya, designated T1, T2, and T3, all from Asmara, the principal city of Eritrea, the Tigrinya-speaking area in Ethiopia, were recorded. All three left Eritrea within the past year and have been in the United States for a number of months. Like most adult Tigrinya speakers, these people all speak Amharic as well, but no influence from that language is detectable in the data reported here.

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2.2.1.6 The words recorded

Since the catheter to which the pressure transducer was connected was simply inserted into the corner of the subject's mouth, pressure data was only obtained for bilabial consonants. Furthermore, only bilabial stops are evaluated here; no analysis of pressure changes during nasals was attempted. The increase in Po during nasals was invariably quite small: approximately 1 cm H_2O at a maximum.

The words /p'ap'a/ 'Pope', /papa/ 'papa', and /baba/ 'carry a child on the back' were recorded in the frame /dägämä ____ bəl/ 'repeat ____!'.[1] Six repetitions of each word were obtained. Neither the ejective /p'/ nor the voiceless unaspirated stop /p/ occur in native words in Tigrinya; they are only found in loans from Greek or Italian. Nonetheless, since the language has both ejectives and voiceless unaspirated stops at the dental and velar places of articulation, I assume that both /p'/ and /p/ have been fully assimilated. The words recorded were all immediately recognized by the three speakers recorded. /b/ is extremely frequent in native vocabulary.

In the next section, each subject's performance is

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first assessed separately and then the subjects are compared and the results summarized.

2.2.2 The results

The results of the air pressure study are presented in the following trio of figures.

Table 2.1

Po vs. larynx height

Figure #	Figure description
2.1.1	Subject T1 - composite plot of Po, larynx height and amplitude for voiceless (dotted line), voiced (dashed line), and ejective (solid line) stops.
2.1.2	Subject T2 - same format
2.1.3	Subject T3 - same format

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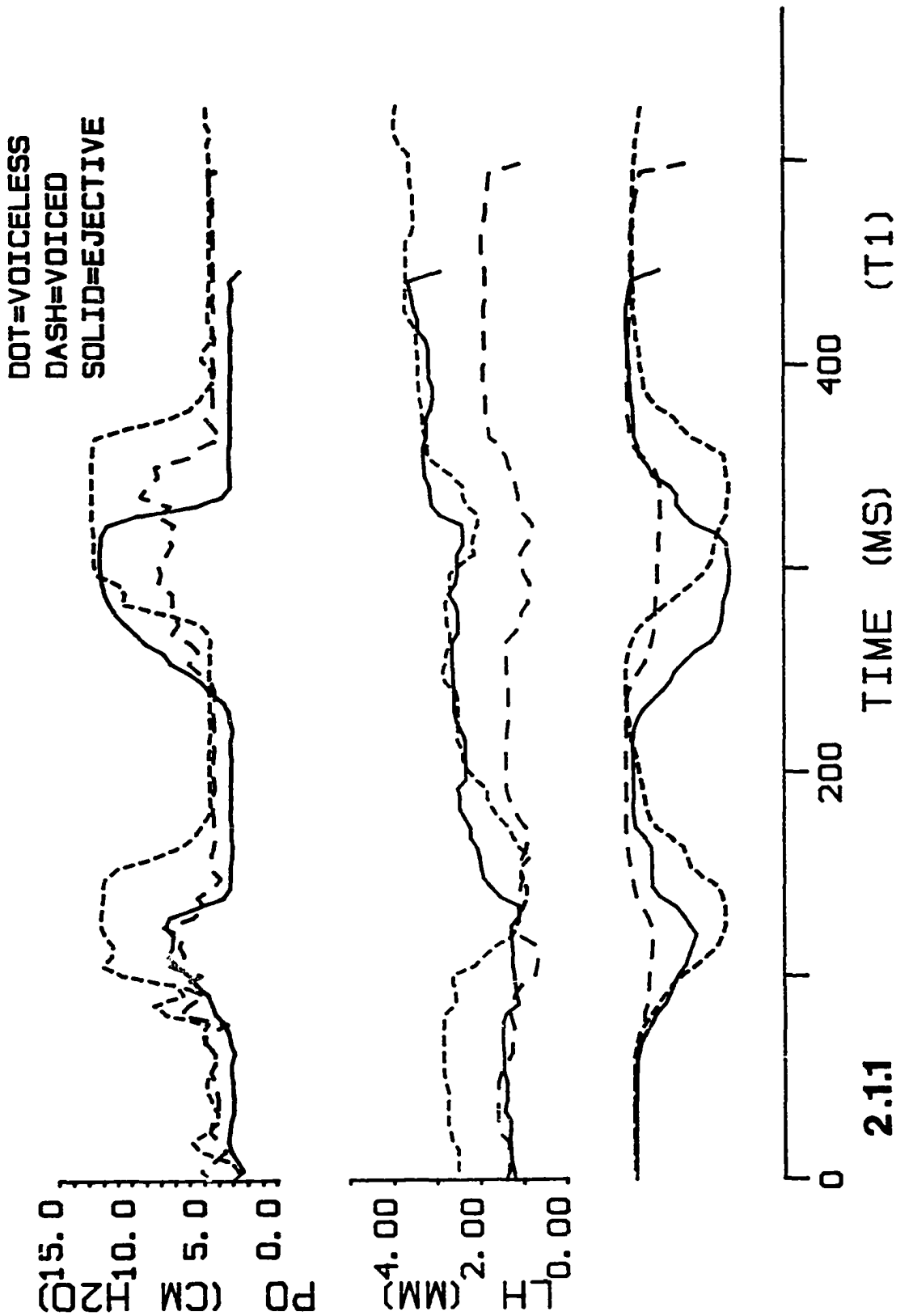

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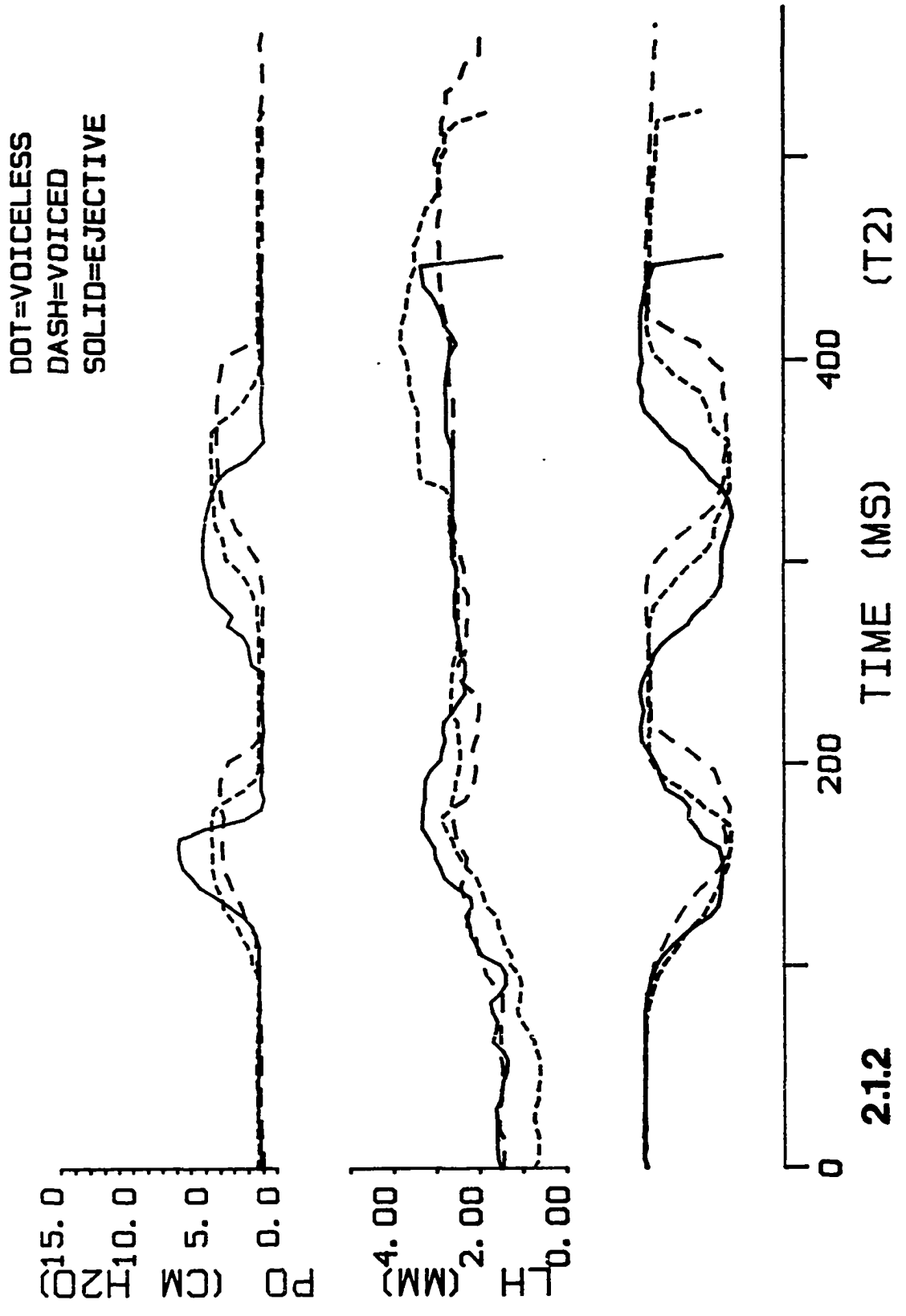

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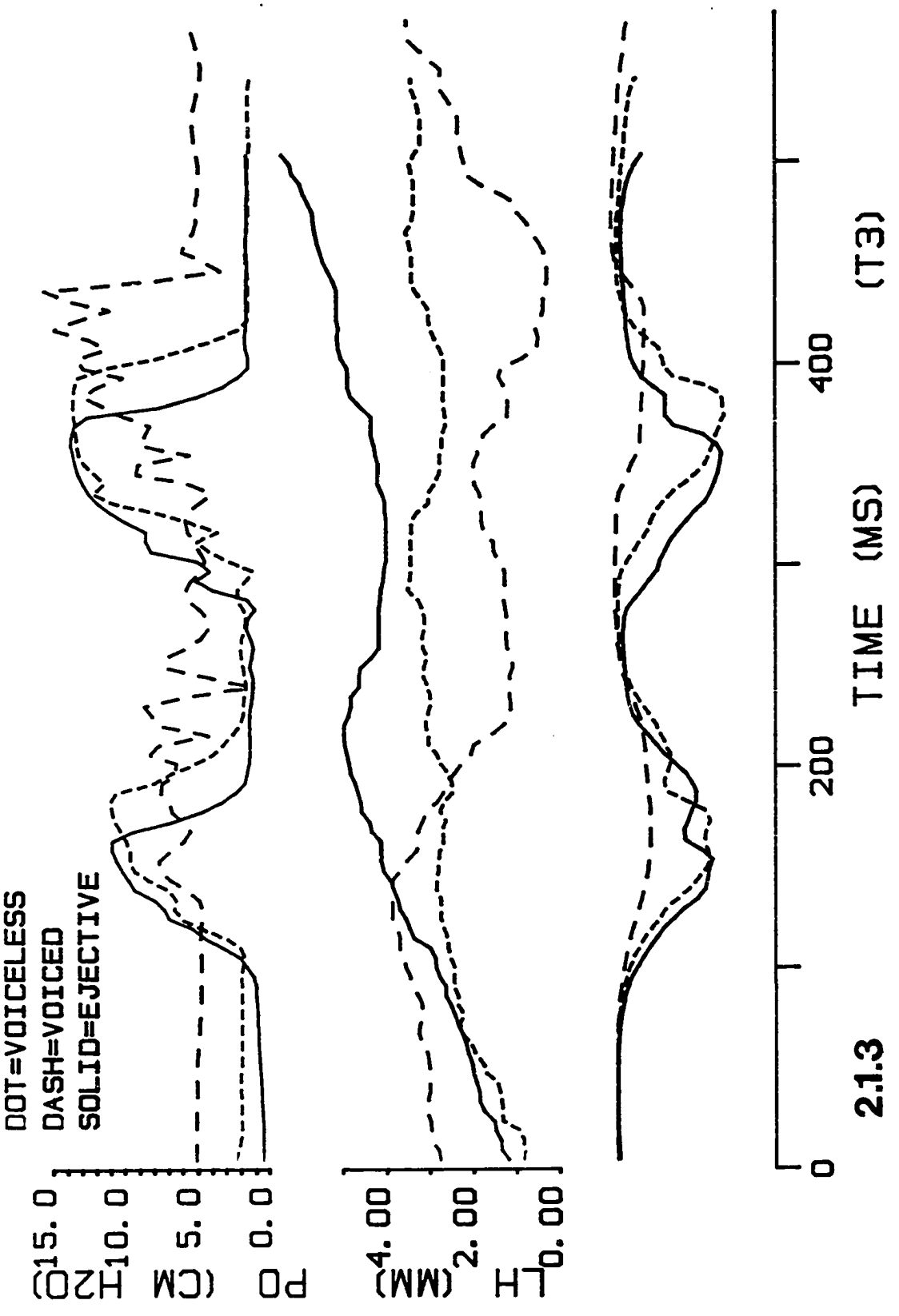

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These figures show averaged air pressure (Po: in cm H_2O) and larynx height (LH: in mm) for the three speakers of Tigrinya. Even a brief comparison of these three figures reveals that the larynx is neither raised nor lowered in the same way in the three speakers examined. Both T1 (fig. 2.1.1) and T2 (fig. 2.1.2) exhibit relatively less larynx movement than T3 (fig 2.1.3): for T1 and T2, the larynx moves across a range of less than 4 mm, while for T3, its range of movement spans at least 6 mm (this difference between T3, on the one hand, and T1 and T2, on the other, carries over to the dental and velar stops discussed in chapter 3). Note that T2's larynx moves somewhat less than T1's; in fact, T2's larynx moved relatively little in all the tokens examined. As a consequence, for this speaker there is markedly little difference in larynx height between ejectives and voiced and voiceless stops. The figures for the other two speakers, on the other hand, show that the larynx is at least consistently higher during ejectives and voiceless stops than voiced ones and in the speech of T3 it is higher still for ejectives than voiceless stops.

I suspect that the greater range of movement exhibited by T3 compared to T1 and T2 comes from T3 having spoken in a more careful, formal style than the other two speakers did. T2, in particular, used a much more casual style than T3. If the larynx moves relatively little in more casual styles,

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then Po will not be elevated as much and the ejectives in particular will have weaker bursts. The pressure increase behind the stop closure is uniformly lower for T2 than either T1 or T3, amounting to no more than 5 cm H_2O for ejectives, compared to nearly 10 cm H_2O for T1 and 13 cm H_2O for T3. This explains the impression of weak articulation of ejectives one gets listening to T2 or for that matter Tigrinyas holding a rapid conversation with one another. The ejectives are simply not very noticeable (Johanna Nichols (p.c.) reports a similar weakness for ejectives in casual conversation in Georgian. However, when Georgians speak to nonGeorgians, they produce much more noticeably glottalized consonants.)

The second point which is obvious from these figures is that larynx movement is not closely synchronized with either the oral closure or release for any of the three speakers. This is true even for ejectives, where raising the larynx during the stop closure is supposed to be the principal mechanism behind the elevation of Po. When words are examined where another stop does not immediately follow the initial stop, as in the words considered in the next chapter, a slightly different picture emerges. The next two figures represent larynx movement during word-initial dental

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and velar stops in Tigrinya, where a sonorant rather than a stop begins the next two syllables. The words illustrated are third person masculine singular forms of the verbs /tälälä/ 'sketch', /dälälä/ 'deal', /t'älälä/ 'wet', /kälälä/ 'enclose', /gälälä/ 'separate', and /k'älälä/ 'easy'. All were spoken by T3, the subject whose larynx moved the most. Each plot represents an average of 4 to 6 tokens of each word. The landmarks in these plots are the oral closure (OC), the oral release (OR), and the beginning of the vowel (BV). Intraoral air pressure could not be measured for stops at these two places of articulation because the catheter was only inserted into the corner of the mouth rather than through the nasal cavity into the pharynx.

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Table 2.2

Larynx movement for dental and velar stops

Figure #	Description
2.2.1	Subject T3 — voiceless dental stop -- larynx height and amplitude
2.2.2	Voiced dental stop -- same format as 2.2.1
2.2.3	Dental ejective -- same format as 2.2.1
2.2.4	Voiceless velar stop -- same format as 2.2.1
2.2.5	Voiced velar stop -- same format as 2.2.1
2.2.6	Velar ejective -- same format as 2.2.1

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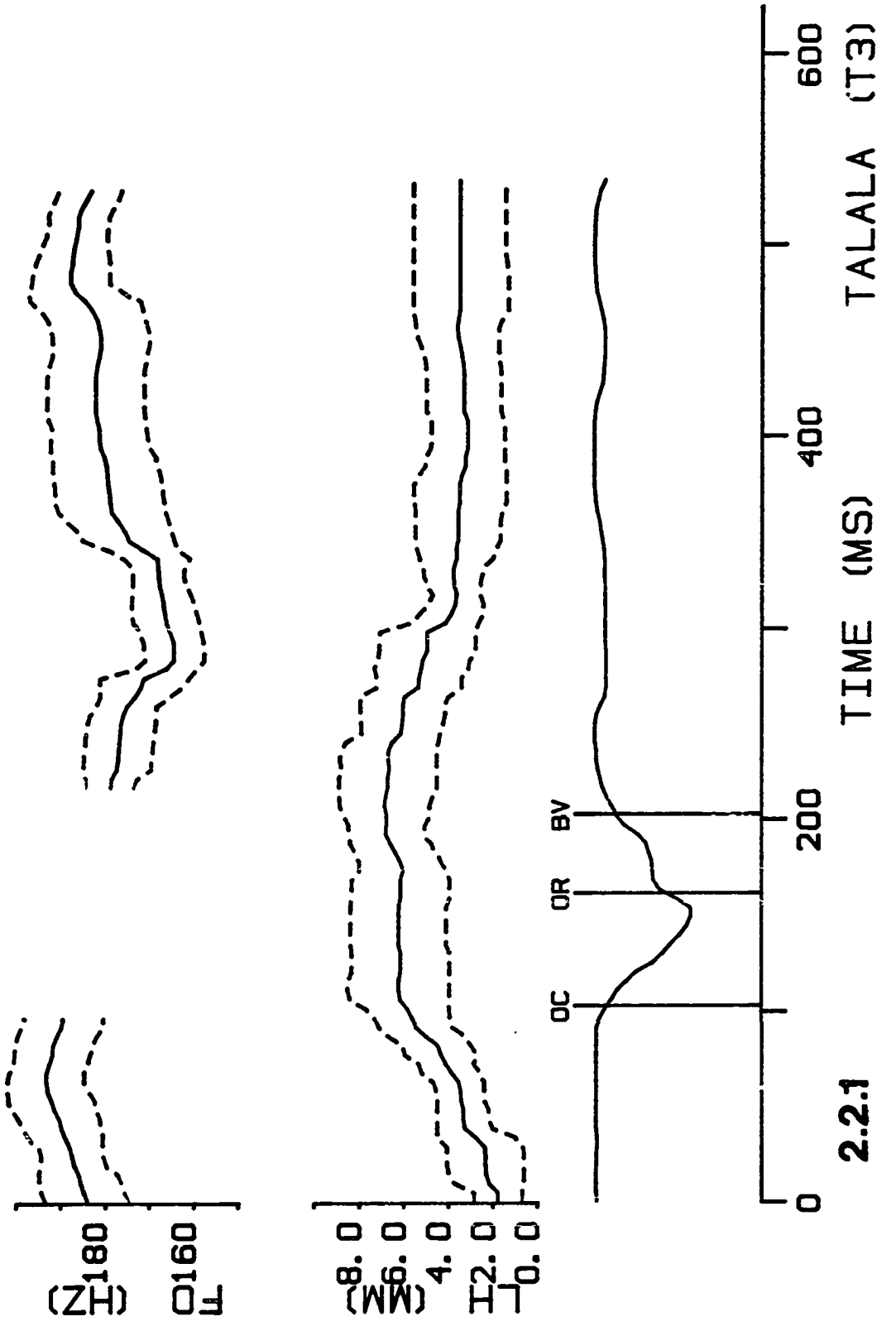

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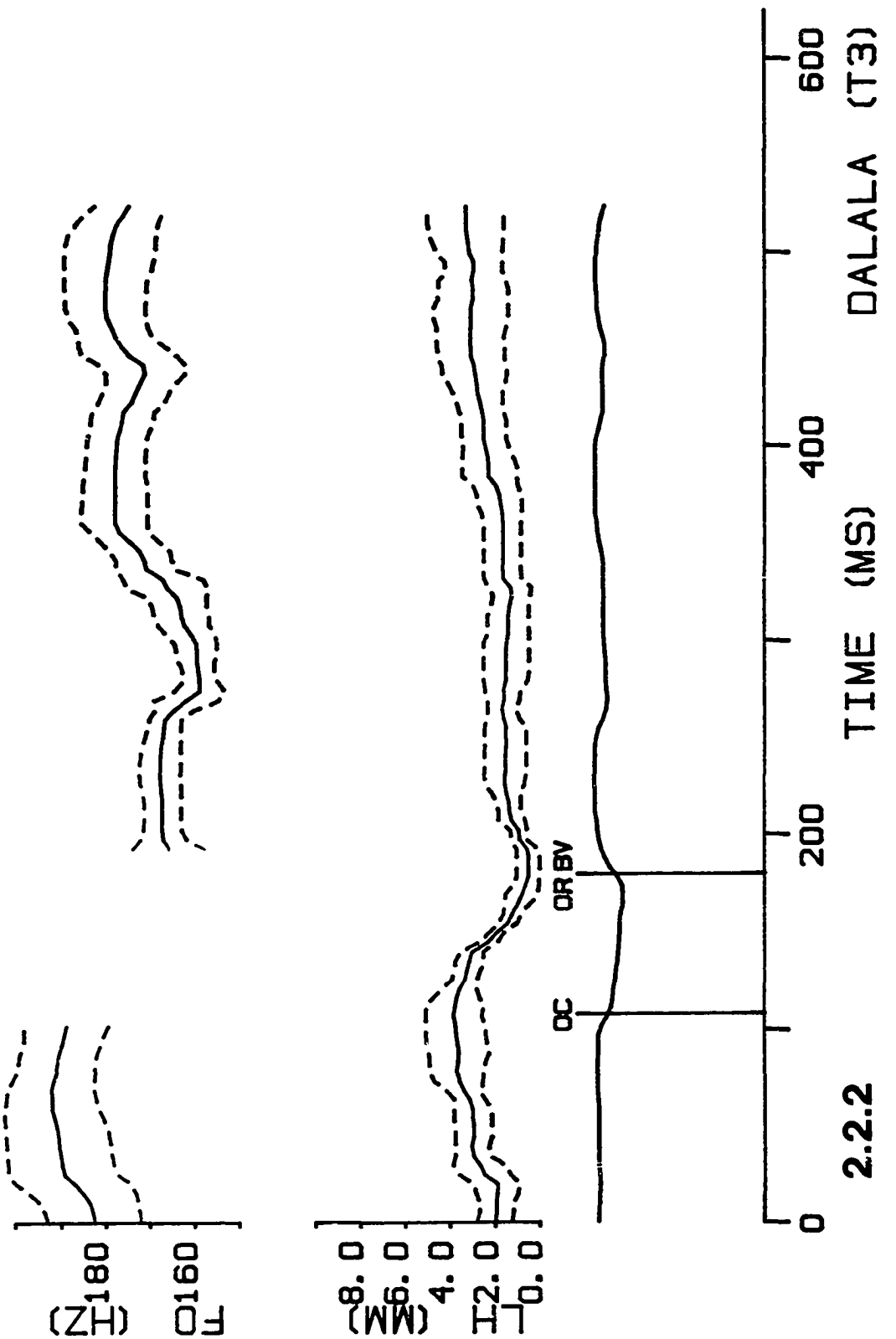

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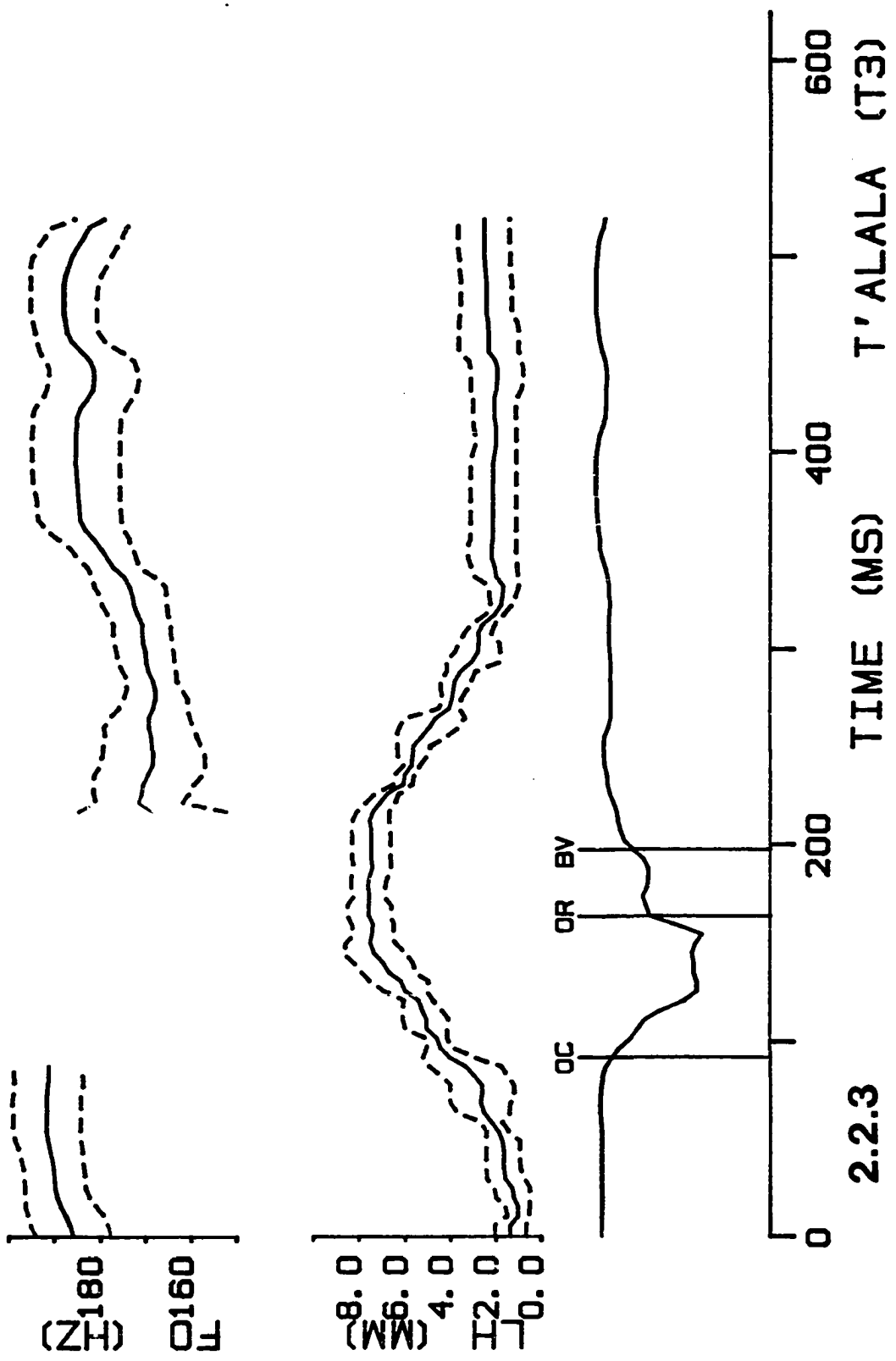

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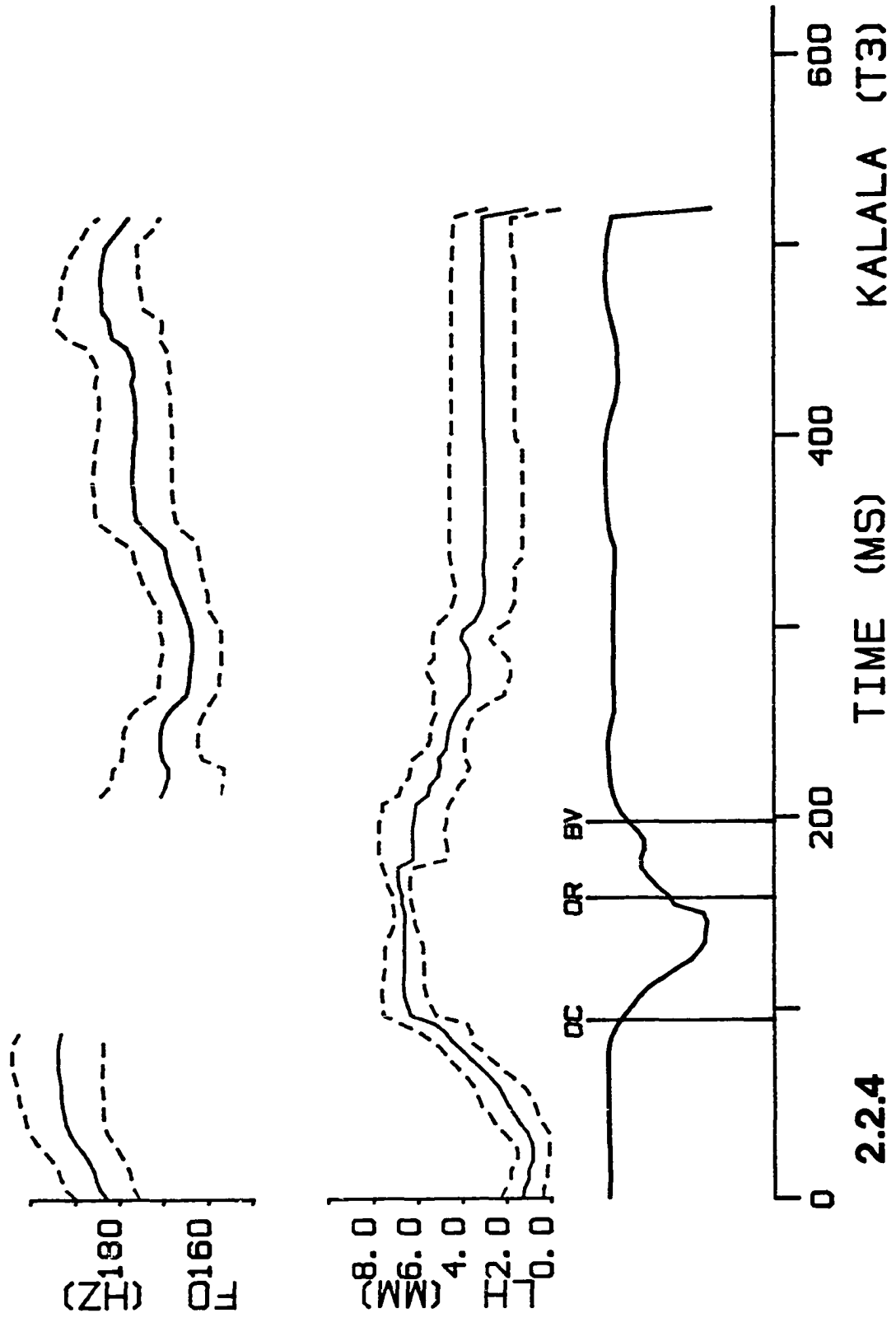

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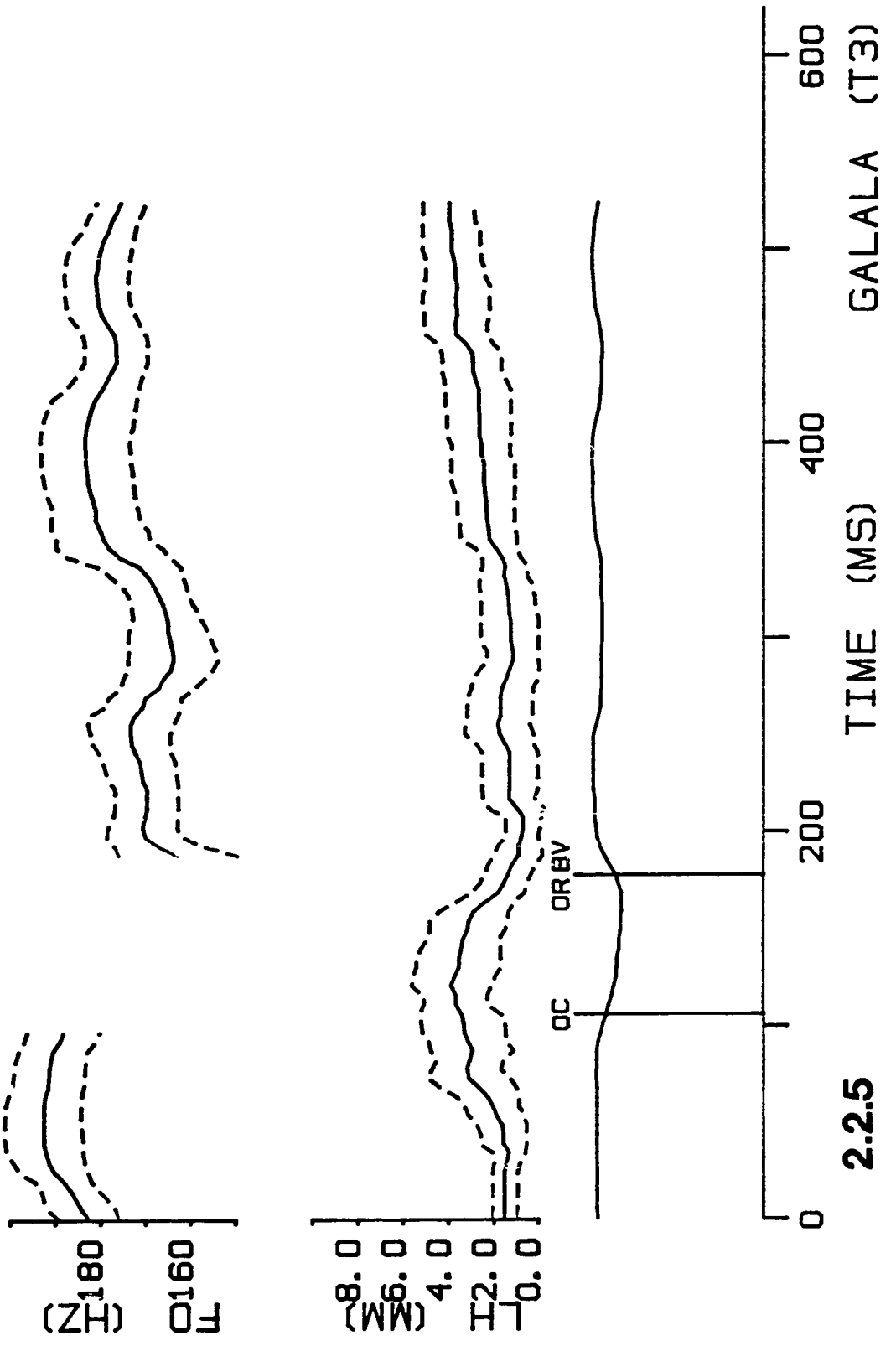

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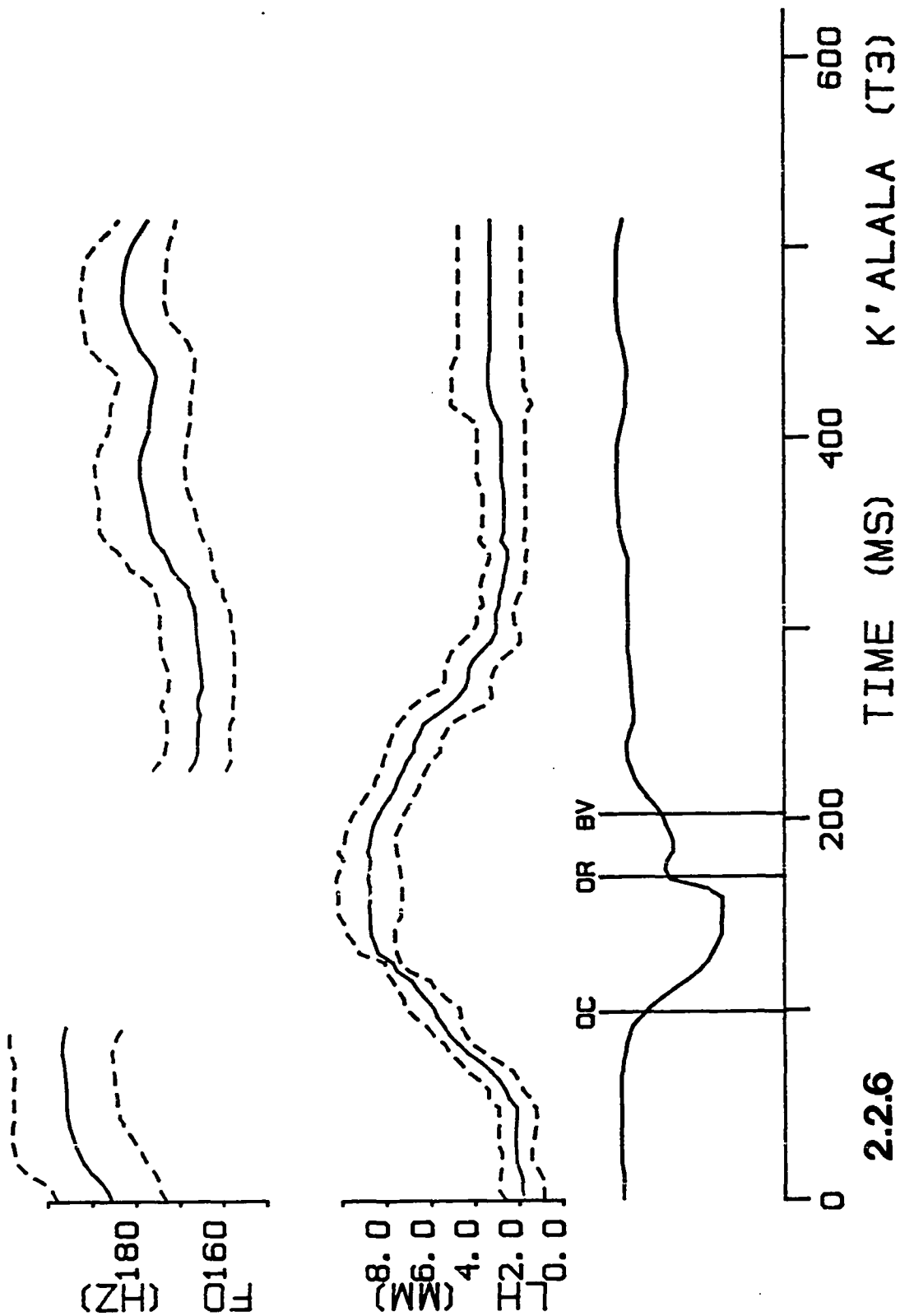

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Figures 2.2.3 and 2.2.6 illustrate average larynx movement curves for dental and velar ejectives spoken by T3 and clearly show that larynx raising does take place across the initial stop in these words, though raising begins well before the stop closure is complete and lowering does not occur until well after the stop is released. A comparison of figure 2.2.1 with 2.2.3 and of 2.2.4 with 2.2.6 shows that although the larynx is raised during voiceless stops, the amount of elevation which occurs is less than is observed for ejectives at each place of articulation. Finally, figures 2.2.2 and 2.2.5 show that larynx remains quite low and is even depressed slightly for voiced dental and velar stops. The very slow movement of the larynx in all these words suggests that in words like /p'ap'as/, the second ejective follows so closely on the first that the larynx has no time to drop back down before it has to be elevated again. As a result, the larynx remains in a relatively high position throughout the word. Similar undershoot, though in reverse, is evident in /baba/, where the larynx fails to rise appreciably between the two voiced stops.

The undershoot and apparent lack of close synchronization with oral articulations that such slow movement of the larynx causes is a problem for any explanation of stop articulation which depends larynx raising or lowering to effect a substantial contraction or expansion of the oral cavity

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during the stop closure. This is because the larynx will already be relatively high or low by the time the closure is complete and any subsequent movement during the closure itself will be too slow to have a pronounced effect on Po. The oral closing and opening gestures are, of course, not instantaneous themselves, lasting some 50 to 55 ms for bilabials and dental/alveolars and as much as 70 ms for velars (Keating, Westbury, & Stevens 1980). This implies that larynx movement may, in fact, follow the oral articulations more closely than the pressure curves in figures 2.1.1-3 imply. Even so, air pressure does not start to increase noticeably until the oral closure is nearly complete and it drops precipitously after the closure is released, so the efficiency of larynx movement in manipluating Po is in no way increased by its being synchronized with the oral articulations. So, if more elevation of Po is required than larynx raising can provide, some other maneuver, such as retracting the tongue root or stiffening the vocal tract walls, would have to be employed; conversely, advancement of the tongue root and relaxing the walls would be required in addition to larynx lowering in stops where lowering Po is the goal.

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Related to this issue is the fact that Po is not noticeably higher for ejectives than it is for voiceless stops for any of these three speakers. If Po were higher for ejective than voiceless stops, then ejectives would have more intense bursts (more intense bursts were observed for ejectives in the speech of another speaker of Tigrinya (Kingston 1982)). Even without differences in Po, the burst spectra of the two classes of stops will be different because the glottis is closed for ejectives but open for voiceless stops. With a closed glottis, the vocal tract rings longer and at a lower frequency -- theoretically, an octave below its ringing frequency during a voiceless stop. A closed glottis also means that the release of an ejective will be distinguishable from that of a voiceless stop by the absence of cavity friction during the aspiration interval. A relatively fast rise time of the following vowel once the glottal closure is released and a difference in fundamental frequency at vowel onset are also observed in some cases (see Chapter 3 for a fuller discussion). In short, it is not so much that the two kinds of stops themselves differ as that the transitions from the stop to the following vowel are distinct.

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2.3 Modelling Tigrinya stops

2.3.1 Introduction

In this section, the results of attempting to model the aerodynamics of of intervocalic ejectives and voiceless stops in Tigrinya using the digital version of Rothenberg's model described by Müller and Brown (1980) are presented.

2.3.2 Input parameters for the model

The principal input parameters used in the simulation of Tigrinya stops are:[2]

a. the volume of the supraglottal cavity, modelled as differences in the compliance (Co) of the air in the cavity, which is proportional to the volume:

bilabial: Co = .0000712

dental: Co = .0000582

velar: Co = .0000418

(units: dynes/cm^5)

b. the compliance of the walls of the vocal tract,

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represented by three values: 1) the wall compliance (Cw), 2) the wall resistance (Rw), and 3) the wall inductance (Lw). Two conditions were modelled, one corresponding to relaxed and, therefore, highly compliant vocal tract walls and the other to tense and less compliant walls:

	Cw	Rw	Lw
relaxed:	.0012	8.0	.021
tense:	.00045	9.9	.015

Units: Cw: liter/cm H_2O

Rw: cm H_2O/liter/sec

Lw: cm H_2O/liter/sec^2

c. the timing of the opening and closing of the supraglottal cavity. The model provides an interval of 255 ms for a simulation. The cross-sectional area of the oral cavity was set at values appropriate for a vowel at the beginning and end of this interval, i.e. 0.3 cm^2. To model the closure of the stop, the cross-sectional area was reduced linearly to 0.001 cm^2 at 100 ms and the closure was maintained for 70 ms. The duration of the opening and closing gestures depended on the place of articulation of the stop: 50 ms for bilabial stops, 55 ms for alveolar stops, and 70 ms for velars. This

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difference in articulator velocity is a attempt to include the effects of differences in the inertia of the lips, tongue tip, and tongue dorsum (cf. Keating, Westbury, & Stevens 1980). Since the duration of the stop closure was kept constant at 70 ms, this difference is realized in the flanking vowels:

	Vowel 1	Closing	Closure	Opening	Vowel 2	
bilabial:	0-50	50-100	100-170	170-220	220-255	(ms)
dental:	0-45	45-100	100-170	170-225	225-255	
velar:	0-30	30-100	100-170	170-240	240-255	
cross-sectional area of the oral cavity	.3-.3	.3-.001	.001-.001	.001-.3	.3-.3	(cm^2)

d. the glottal resistance, which was varied from moderate levels during the preceding and following vowels to a relatively low level during the closure for voiceless stops and to a relatively high level during the closure for ejectives. Glottal resistance is simulated as variation in glottal area: glottal area increased, lowering resistance to air flow during voiceless stops and decreased, increasing resistance for ejectives. During the flanking vowels, the glottal area was set at 0.04 cm^2 , which produces a glottal resistance of

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approximately 70 cgs ohms. During the closure interval for voiceless stops, the cross-sectional area of the glottis was increased linearly to 0.2 cm^2 , which reduces the glottal resistance to approximately 0.7 cgs ohms -- a reduction by two orders of magnitude --, peaking 10 ms before the stop release. Abduction of the glottis began at the moment the stop closure was complete and therefore took 60 ms; adduction required 50 ms. The glottal area during the flanking vowels has halved to 0.02 cm^2 , which increases the glottal resistance to approximately 280 cgs ohms -- a fourfold increase --, during the closure interval of ejectives in an attempt to model the medial compression of the vocal folds which takes place in this type of stop. This increase in glottal resistance did not stop transglottal air flow entirely, but further reduction so severely reduces the increase in Po during the stop closure that the elevation of Po expected for ejectives could not be obtained (figures 2.5.1-12 present results of modelling ejectives with a glottal area of only 0.002 cm^2 , which increases the glottal resistance to approximately 28000 cgs ohms -- 4000 times the resistance during the flanking vowels). Adduction of the

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folds for ejectives began at the moment of oral closure and abduction began shortly after the cross-sectional area of the oral cavity returned to vocalic state; both took 20 ms.

e. the change in the volume of the oral cavity brought about by the vertical movement of the larynx. All values in the simulation of this parameter are based on the data from T3 since his larynx moved the most. The amount of larynx raising which occurs between a point 100 ms before the oral closure was complete and the moment when the stop was released was determined and the amount of cavity contraction that this would cause was calculated. It was assumed that the cross-sectional area of the pharynx immediately above the glottis was 4 cm sq. Raising the larynx 1 mm will decrease the volume of the oral cavity by 0.4 cc. For T3, the larynx was raised between 1.5 mm for /p/ and 6.6 mm for /k'/, a range which produces volume changes from 0.6 to 2.7 cc in the interval over which larynx movement was considered. This contraction is modelled as a negative-going sinusoid, representing air flow (actually a current source), whose half-period is equal to 170 ms, the mean interval from the point when larynx

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movement was first assessed to the release of the stop. The peak flow represented by the change in cavity volume, when flow is represented as a sinusoid, can then be obtained from the following equation:

$$\text{Peak flow} = \frac{\text{Pi x Volume change}}{\text{Period}}$$

Substituting, one obtains the following values for peak flow for the various stops:

Stop	Larynx raising (mm)	Volume change (cc)	Peak flow (cc/sec)
p	1.5	-0.6	-5.5
p'	3.1	-1.2	-11.5
t	4.0	-1.6	-14.8
t'	5.8	-2.3	-21.4
k	5.6	-2.2	-20.7
k'	6.6	-2.6	-24.4

The values for volume change and peak flow are negative because raising the larynx contracts the cavity.

2.3.3 Results of the modelling

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2.3.3.1 Simulations of voiceless stops and ejectives

The principal output parameters are displayed in the following dozen figures.

a.

Po = intraoral (supraglottal) air pressure

Ps = subglottal air pressure

(lower left panel)

b.

Uo = air flow through the oral cavity

Ug = air flow through the glottis

(lower right panel)

c. Ie = change in the volume of the oral cavity

(upper right panel)

d. Change in oral and glottal aperture:

i) oral aperture: 0.3-0.001-0.3 cm^2.

ii) glottal aperture: 0.04-0.2-0.04 cm^2 voiceless stops

0.04-0.02-0.04 cm^2 ejectives

(upper left panel)

The change in the volume of the oral cavity (Ie) represents a lumping of the contraction brought about by raising the larynx and the expansion resulting from the compliance of the vocal tract walls, the latter counteracting to some

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extent the elevation in Po brought about by the former. Also included in this parameter is the effect of the different cavity volumes behind the three places of articulation modelled. As noted above, the effects on Po of a given contracting maneuver or the movement of a certain volume of air into the oral cavity are both inversely proportional to the volume of the cavity behind the closure.

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Table 2.3

Modelling Tigrinya voiceless stops and ejectives

Figure #	Description
2.3.1	Voiceless bilabial stop with relaxed vocal tract walls and a 5.5 cc/sec contraction of the oral cavity.
2.3.2	Same as 2.3.1, except with tense walls.
2.3.3	Ejective bilabial stop with relaxed walls and a 11.5 cc/sec contraction.
2.3.4	Same as 2.3.3, except with tense walls.
2.3.5	Voiceless dental stop with relaxed walls and a 14.8 cc/sec contraction.
2.3.6	Same as 2.3.5, except with tense walls.
2.3.7	Ejective dental stop with relaxed walls and a 21.4 cc/sec contraction.
2.3.8	Same as 2.3.7, except with tense walls.
2.3.9	Voiceless velar stop with relaxed walls and a 20.7 cc/sec contraction.
2.3.10	Same as 2.3.9, except with tense walls.
2.3.11	Ejective velar stop with relaxed walls and a 24.4 cc/sec contraction.
2.3.12	Same as 2.3.11, except with tense walls.

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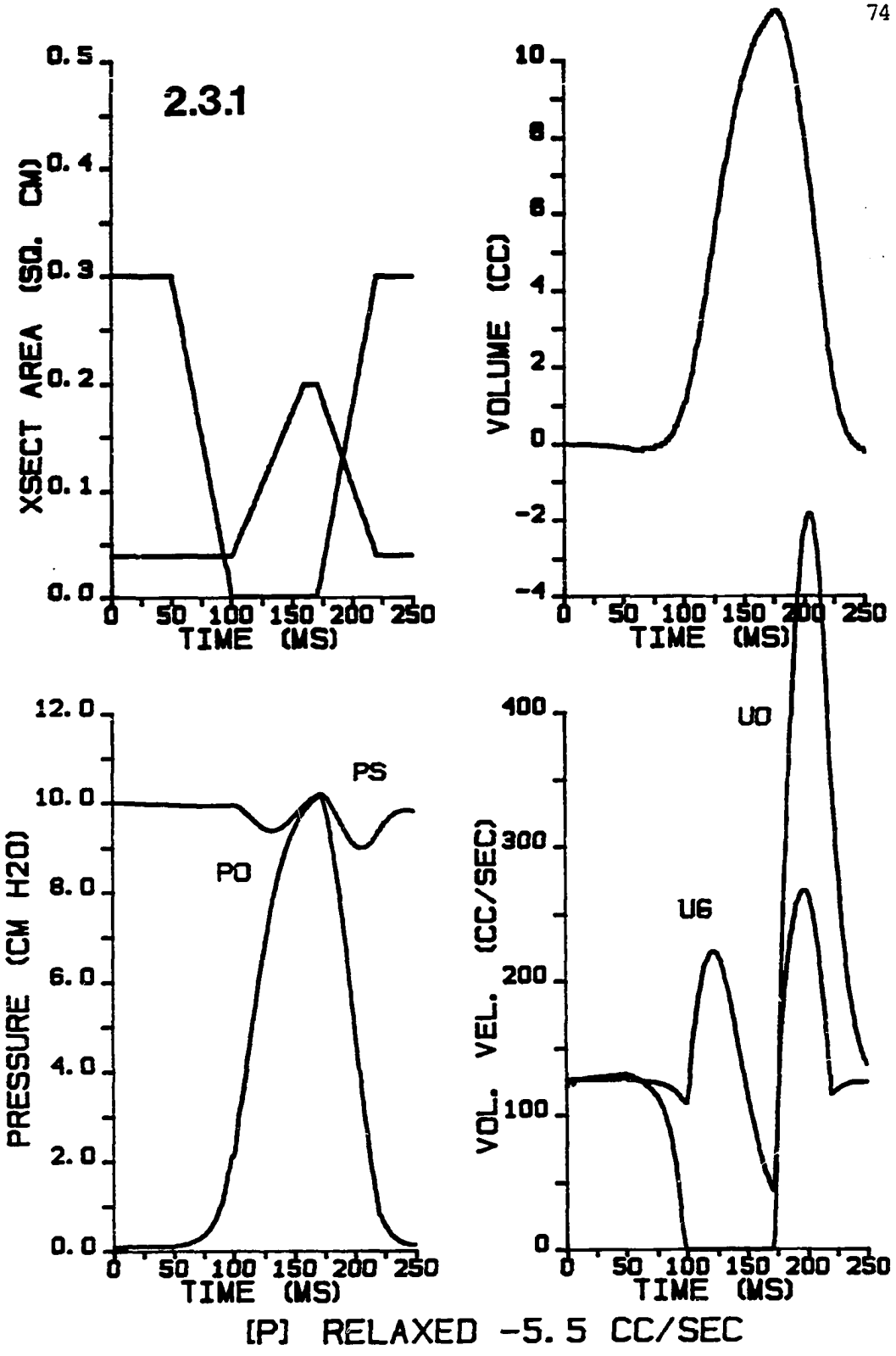

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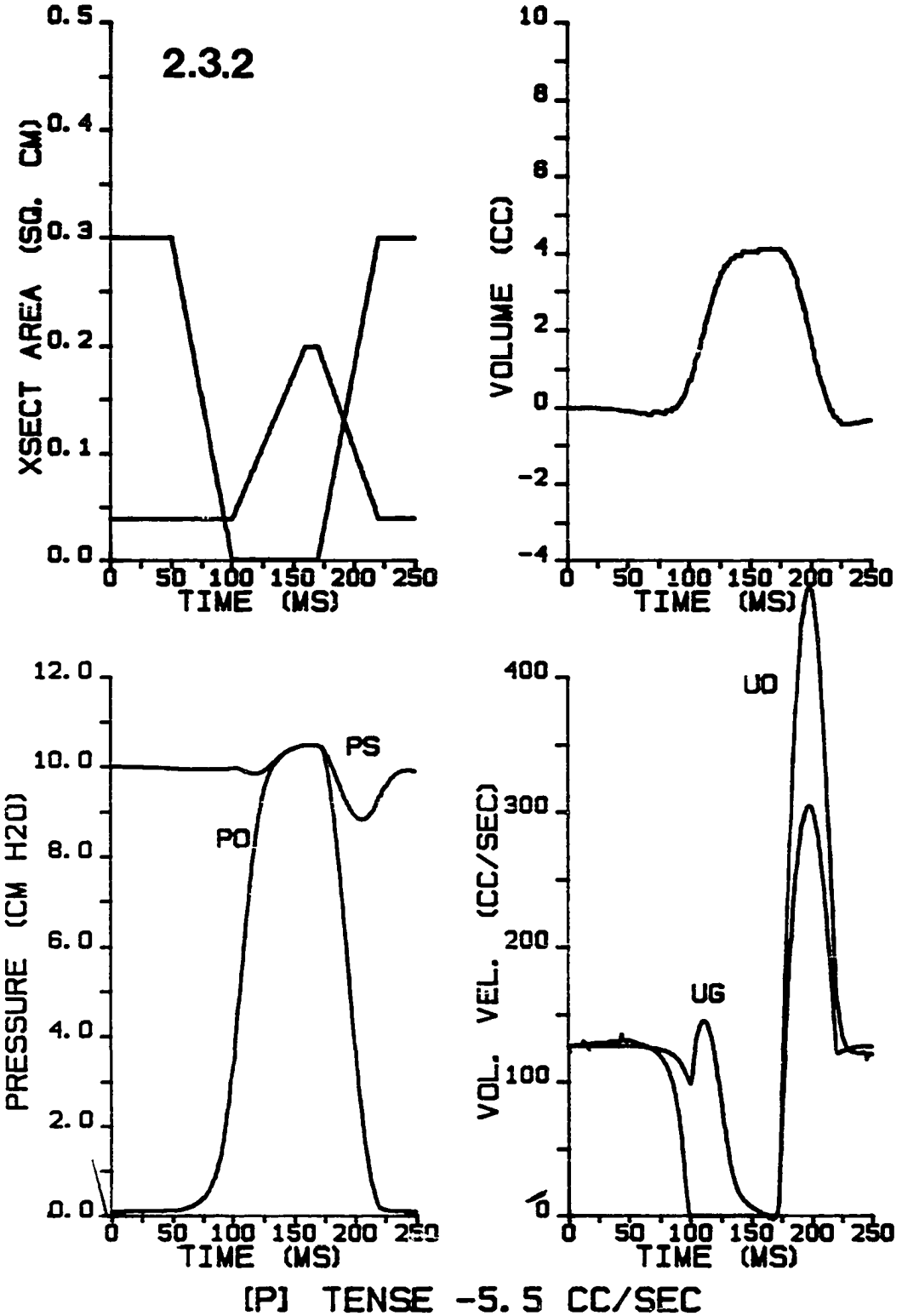

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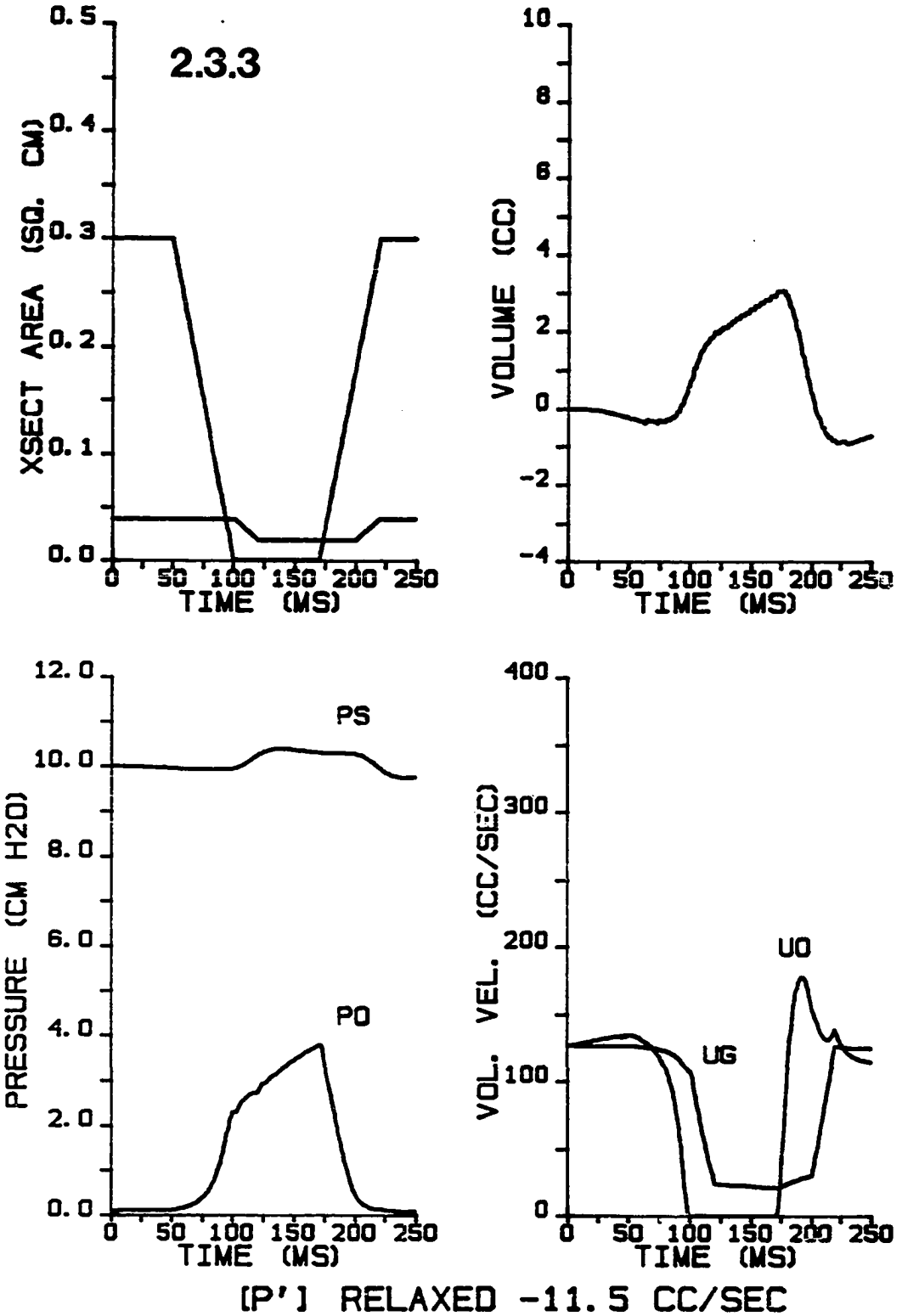

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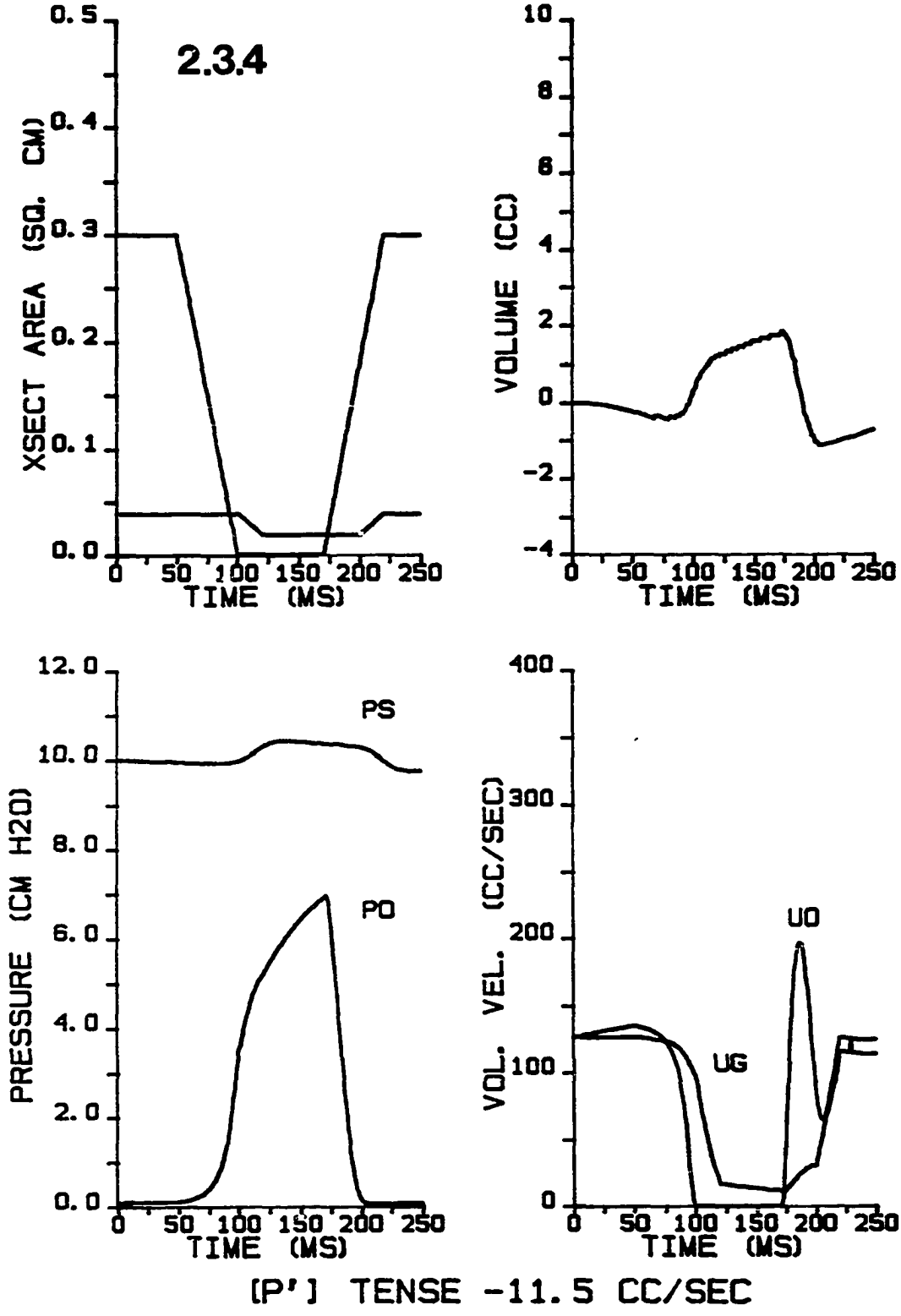

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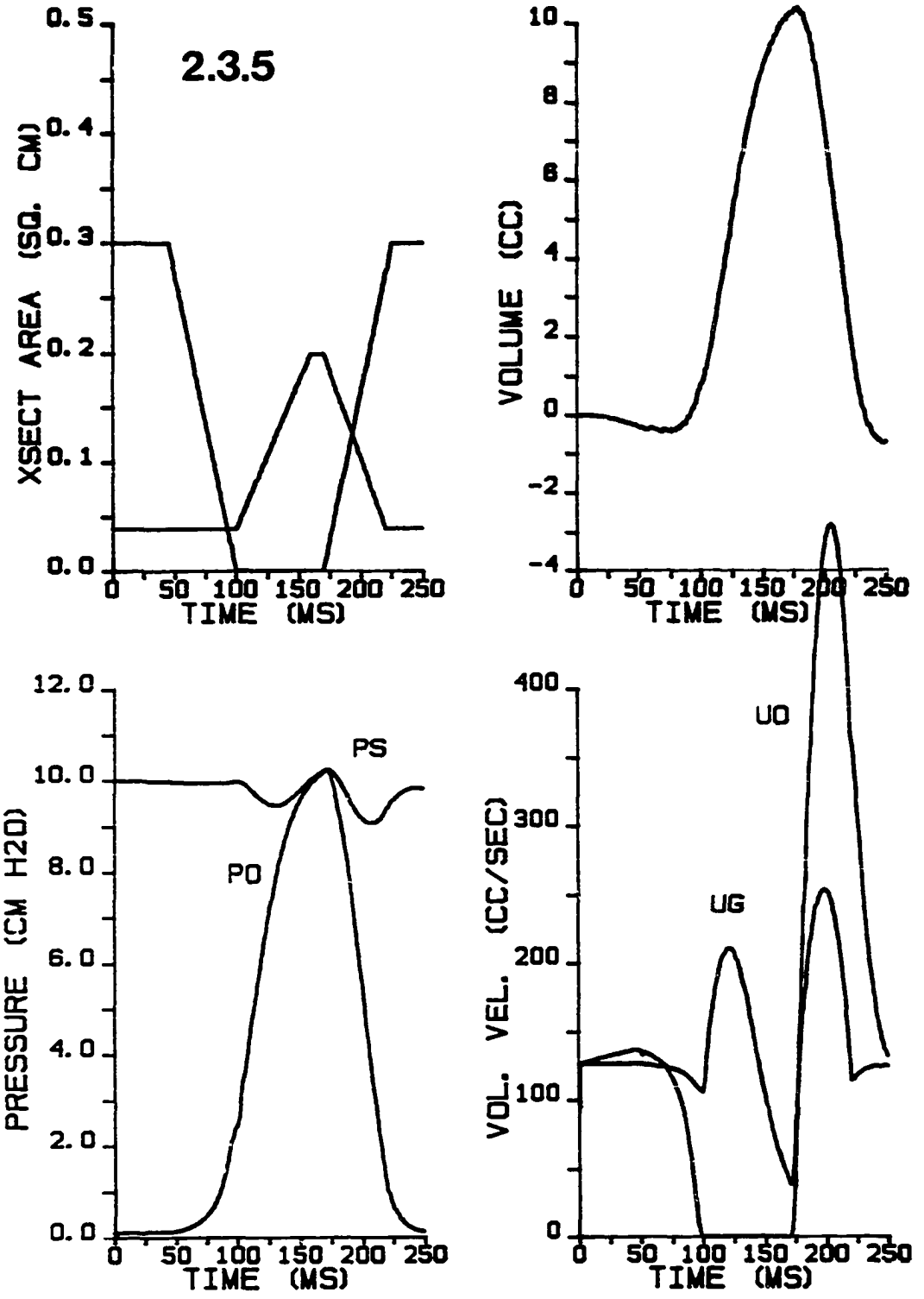

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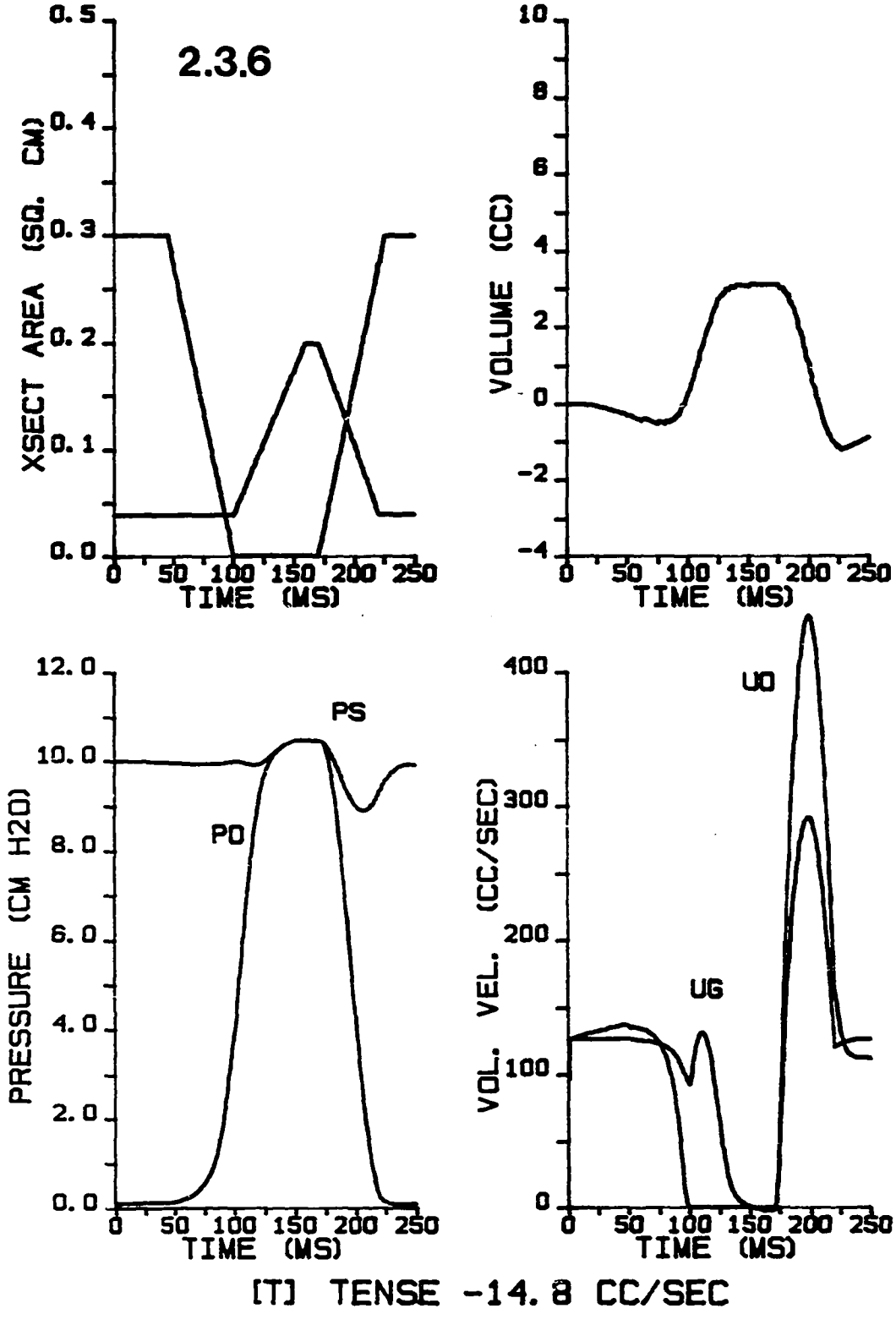

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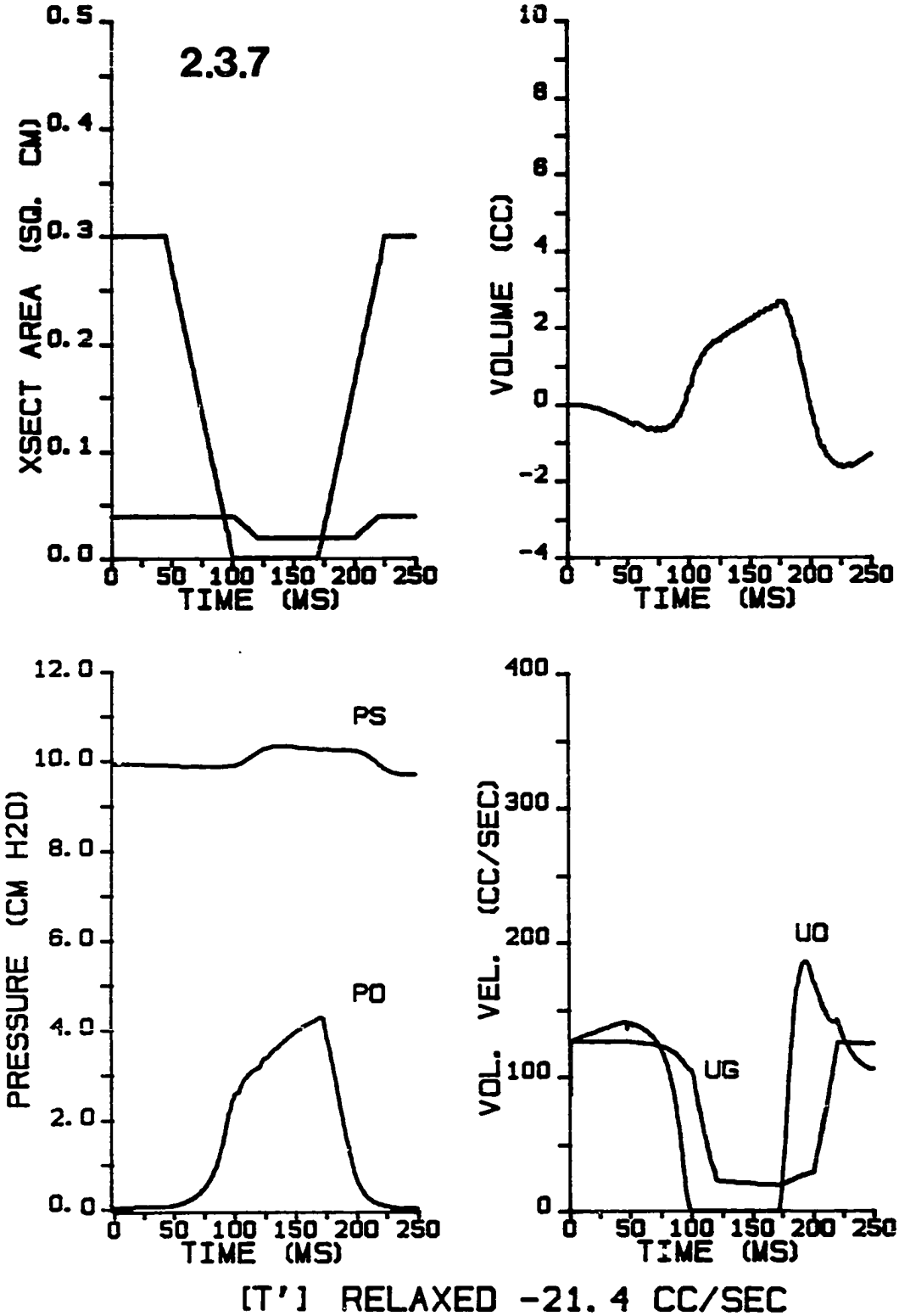

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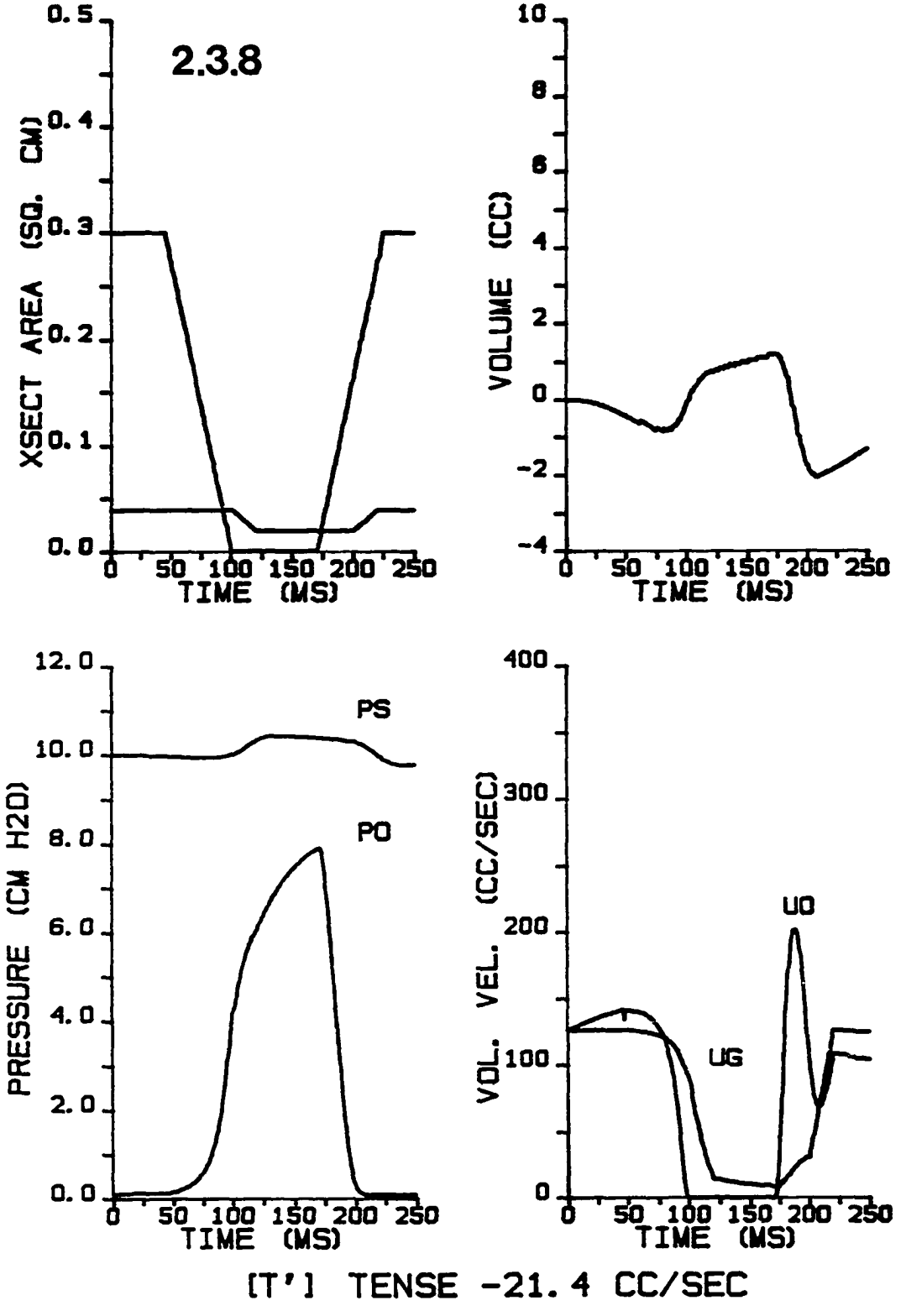

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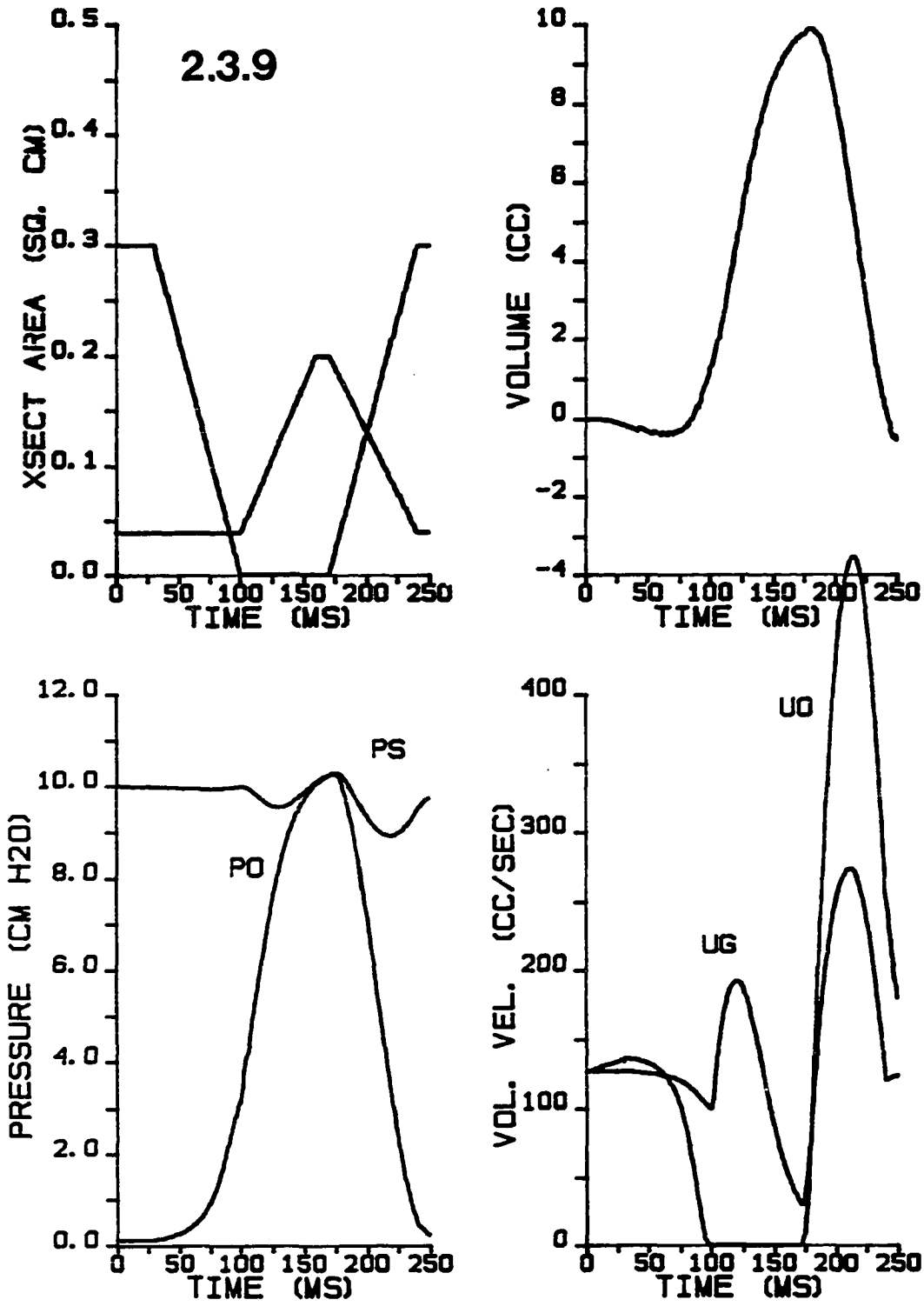

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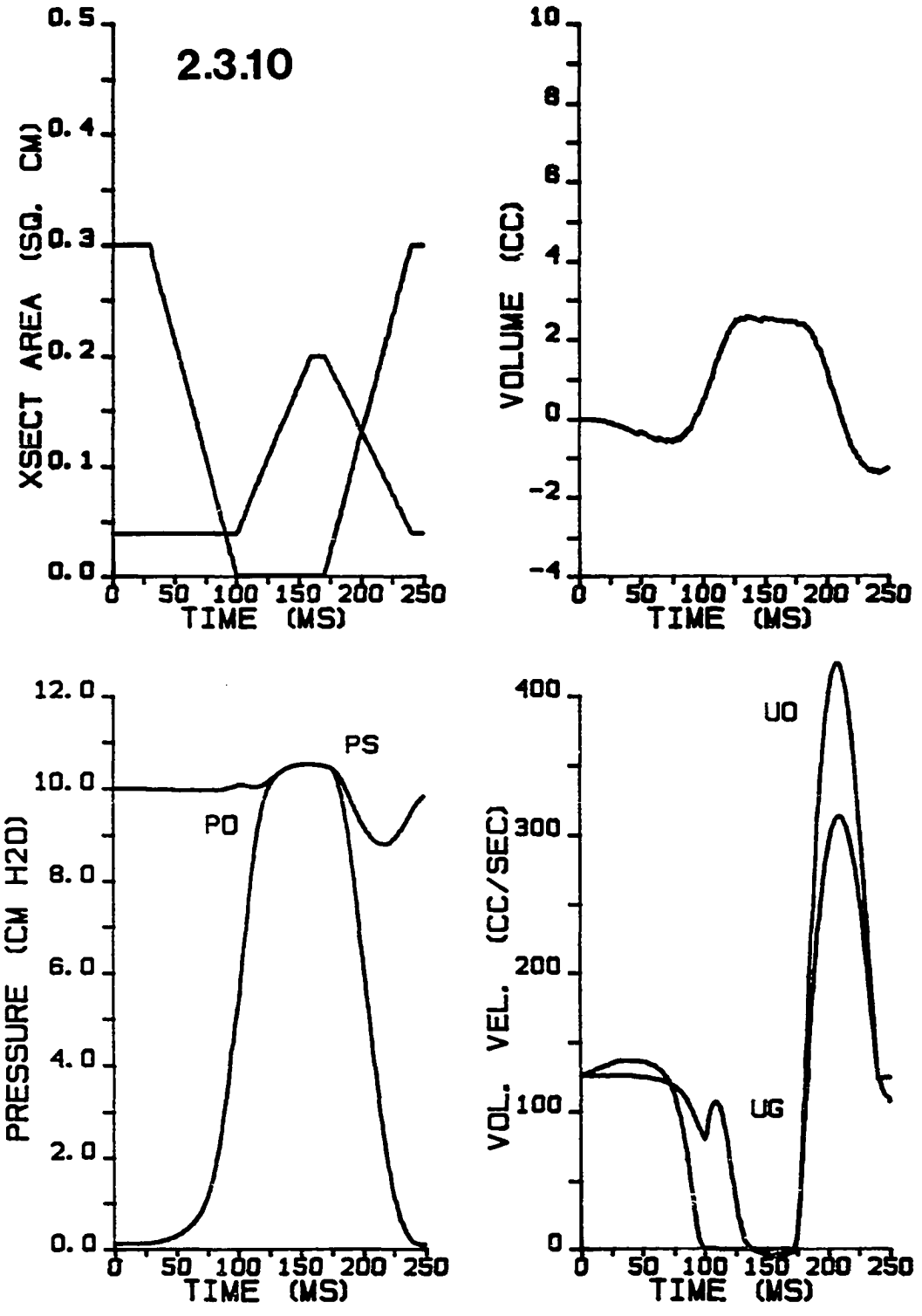

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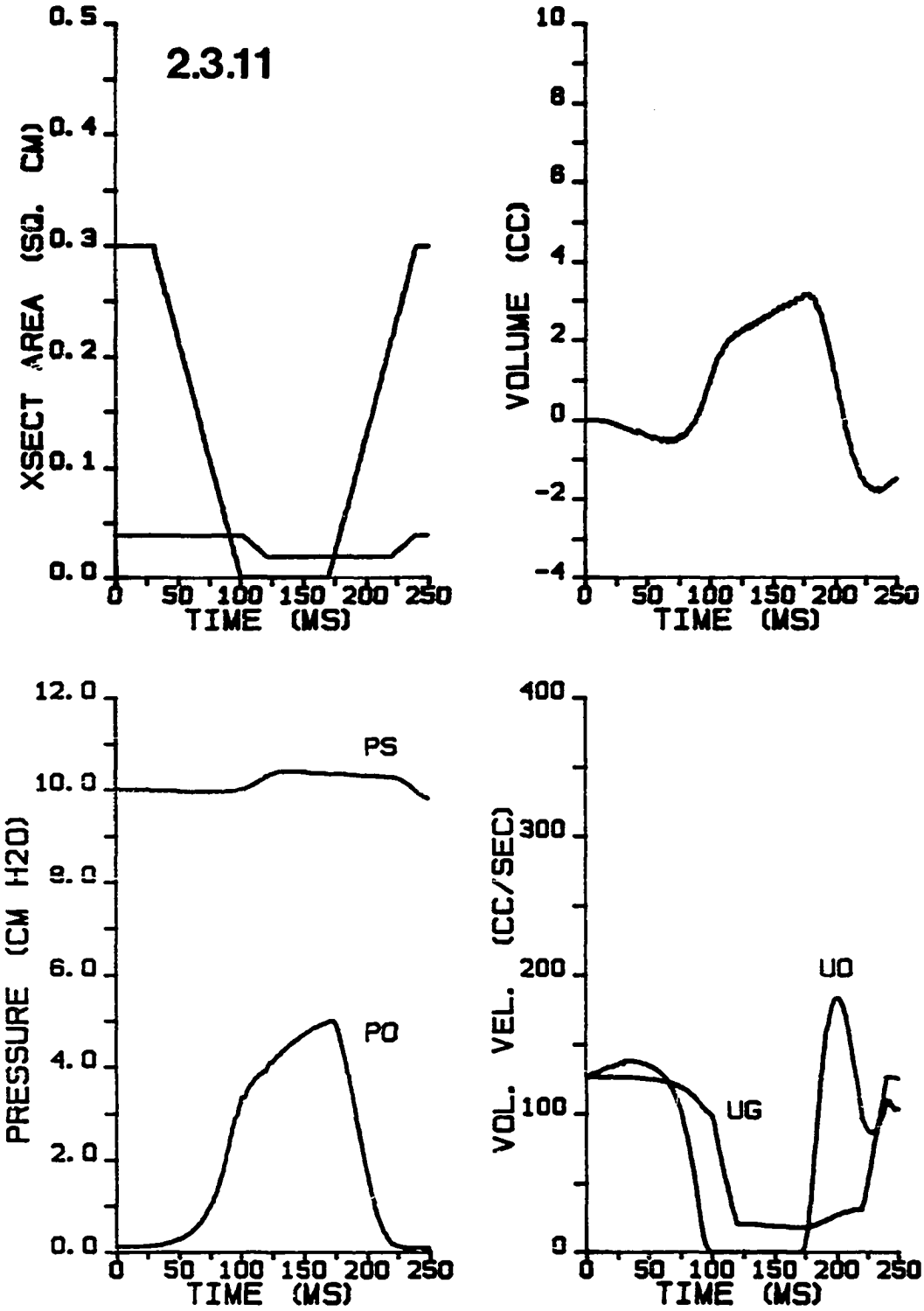

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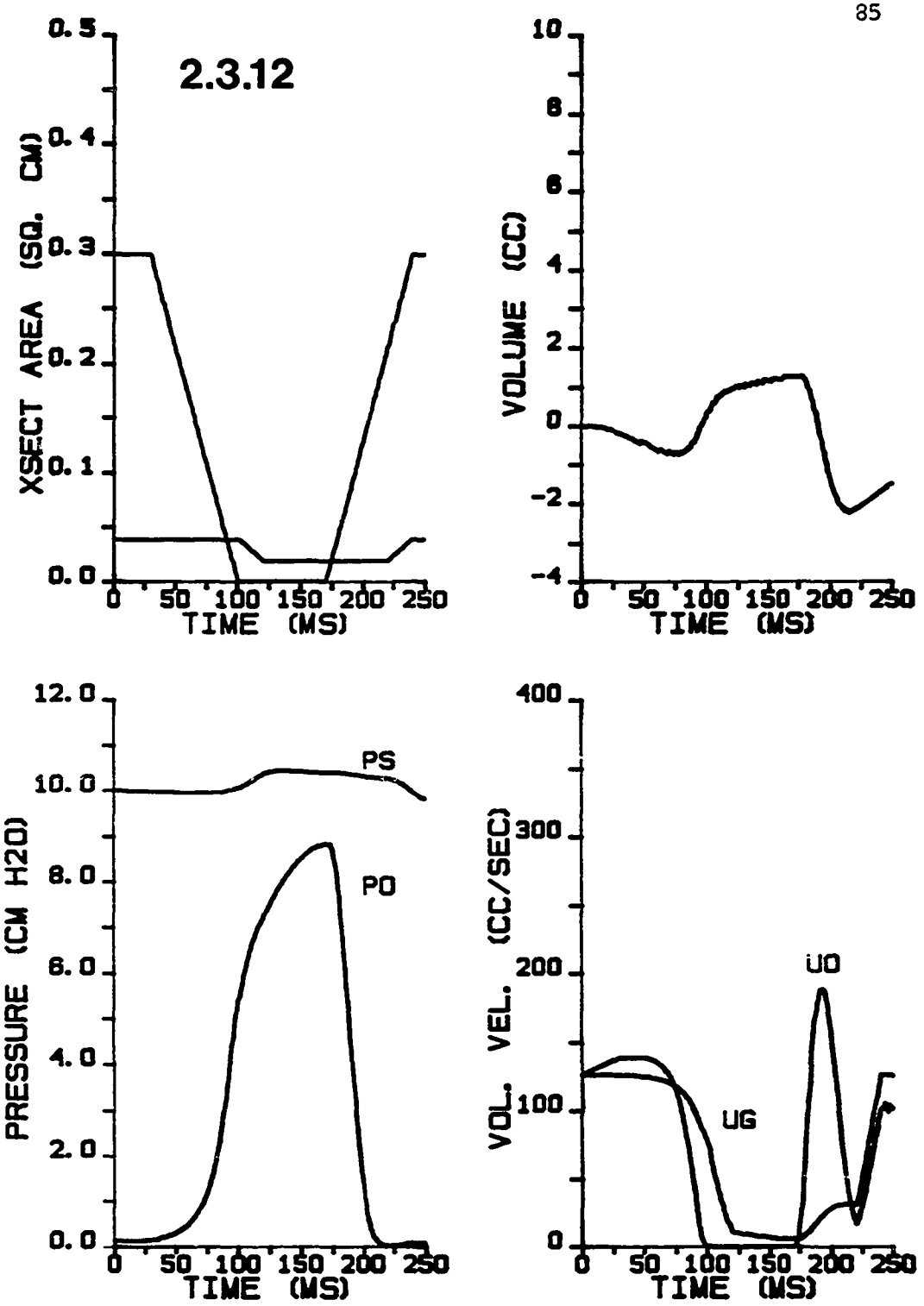

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It is immediately apparent from these figures (compare 1 with 3, 2 with 4, 5 with 7, 6 with 8, 9 with 11, and 10 with 12) that increasing glottal resistance by constricting the glottis in ejectives (the upper left panel in figures 3, 4, 7, 8, 11, 12) reduces air flow through the glottis so markedly that, despite the active contraction of the oral cavity brought about by raising the larynx (the upper right panel in these figures), Po does not increase dramatically (lower left panel). Po is higher at all places of articulation and with both degress of wall compliance for voiceless stops than ejectives, apparently because the high rate of air flow through the widely abducted glottis is more effective than the small amount of contraction that larynx raising causes. Reducing the compliance of the vocal tract walls does contribute positively to the elevation of Po during ejectives, in each case nearly doubling it (compare 3 with 4, 7 with 8, and 11 with 12). With the large glottal aperture used in the modelling of the voiceless stops, Po could not exceed Ps, so the peak value of Po is not increased by tensing the walls. The effect of wall tensing on Po during voiceless stops is reflected instead in an acceleration of the rate by which Po increases (similar results were reported by Müller and Brown 1980).

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Because Po was not elevated as much as expected in any of the ejective simulations, larynx raising cannot be the only contracting maneuver for these stops. Accordingly, the effects of additional amounts of contraction are simulated in figures 2.4.1-9. The amount of contraction indicated at the bottom of each figure are 1.5, 2, and 3 times the values calculated from larynx elevation alone for each place of articulation. Tense walls are assumed in all cases.

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Table 2.4

Modelling ejectives with additional contraction of the oral cavity

Figure #	Description
2.4.1	Ejective bilabial stop with 17.3 cc/sec contraction = 1.5 x the contraction in 2.3.4.
2.4.2	Same as 2.4.1, except with 23 cc/sec contraction = 2 x the contraction in 2.3.4.
2.4.3	Same as 2.4.1, except with 34.5 cc/sec contraction = 3 x the contraction in 2.3.4.
2.4.4	Ejective dental stop with 32.1 cc/sec contraction = 1.5 x the contraction in 2.3.8.
2.4.5	Same as 2.4.4, except with 42.8 cc/sec contraction = 2 x the contraction in 2.3.8.
2.4.6	Same as 2.4.4, except with 64.2 cc/sec contraction = 3 x the contraction in 2.3.8.
2.4.7	Ejective velar stop with 36.6 cc/sec contraction = 1.5 x the contraction in 2.3.12.
2.4.8	Same as 2.4.7, except with 48.8 cc/sec contraction = 2 x the contraction in 2.3.12.
2.4.9	Same as 2.4.7, except with 73.2 cc/sec contraction = 3 x the contraction in 2.3.12.

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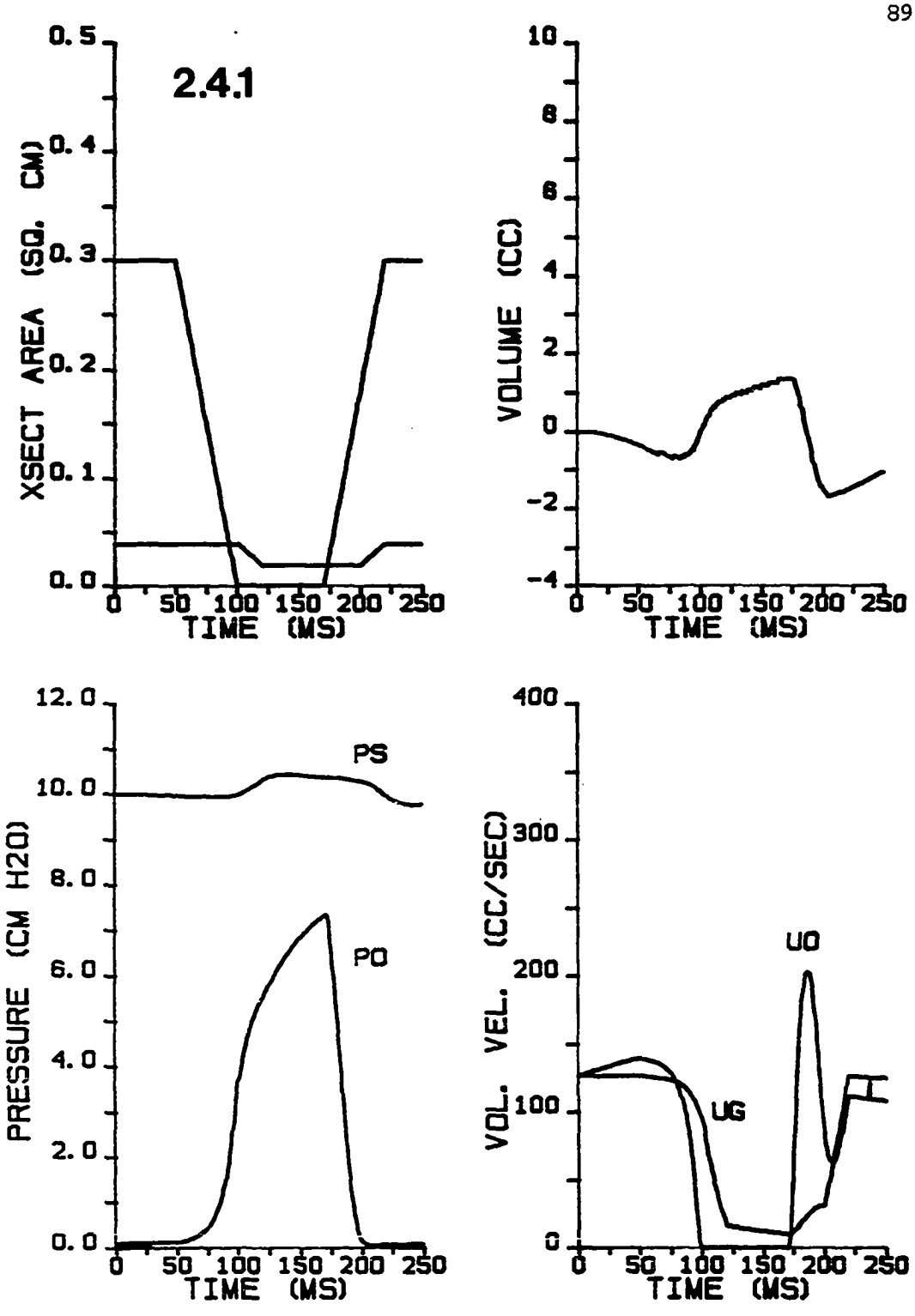

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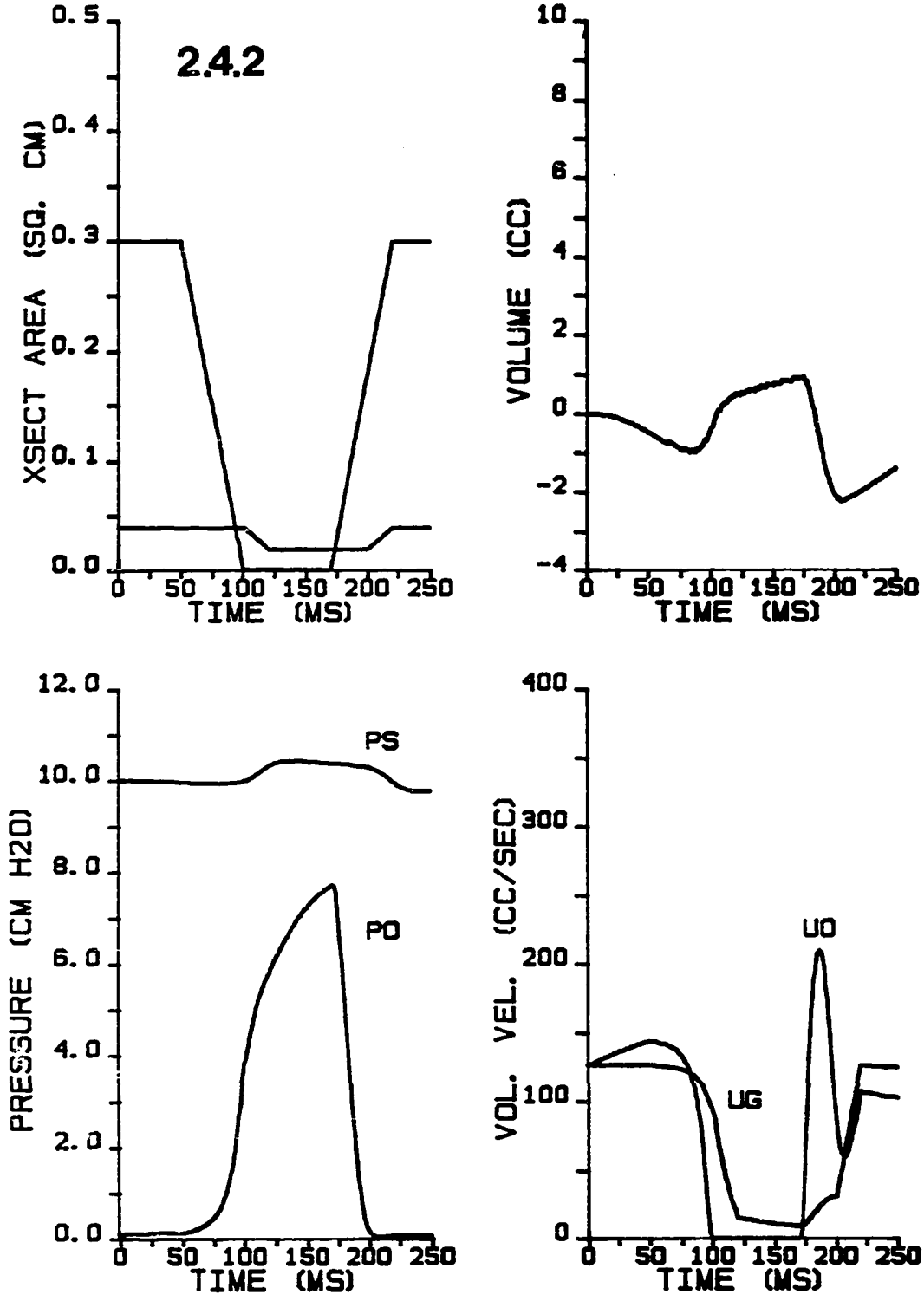

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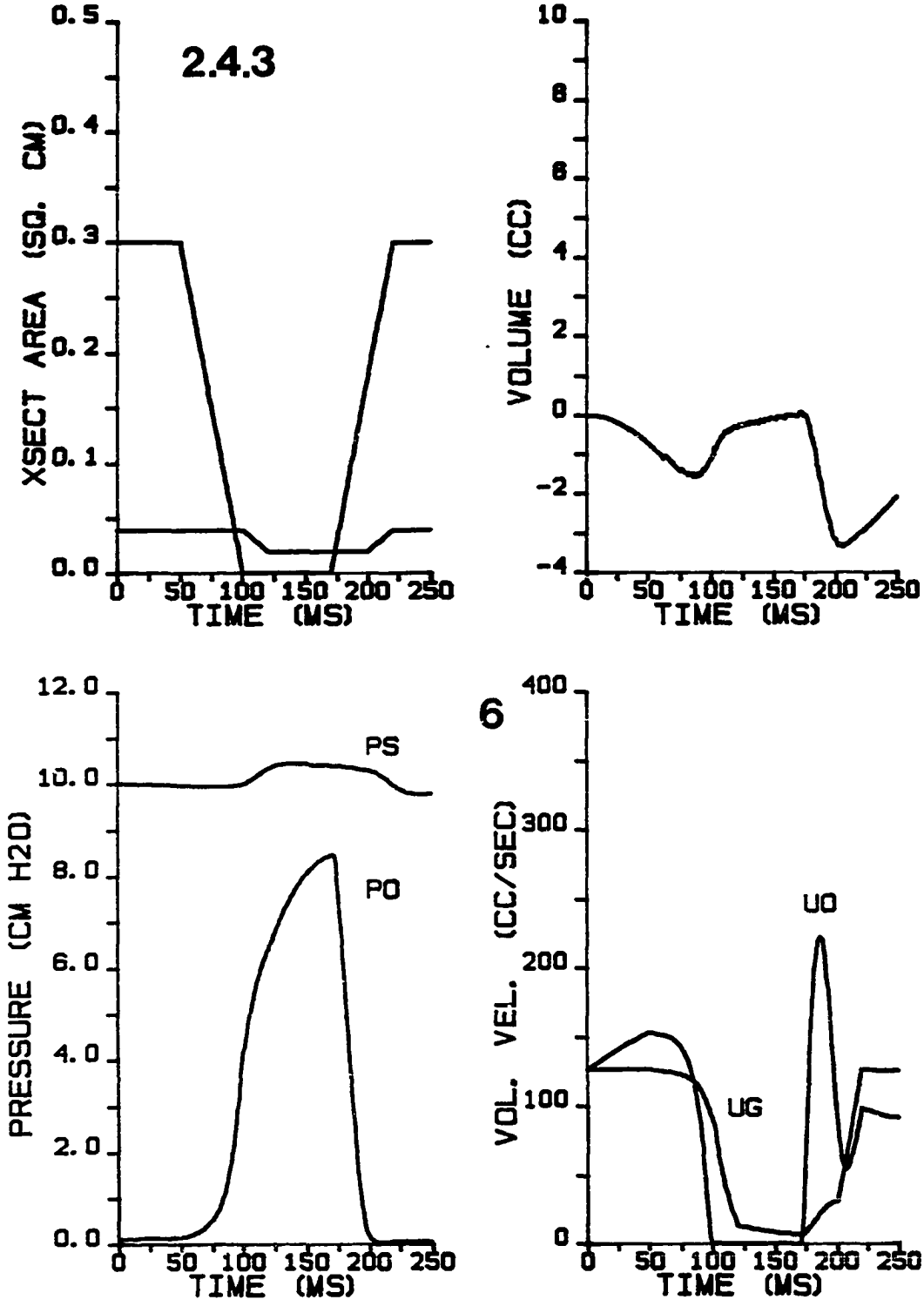

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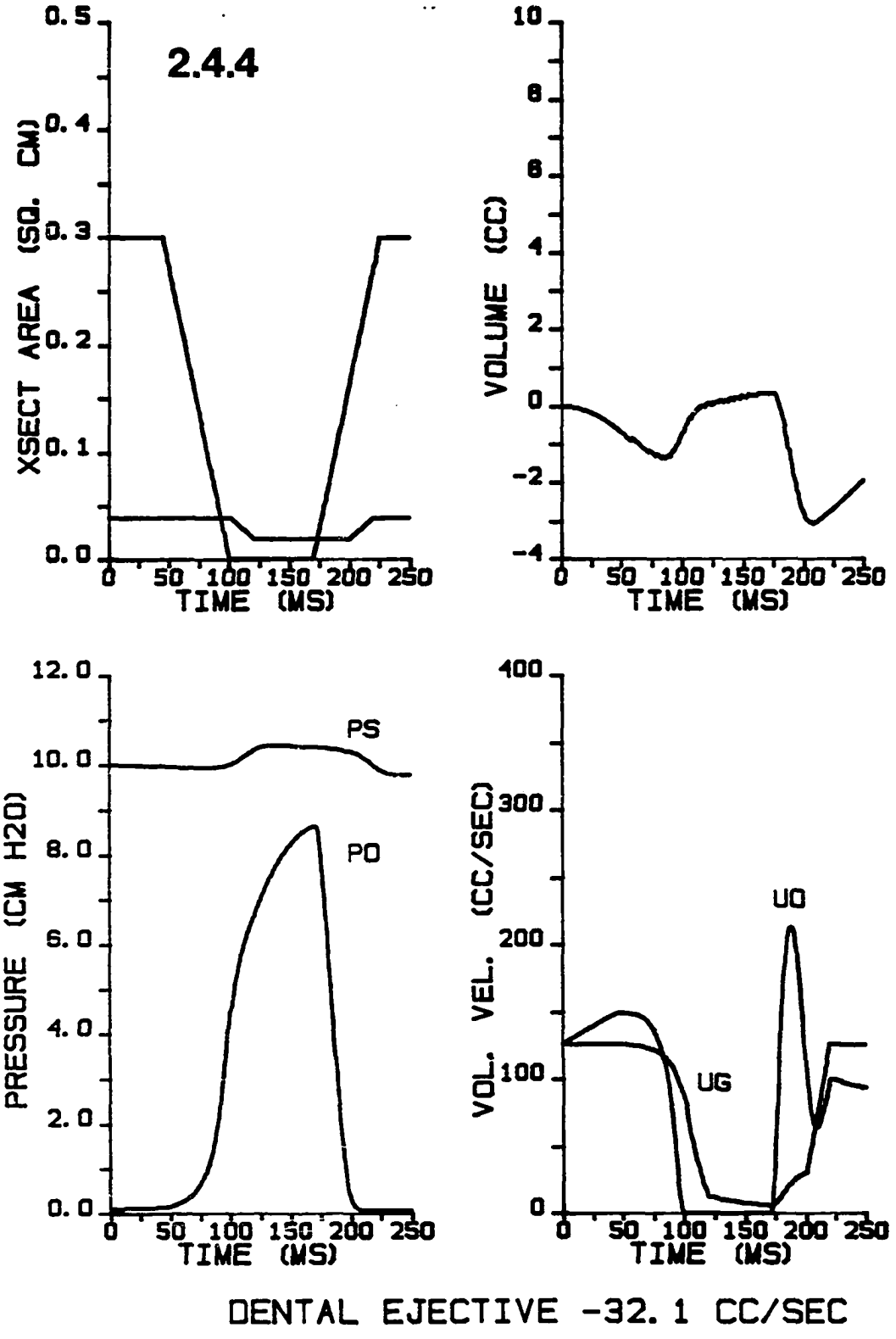

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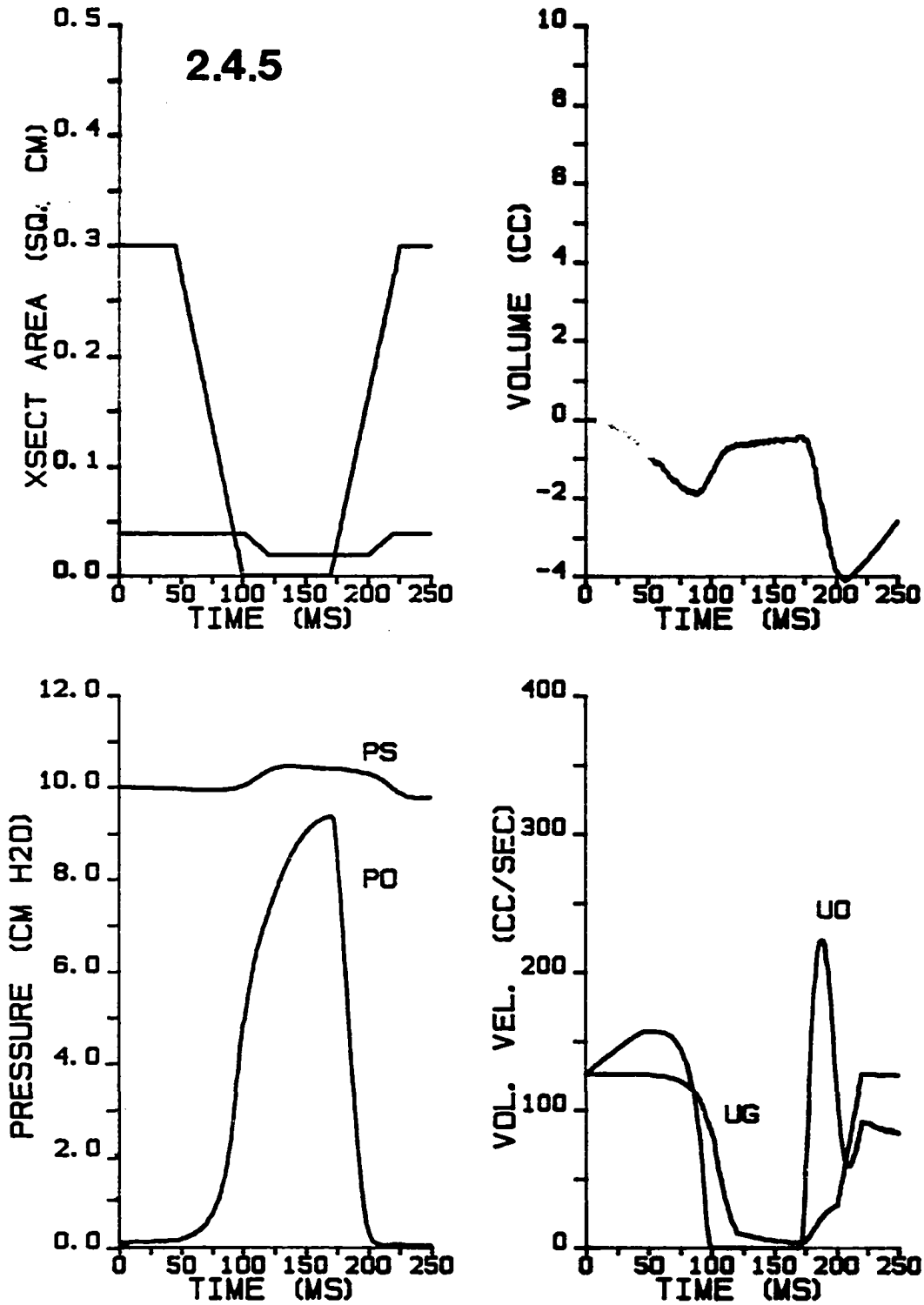

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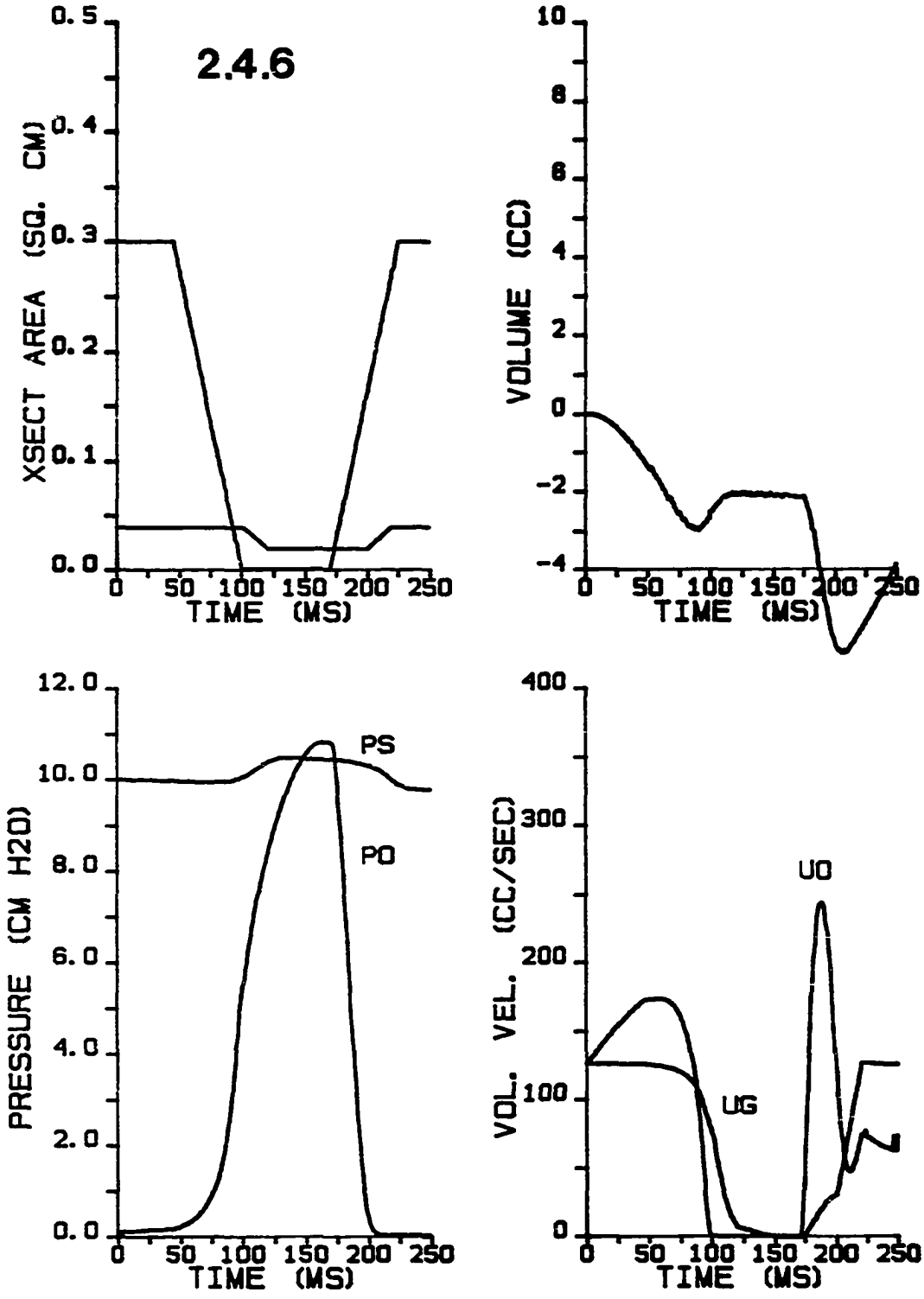

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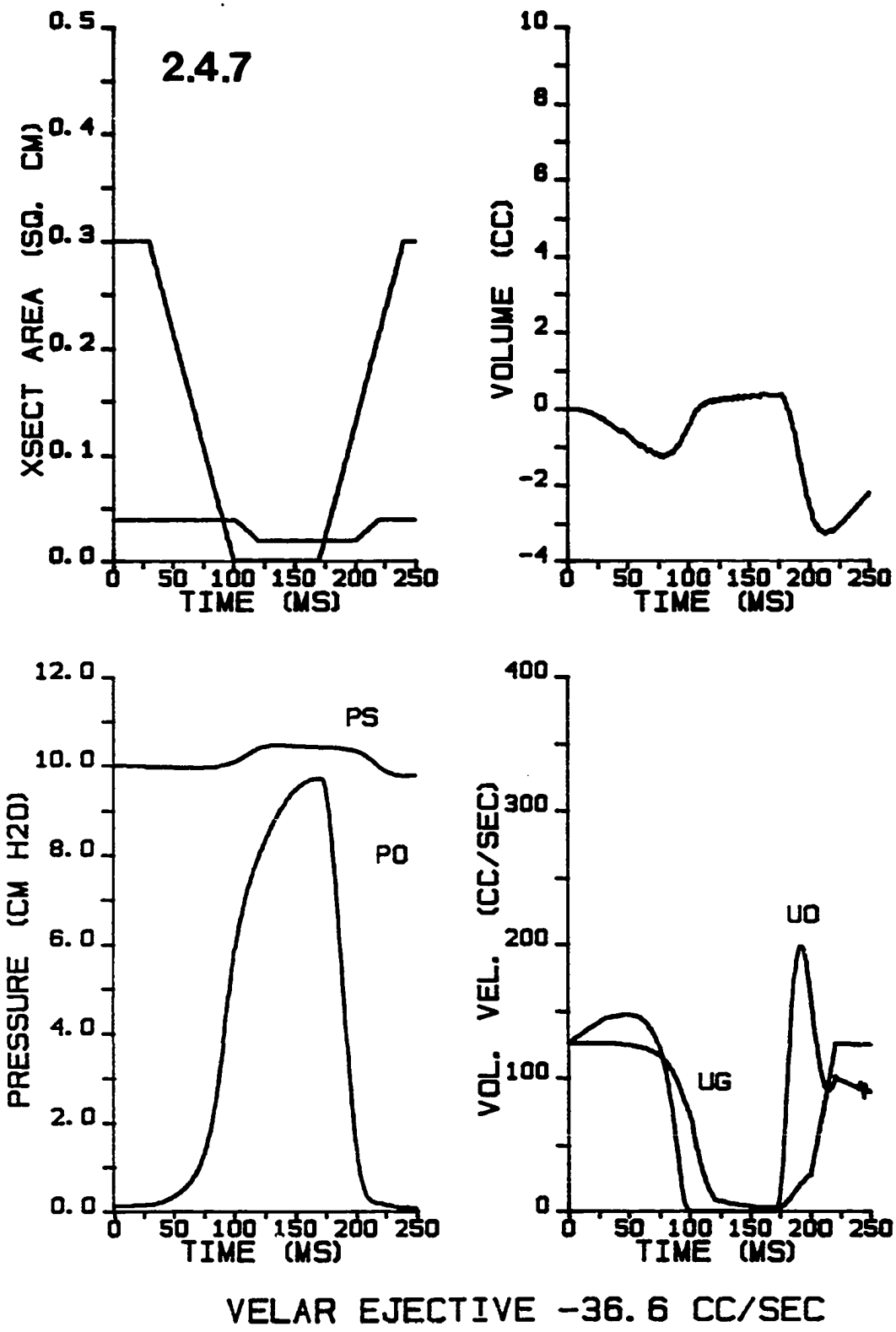

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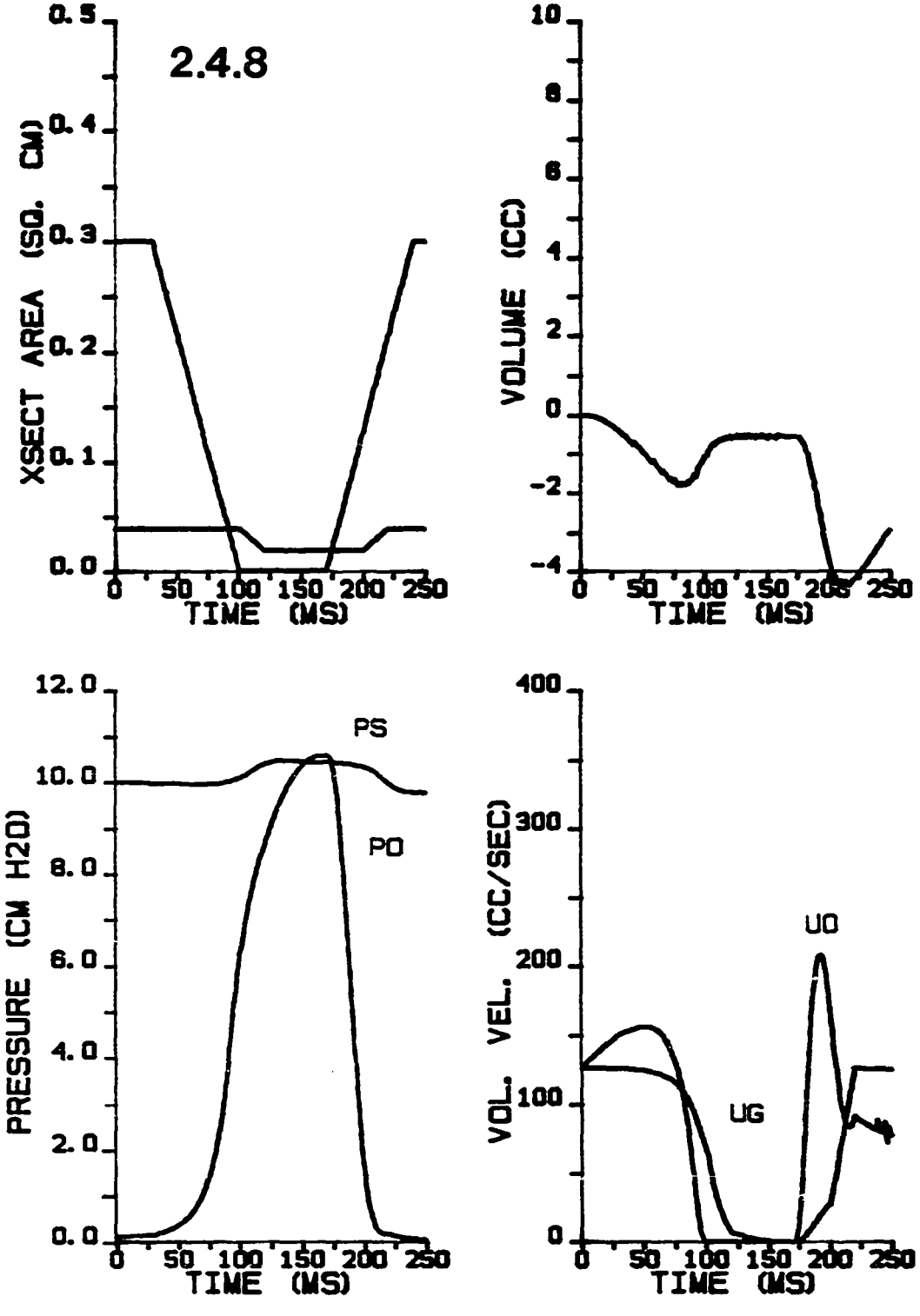

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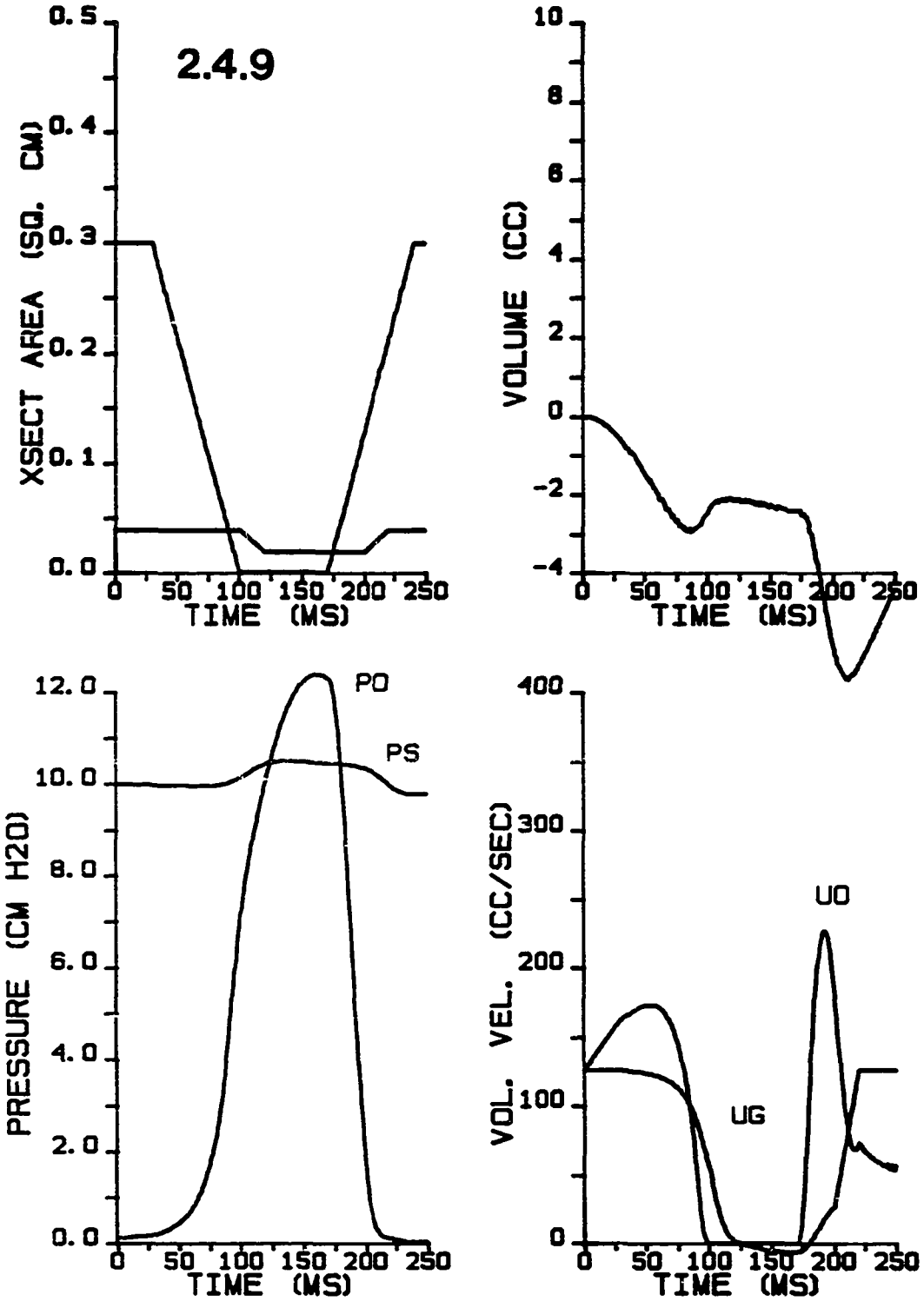

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Only with this additional amount of contraction does Po reach the levels expected for an ejective, though Po only exceeds Ps in simulations of dental and velar stops. The failure to elevate Po markedly even with considerable additional contraction during the bilabial ejectives is, in fact, a welcome result since it provides an explanation for the frequent gap in ejective series at this place of articulation (see Javkin 1977).

Though it is not entirely clear how this additional contraction is to be obtained, certain guesses can be made. The articulatory gestures for producing the stop closures for dental and velar stops themselves reduce the volume of the oral cavity, since they both require raising of the tongue body (Westbury's data (1979, 1983) shows expansion of the pharynx as a result of advancing the tongue root for alveolar stops in English, however). Also, the greater elevation of the larynx which takes place during dental and velar stops, compared to bilabial ones, presumably occurs because raising the tongue body raises the hyoid bone and with it the larynx. Finally, it is possible with bilabial and velar stops to reduce the volume of the pharynx by retracting the tongue root.

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2.3.2.2 Simulations of ejectives with a smaller glottal area

In the following figures, the results of modelling ejectives with the smaller Ø.ØØ2 cm sq. glottal area are presented. As noted above, when the glottis is reduced to this size, extremely little elevation of Po occurs. In these simulations, because the glottal area is extremely small, we can expect that Po will be entirely independent of Ps and therefore only subject to changes in oral cavity volume such as those brought about by raising the larynx. These figures better represent the classical view of what a ejective is, a stop during which intraoral air pressure is increased entirely through the action of the glottalic mechanism (cf. Catford 1939, Ladefoged 1971). Four amounts of cavity contraction were simulated for each place of articulation, the first in each case equal to that which could be accomplished by larynx movement alone. The other three simulations for each place of articulation represent 2, 3, and 4 times the amount of contraction which could be obtianed from larynx movement alone and should be compared to the simulations with additional cavity contraction but a larger average glottal area just described.

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Table 2.5

Po vs. larynx height with a small glottal area

Figure #	Figure description
2.5.1	Bilabial ejective with tense walls and a 11.5 cc/sec, the amount of contraction possible by larynx movement alone, compare figure 2.3.4. contraction.
2.5.2	Same as 2.5.1, except with 23 cc/sec contraction = 2 x the contraction in 2.5.1, compare figure 2.4.2.
2.5.3	Same as 2.5.1, except with 34.5 cc/sec contraction = 3 x the contraction in 2.5.1, compare figure 2.4.3.
2.5.4	Same as 2.5.1, except with 46 cc/sec contraction = 4 x the contraction in 2.5.1.
2.5.5	Dental ejective with tense walls and a 21.4 cc/sec contraction, the amount of contraction possible by larynx movement alone, compare figure 2.3.8.
2.5.6	Same as 2.5.5, except with 42.8 cc/sec contraction = 2 x the contraction in 2.5.5, compare figure 2.4.5.
2.5.7	Same as 2.5.6, except with 64.2 cc/sec contraction = 3 x the contraction in 2.5.5, compare figure 2.4.6.
2.5.8	Same as 2.5.5, except with 85.6 cc/sec contraction = 4 x the contraction in 2.5.5.
2.5.9	Velar ejective with tense walls and a 24.4 cc/sec contraction, the amount of contraction possible by larynx movement alone, compare figure 2.3.12.

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2.5.10 Same as 2.5.9, except with 48.8 cc/sec contraction = 2 x the contraction in 2.5.9, compare figure 2.4.8.

2.5.11 Same as 2.5.9, except with 73.2 cc/sec contraction = 3 x the contraction in 2.5.9, compare figure 2.4.9.

2.5.12 Same as 2.5.9, except with 97.6 cc/sec contraction = 4 x the contraction in 2.5.9.

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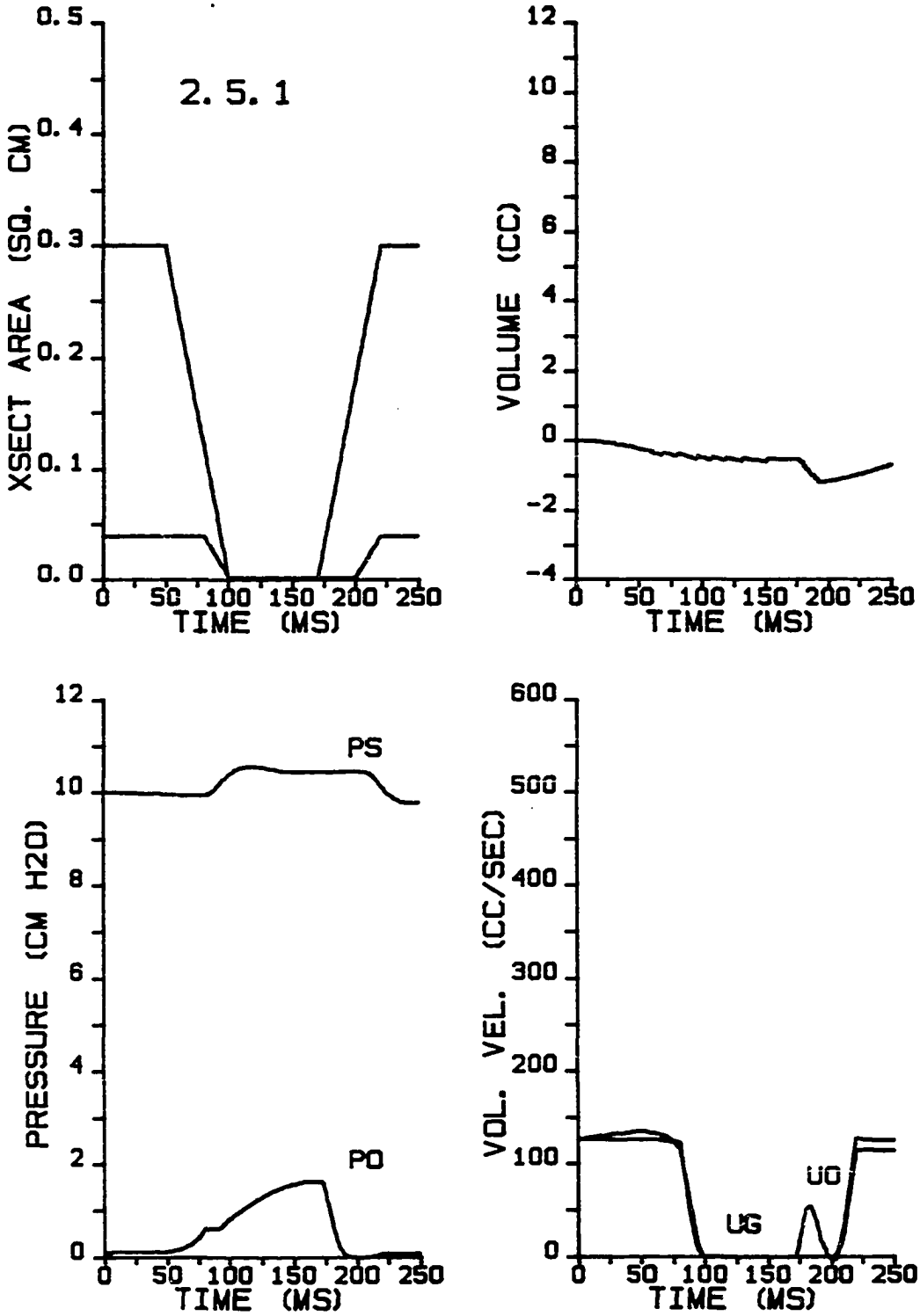

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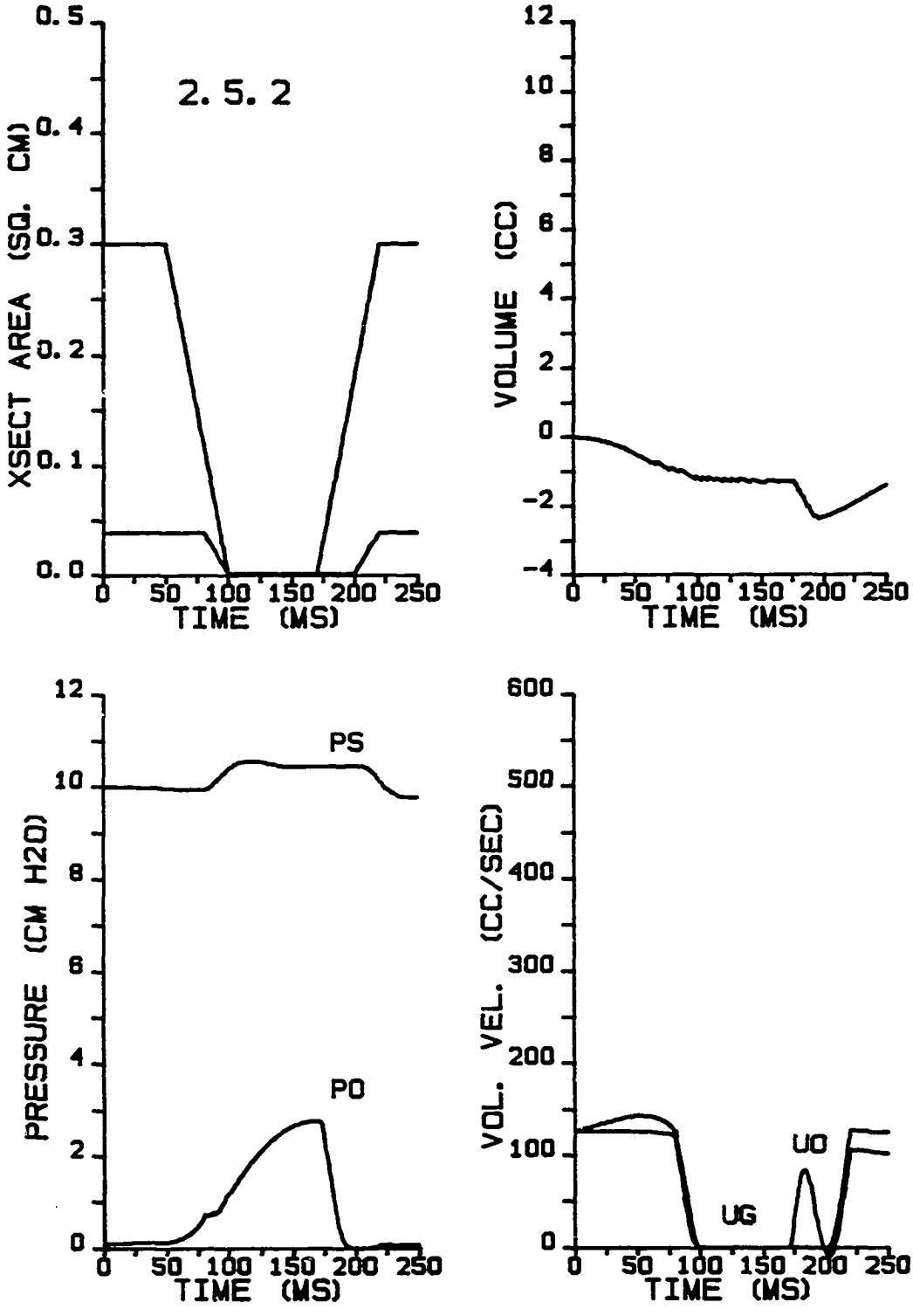

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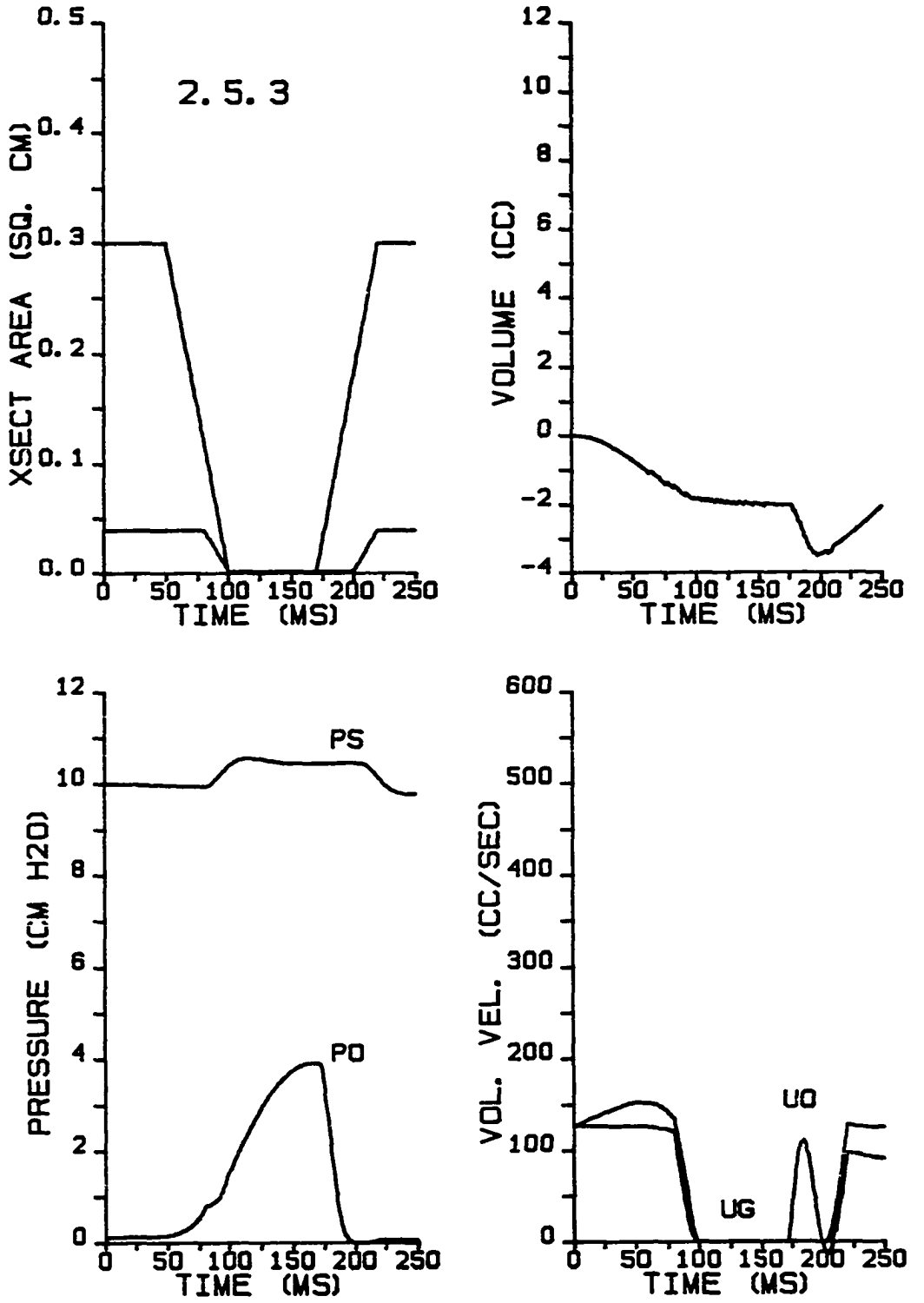

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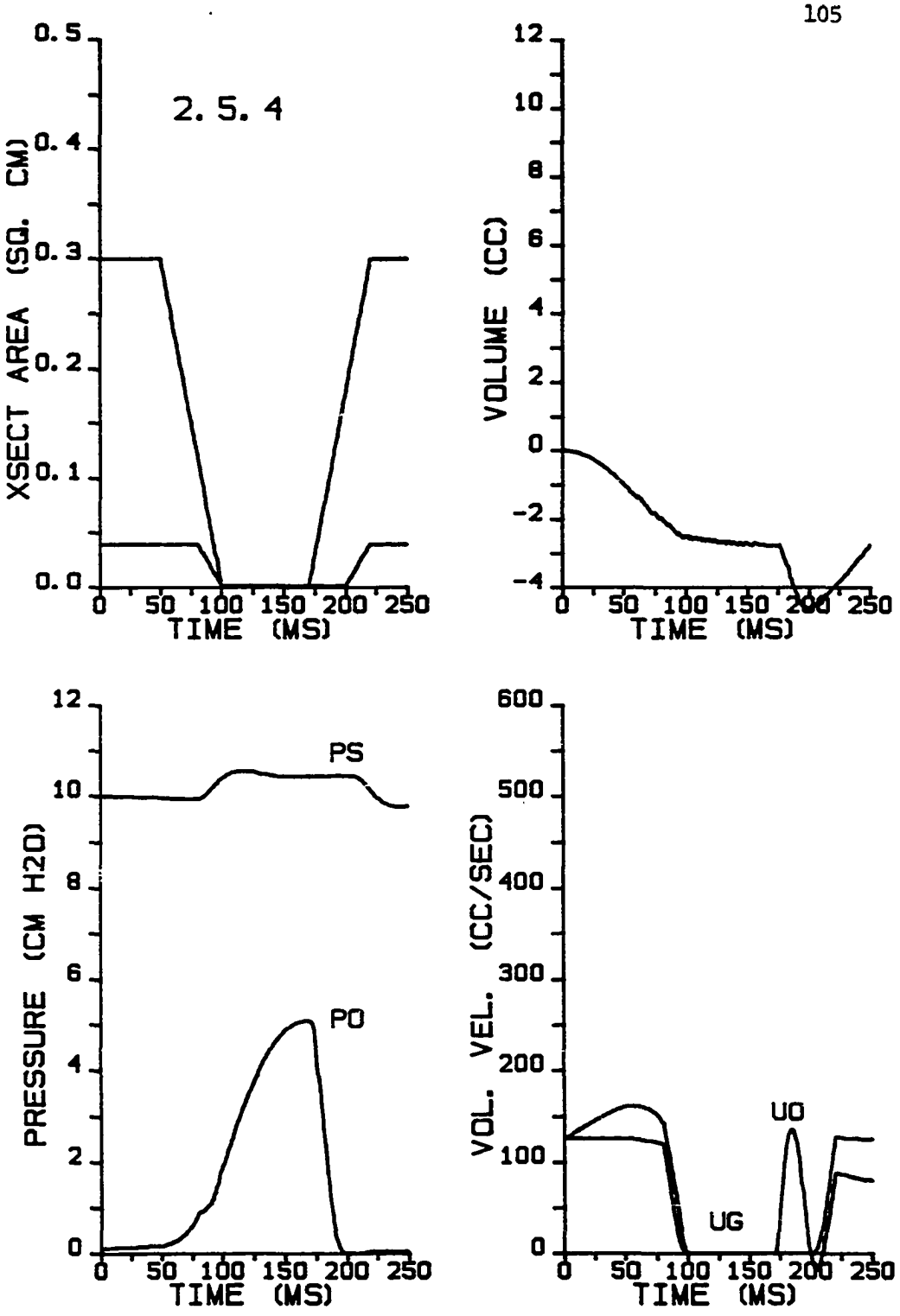

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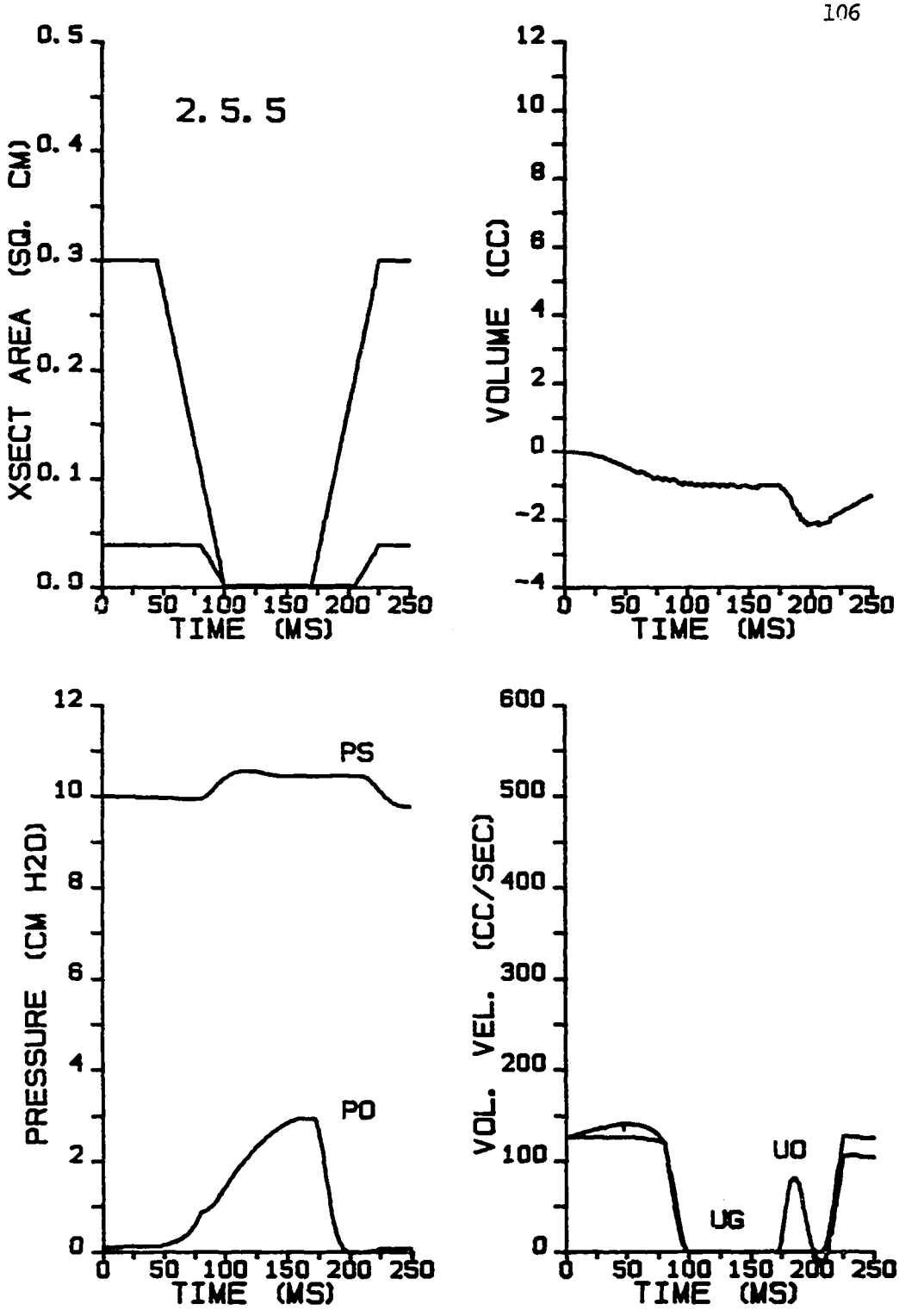

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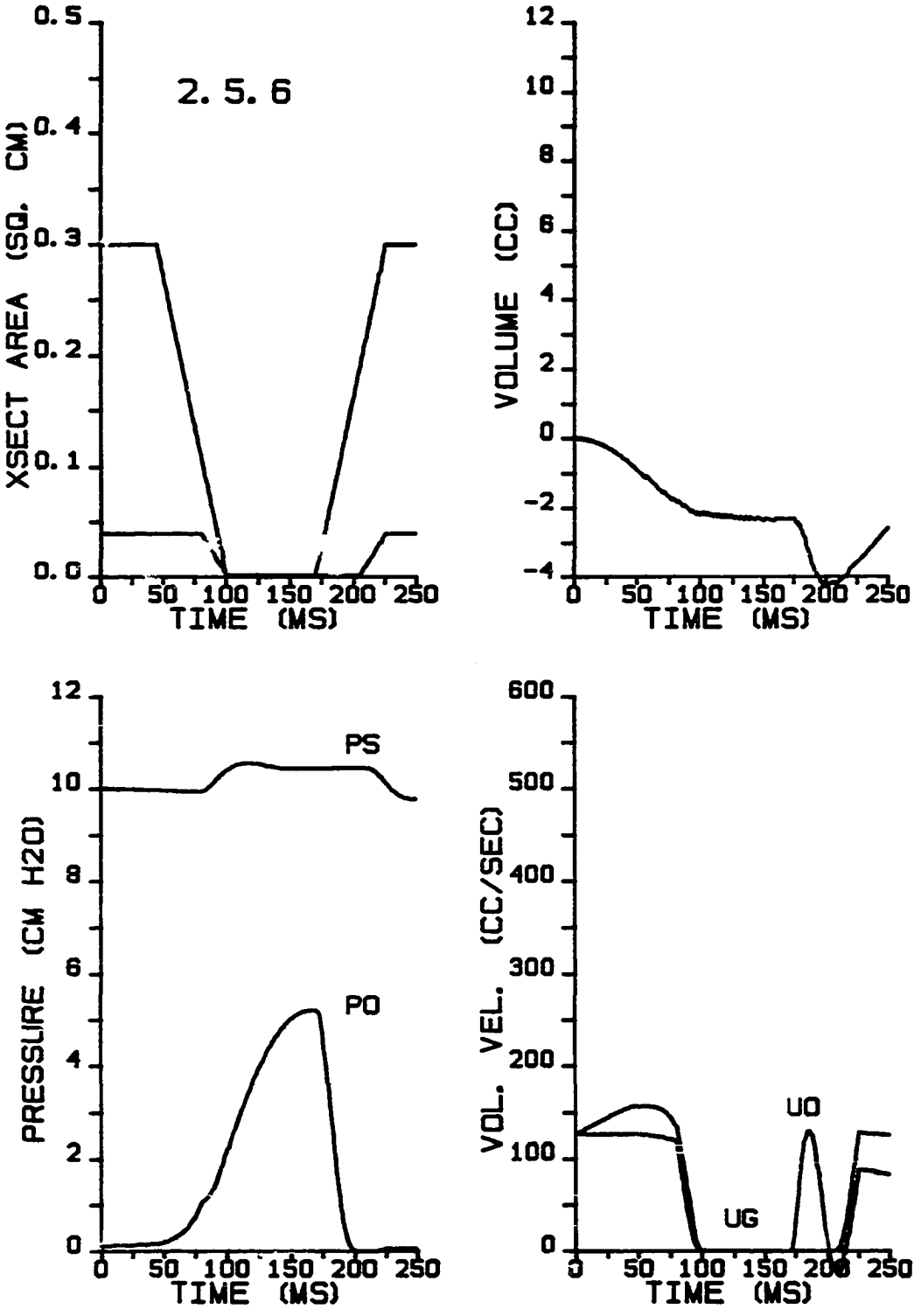

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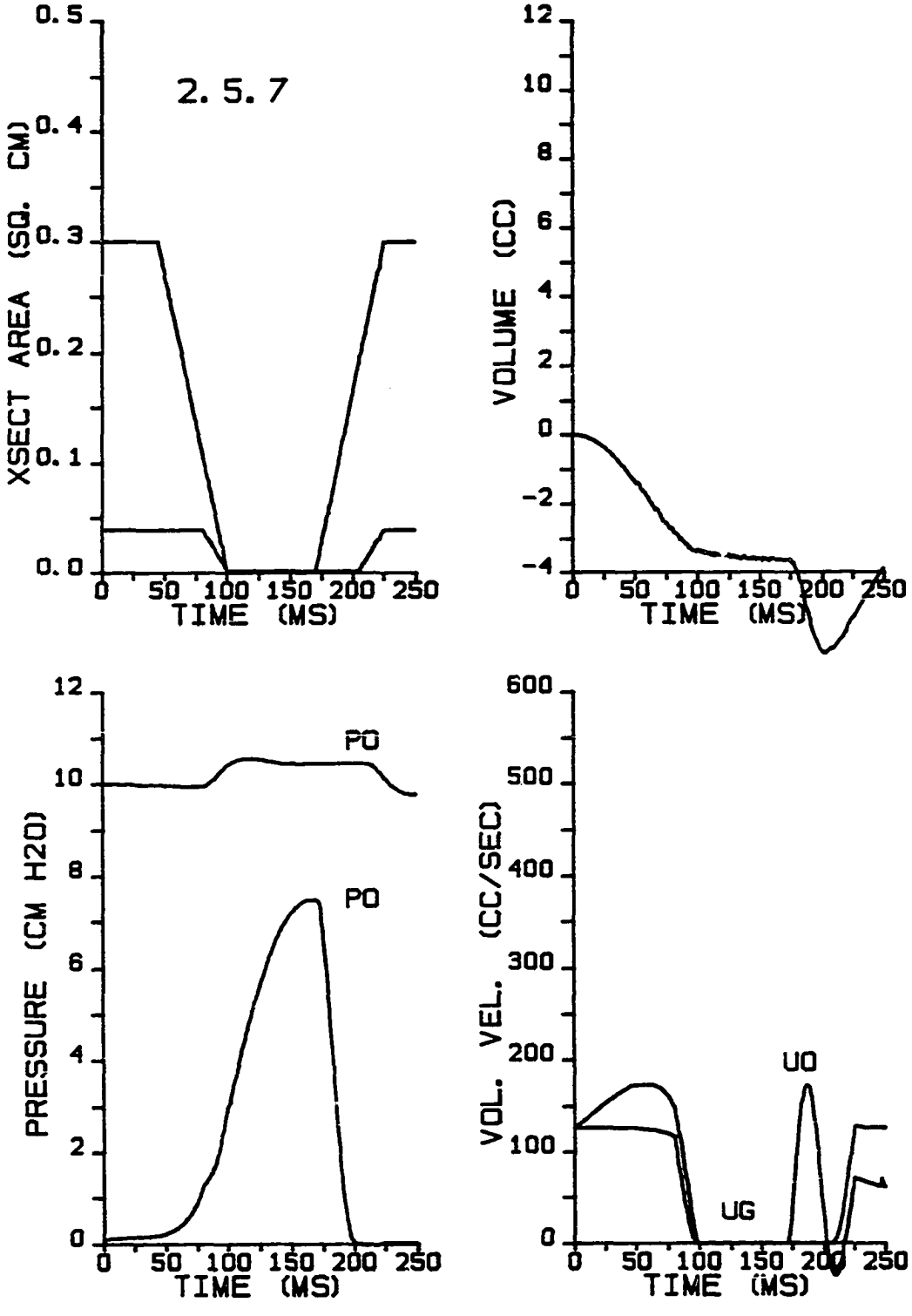

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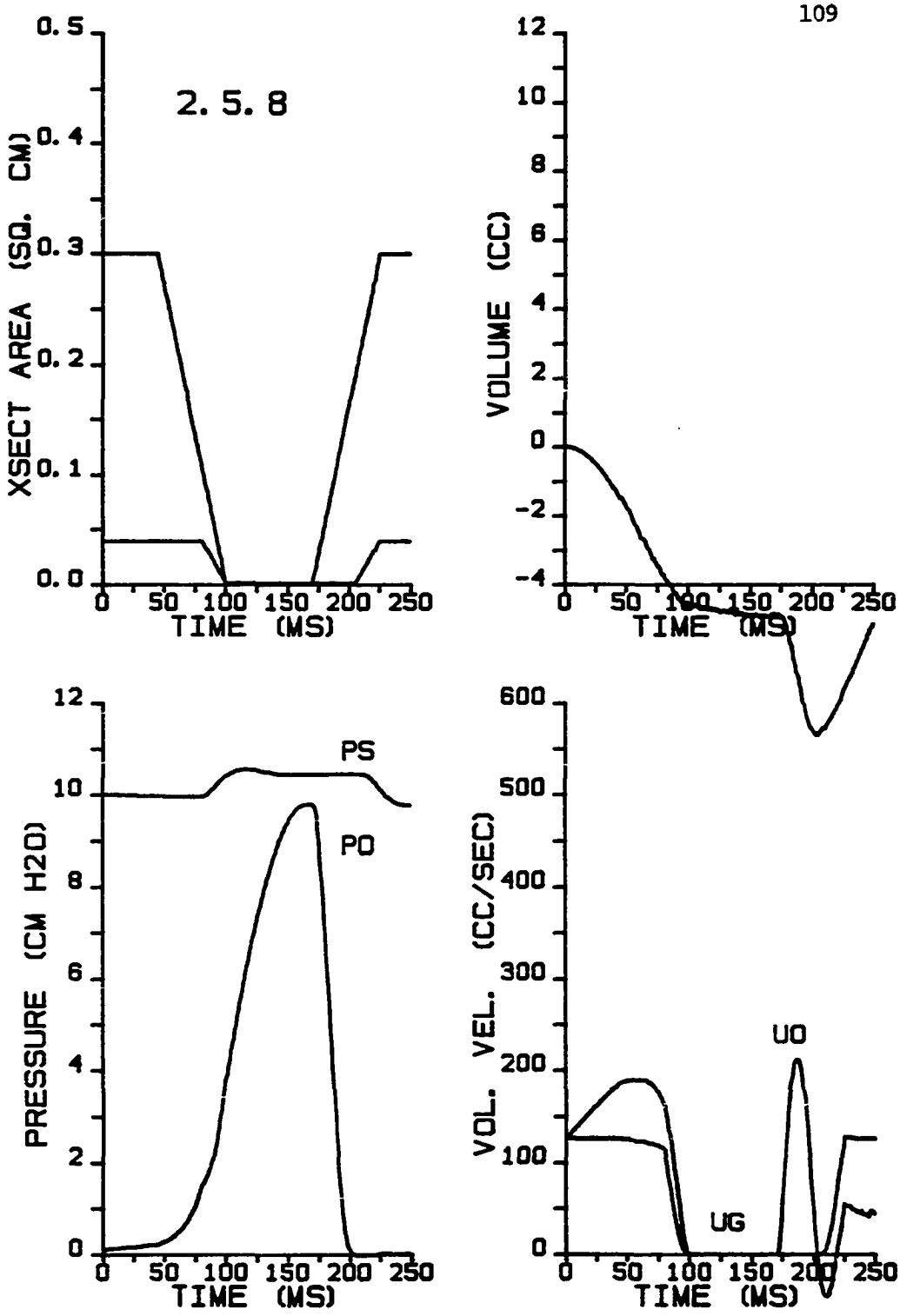

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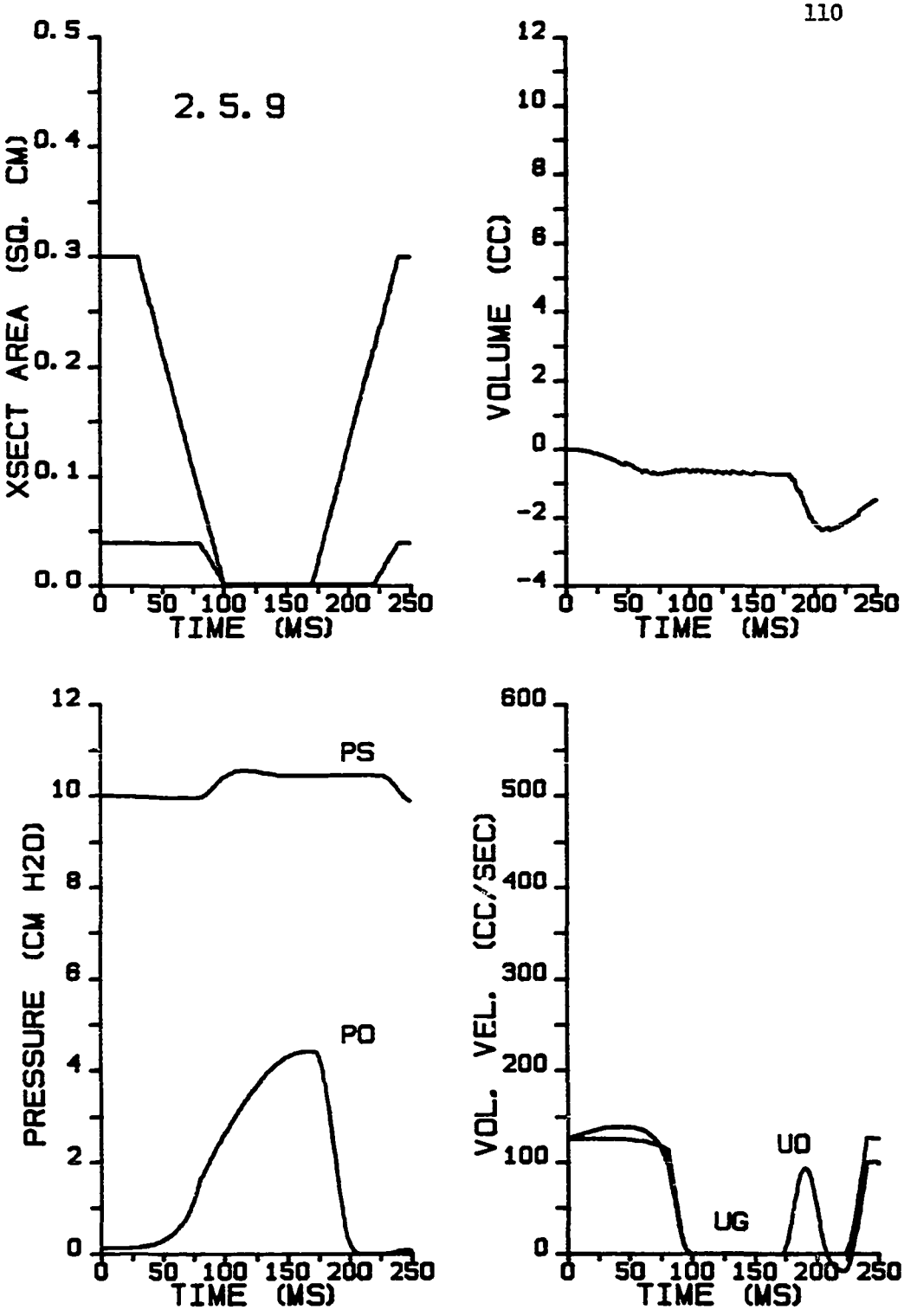

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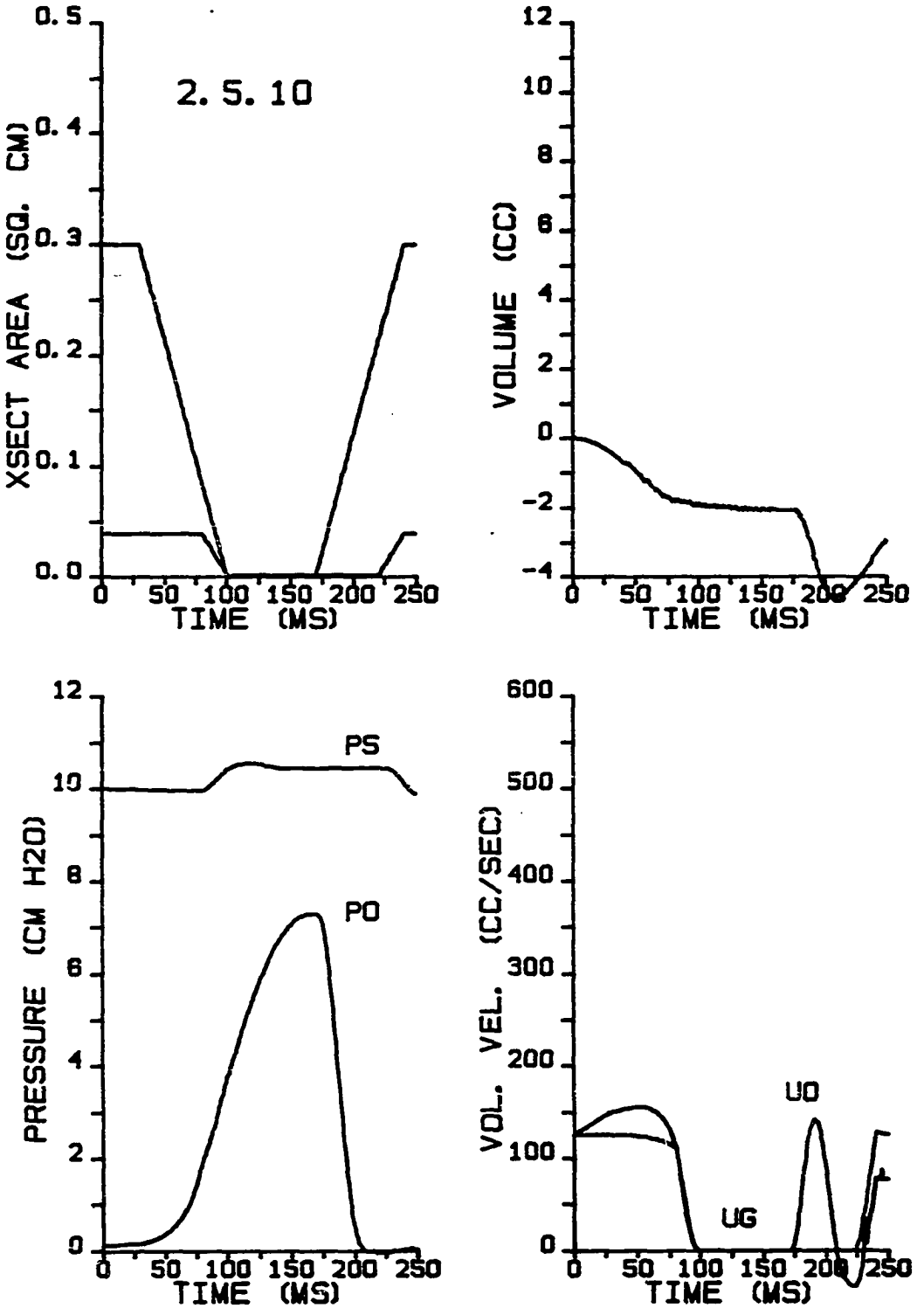

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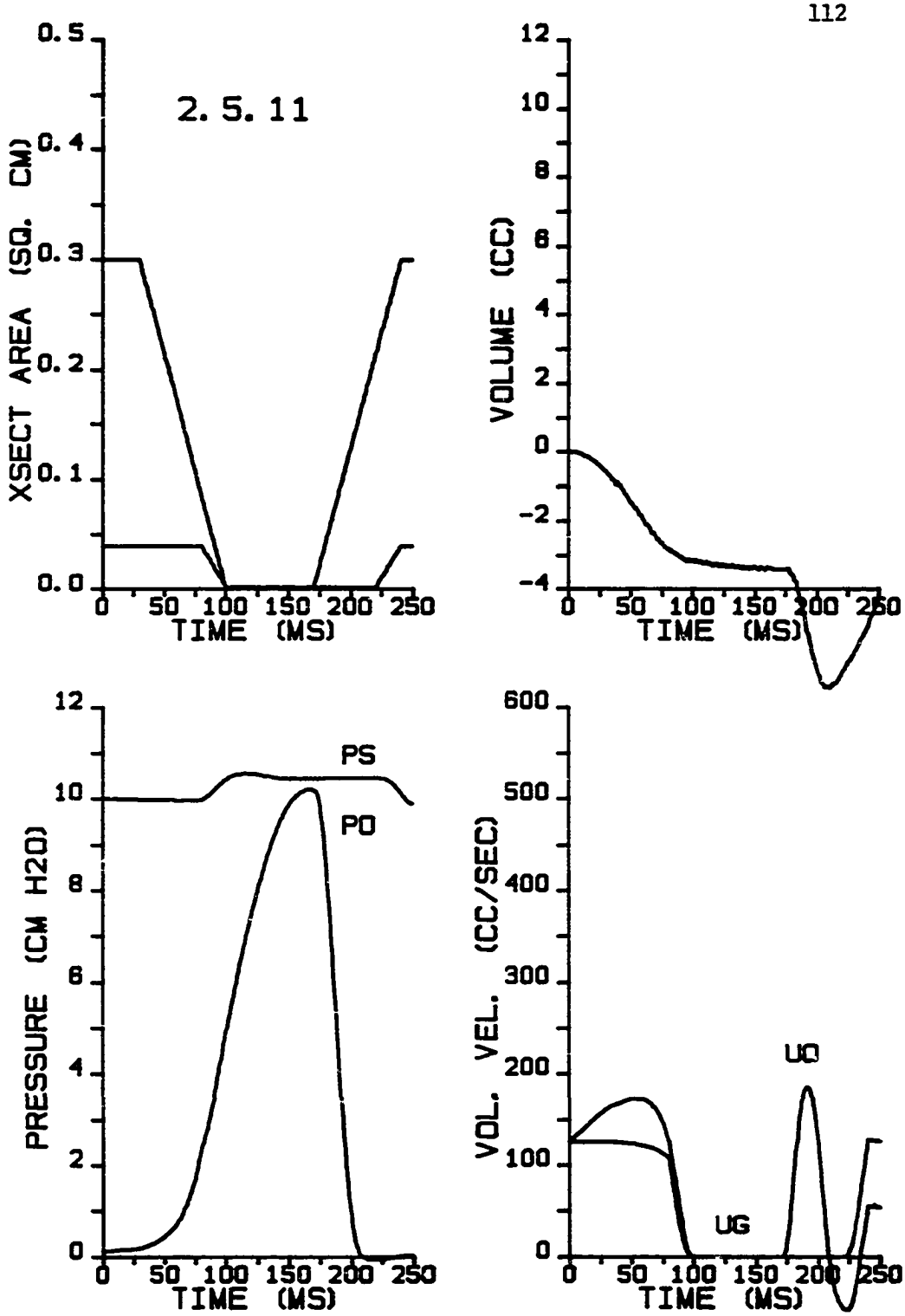

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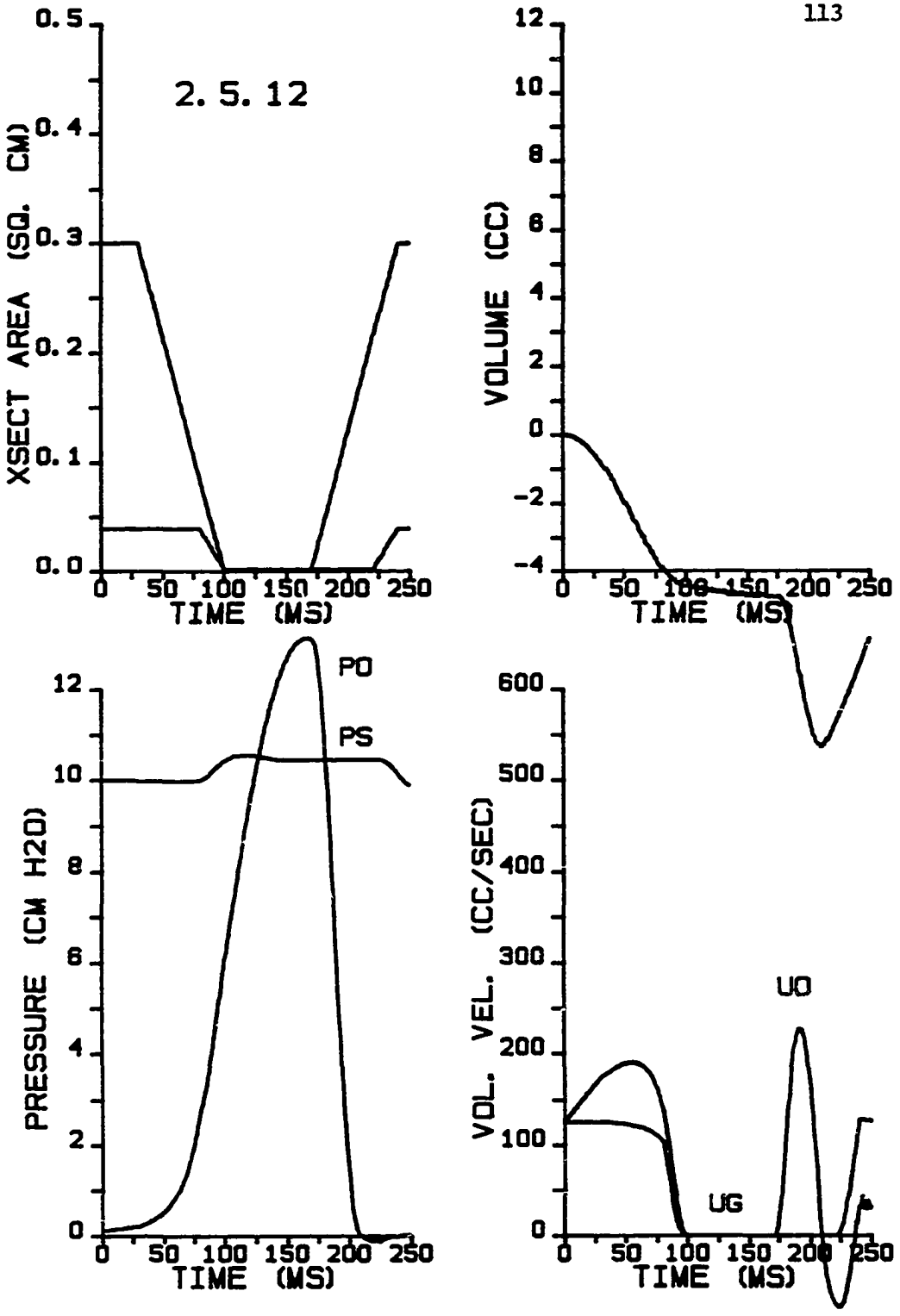

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The failure of larynx raising to dramatically elevate Po by itself (see figures 1, 5, and 9) makes it even plainer than it was in the earlier simulations that larynx raising is aerodynamically ineffective.

2.4 Summary

The data and simulations presented in this chapter allow two conclusions. First, larynx elevation is simply too slow and too loosely coordinated with the stop closure and release to dramatically reduce the volume of the oral cavity and thereby raise Po during ejectives. Second, the modelling of ejectives shows that the amount of cavity contraction which can be obtained by larynx elevation alone is too small to raise Po to expected levels. Additional contracting maneuvers must be employed, together with tensing the walls of the vocal tract.

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Notes

1. The vowel conventionally transliterated /ä/ in this language is a low, usually front, vowel ranging from [ɛ] to [ʌ] in quality. The /ə/ is a higher, usually central, vowel ranging from [ɪ] to [i̇]. Otherwise, the symbols have their IPA values.

2. Values for the compliance of the air mass in the oral cavity and the compliance, resistance, and inductance of the walls of the vocal tract were taken from Müller and Brown (1980), while estimates of changes in the cross-sectional area of the oral cavity and the glottis were obtained in part from Keating (1984) and in part from Müller and Brown. The length of articulator contact was different for each place of articulation:

bilabial: 0.2 cm

dental: 0.3

velar: 0.7

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Chapter 3

Fo perturbations and larynx height

3.1 Introduction

As indicated in chapter 1, some unavoidable change in larynx height, vocal fold separation, or vocal fold length or stiffness perturbs the fundamental frequency of vowels following stops.[1] Specifically, at vowel onset, Fo is elevated after voiceless stops and depressed after voiced ones (for review see Hombert, Ohala, & Ewan 1979). The manipulation of vocal fold length through the contraction of the cricothyroid is probably the most direct way of affecting the rate at which the folds vibrate, the more stretched they are, the more rapid the vibration. Halle and Stevens (1971) have suggested that vocal fold stretch is reduced during voiced stops to make vocal fold vibration more likely by reducing the elasticity of the folds. The depression of Fo after a voiced stop is, in their view, the result of relaxing the cricothyroid which would reduce vocal fold stretch in this way, while the elevation of Fo after a voiceless stop would result from stretching the folds by contracting

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that muscle. Stretching the folds makes them less likely to vibrate, even if they are close enough together to do so. Because Halle and Stevens' hypothesis explains Fo perturbations after stops as a direct result of relaxing or stretching the folds, it has been referred to as the "horizontal tension" hypothesis by Hombert, Ohala, and Ewan (1979).

However, though cricothyroid activity rises and falls with Fo during vowels, it is suppressed during the closure interval of both voiced and voiceless stops. As a consequence, the folds are neither especially relaxed or stretched during voiced or voiceless stops (Hirose & Gay 1972, Hirose & Ushijima 1978, Hirose, Yoshioka, & Niimi 1978, cf. Dixit & MacNeilage 1980). Cricothyroid activity increases in much the same way in the transition from both voiced and voiceless stops to the following vowel, so the level of activity of this muscle is probably responsible for changing the state of the folds to that appropriate for vowels, independent of the presence or absence of vocal fold vibration during the preceding stop. The cricothyroid is also responsible during the vowel for the relatively slow changes in the rate of vocal fold vibration which make up the stress and intonation contours of words and phrases (Ohala 1970, 1978).

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If direct adjustment of vocal fold tension is the mechanism which underlies the Fo perturbations, then it is probably changes in vocal fold stiffness produced by contracting or relaxing the vocalis and lateral cricoarytenoid which determine the likelihood of vocal fold vibration during a stop (assuming the folds are close enough together) rather than cricothyroid-induced changes in vocal fold length (= stretch). Contracting these muscles will stiffen the folds, while relaxing them will leave the folds slack. Since changes in stiffness will affect the elasticity of the folds, as changes in stretch will, these adjustments will also influence the likelihood of voicing. The activity of these two muscles rather than the cricothyroid would be responsible for the Fo perturbations after stops as well if this activity is maintained beyond the end of the stop into the following vowel.

There is no evidence that the vocalis and lateral cricoarytenod are responsible for Fo perturbations after voiced or voiceless stops, but differences in the level of activity of these muscles distinguish the tense and lax stops of Korean from one another. Both muscles show noticeably higher levels of activity for the tense stops than the lax ones, and Fo is elevated after tense stops, but depressed

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after lax ones (Hirose, Lee, & Ushijima 1974, Hirose, Park, Yoshioka, Sawashima, & Umeda 1981).

The reduction of vocal fold length or stiffness which the low Fo after voiced stops implies, contrasting with the stretching or stiffening implied by the higher Fo after voiceless stops, tempts one into suggesting that the Fo perturbations are the result of relaxing or tensing adjustments whose purpose is to encourage or inhibit voicing during the stop. For Halle and Stevens (1971) the interaction between oral and glottal articulations represented by the Fo perturbations is a consequence of a set of articulatory adjustments intended to compensate for the direct interference with vocal fold vibration brought about by the increase in Po that the stop closure inevitably causes. Though the particular muscle that they held responsible for these changes in the tension of the vocal folds, the cricothyroid, can probably not be the source the perturbations, their hypothesis can be maintained in an altered form if the vocalis and/or lateral cricoarytenoid can be shown to contract less during voiced than voiceless stops.

Another mechanism has been proposed, by Hombert, Ohala, and Ewan (1979), to explain Fo perturbations: vertical move-

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ment of the larynx. Like the level of cricothyroid activity, the height of the larynx correlates directly with Fo during vowels; and, furthermore, the larynx is lower during voiced stops than voiceless ones (Kent & Moll 1969 Perkell 1969, Hombert, Ohala, & Ewan 1979, Westbury 1979, 1983, Riordan 1980). Hombert, Ohala, and Ewan suggest that lowering the larynx depresses Fo by reducing the vertical stretch on the folds. Their explanation resembles that of Halle and Stevens (1971) in that the principal mechanism behind the Fo perturbations is one which would directly affect the likelihood of voicing, since lowering the larynx expands the oral cavity and raising it contracts the cavity. To contrast it with the Halle and Stevens' hypothesis, these investigators refer to their explanation as the "vertical tension" hypothesis.

In the articulation of the socalled "glottalic" consonants, ejectives and implosives, there is a dramatic vertical movement of the larynx (Catford's "glottalic airstream mechanism" (1939), see also Ladefoged (1971)), so these consonants provide a means of testing whether larynx movement perturbs Fo. Ejectives should elevate Fo, and implosives should depress it. Furthermore, since the movement up and down of the larynx is presumably greater for

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ejectives and implosives than for voiceless and voiced stops, respectively, the glottalic consonants should raise and lower Fo even more than the corresponding oral stops do. Ejectives do not, however, elevate Fo in all languages, and in one language where they do, they elevate it no more than a voiceless stop does (Kingston 1982). Implosives are even more problematic since phonological evidence suggests that they actually elevate rather than depress Fo in a number of languages, though it is not clear that they do so in all languages they occur in.

As a member of the class of articulatory interactions whose acoustic results cross segment boundaries, the perturbation of Fo after stops is interesting for two reasons. First, since the lips, tongue, soft palate, larynx, and vocal folds can in principle act independently of one another, perturbations may result from the loose synchronization of physiologically independent articulators. This will be particularly likely if differences in inertia result in one articulator being markedly faster or slower than another.[2]

Second, perturbations of one segment by another open the way to the perturbation developing into a distinctive

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rather than redundant feature of the perturbed segment, particularly if the contrast between the segments which originally brought about the perturbation is lost. The voicing distinction in initial stops has collapsed in many Southeast Asian languages (Matisoff 1972, Li 1975, Mazaudon 1976). and in the Khoisan language, Nama (Beach 1938). In these languages, higher tones have developed from the elevation of Fo after original voiceless stops and lower tones have developed from the depression of Fo after original voiced ones. In some West African languages, voiceless stops allow high tones to spread through them from the preceding vowel, but block the spreading of low tones, because they elevate Fo on the following vowel. Conversely, voiced stops, because they depress the following vowel's Fo, allow low but not high tones to spread through them (Hyman & Schuh 1974). The perturbation of Fo occurs because whatever laryngeal mechanism changes vocal fold tension during the stop is slower to adjust to the state required for the following vowel than are the oral articulators.

Section 3.2 below contains an elaboration of the question of Fo perturbation by oral and glottalic stops. In section 3.2.1, the phonological consequences of these perturbations are discussed in detail. This is followed by an

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evaluation of the principal mechanisms which have been proposed to explain the Fo perturbations by oral stops and a discussion of their applicability to glottalic consonants in section 3.2.2. Section 3.3 presents a results of experiments designed:

i) to measure how ejectives perturb Fo of neighboring vowels and

ii) to determine the timing and extent of larynx movement during these consonants.

3.2 Fo perturbations by oral and glottalic stops

3.2.1 Phonological developments from these perturbations

In some languages, the perturbation of Fo following voiced and voiceless stops has come to be reinterpreted as new tonal distinctions on the following vowel. Usually this development accompanies a collapse of the voicing distinction in the stops themselves and is quite common in Southeast Asian languages; for example in the Tai language, Lungchow (Li 1975), words in prototone B developed different tones depending on the original initial consonant of

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the syllable,[3]

(3.1)

*taan > taan 55 'window'

*daa > taa 11 'wharf, ford'

*t^hii > t^hii 55 'thick'

*ɗaa > daa 55 'to scold'

*nan > nan 11 'to sit'

*Naai > naai 55 'tired'

The symbol N represents a voiceless nasal.

After original aspirated and unaspirated stops as well as after original implosives and voiceless sonorants, a high level (55) tone developed in this language, while after voiced stops and sonorants a low level (11) tone now appears. The earlier contrast between */t/ and */d/ has merged to /t/, but a new /d/ has developed from the implosive */ɗ/. Voiced and voiceless sonorants have merged to the voiced member of the opposition. The course of the tone split in Lungchow can be divided into four stages:

(3.2)

i) Before the sound change began. At this stage, syllables beginning with voiced and voiceless stops, for example, */daa/ 'wharf, ford' and */taan/

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'window', are distinguished primarily by voice onset time (VOT). Fo perturbations occur automatically as a result of the normal articulation of the stops, but they are at best only a secondary cue to the discrimination of voiced from voiceless stops.

ii) however, since most documented cases of tonogenesis from perturbations induced by voiced and voiceless stops occur in the languages which were already tonal (J.-M. Hombert p.c.)[4], a listener may eventually reinterpret the perturbation of Fo as allotones, i.e. a feature of the vowel rather than the consonant, even though they are produced as part of the articulation of the consonant (see Haudricourt (1972a) and Mazaudon (1976) for similar arguments). This shift leads to

iii) the transition stage, when the perceptual importance of Fo has increased to the point where Fo and VOT are on equal footing as cues to the voicing contrast.[5] At this stage, some listeners may only pay attention to Fo and since perception is likely to determine production, they will produce

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/taan/ 55 < */taan/ and /taa/ 11 < */daa/. It is important to note that Fo has simply replaced VOT; it is not the case that VOT differences have simply eroded away. For these speakers, the sound change is complete, but the language as a whole is in transition because some speakers are still attending to and producing VOT differences. Because the Fo perturbations occur automatically in the speech of these more conservative speakers, they will not retard the transition from VOT to Fo. Eventually,

iv) the sound change is complete when all speakers use Fo alone. A higher tone appears on words which originally began with voiceless stops and a lower one on words which had voiced initials.

The first, second, and third stages in this sequence could all be considered to represent the stage of the language before the sound change has occurred. The fourth stage represents the stage of the language after the sound change -- merger of the voicing contrast and compensatory tone splitting -- is complete. Though the second and third stages are hypothetical and it is an article of gospel in

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historical linguistics that transitional stages in language change cannot be directly observed, evidence that listeners can distinguish voiced from voiceless stops when the only phonetic difference is in the fundamental frequency of the following vowel (Fujimura 1971) suggests that the transitional stages could be documented.

Since listeners are concerned primarily with distinguishing one message from another, they may be more or less indifferent to which cues they attend to accomplish this task, in this case voicing in the stop or the pitch of the following vowel. As a consequence, it may be difficult in the transition stages of the sound change to be sure whether listeners take differences in Fo to be a cue to the identity of the initial stop or to the tone of the vowel. Nonetheless, there is no obvious reason why different members of the speech community should not rely more on one cue than another. Difference among listeners in the perceptual weight they assign to different cues to voicing has been doemnstrated for English by Massaro and Cohen (1976, 1977). All that is required for the sound change to become complete is for a particular listener is to stop attending to VOT entirely. From this point of view, there is no transitional stage in the sound change for individual listeners (or

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individual lexical items), but only for the speech community (or lexicon) as a whole.

There are two other ways in which the voicing distinction interacts with tone. Breathy-voiced obstruents in Southern Bantu languages depress the beginning of following high tones, producing a rising tone, as in the Zulu examples below (the dashes above the vowels represent relative pitch levels; / represents a rising pitch, and \ a falling one; the letters H (high) and L (low) below the line of segments represent the phonemic tone of each syllable. The conventional symbols for indicating tones are placed immediately over the vowels: high [á], low [à], rising [ǎ], and falling [â]. Note that the symbol for a rising tone, /, and the acute accent used for a high tone, [á], and the symbol for a falling tone, \, and the grave accent used for a low tone, [à], have different values. A superscript /^{h}/ following a consonant indicates breathy-voice. Data from Rycroft (1963) and Cope (1970)):

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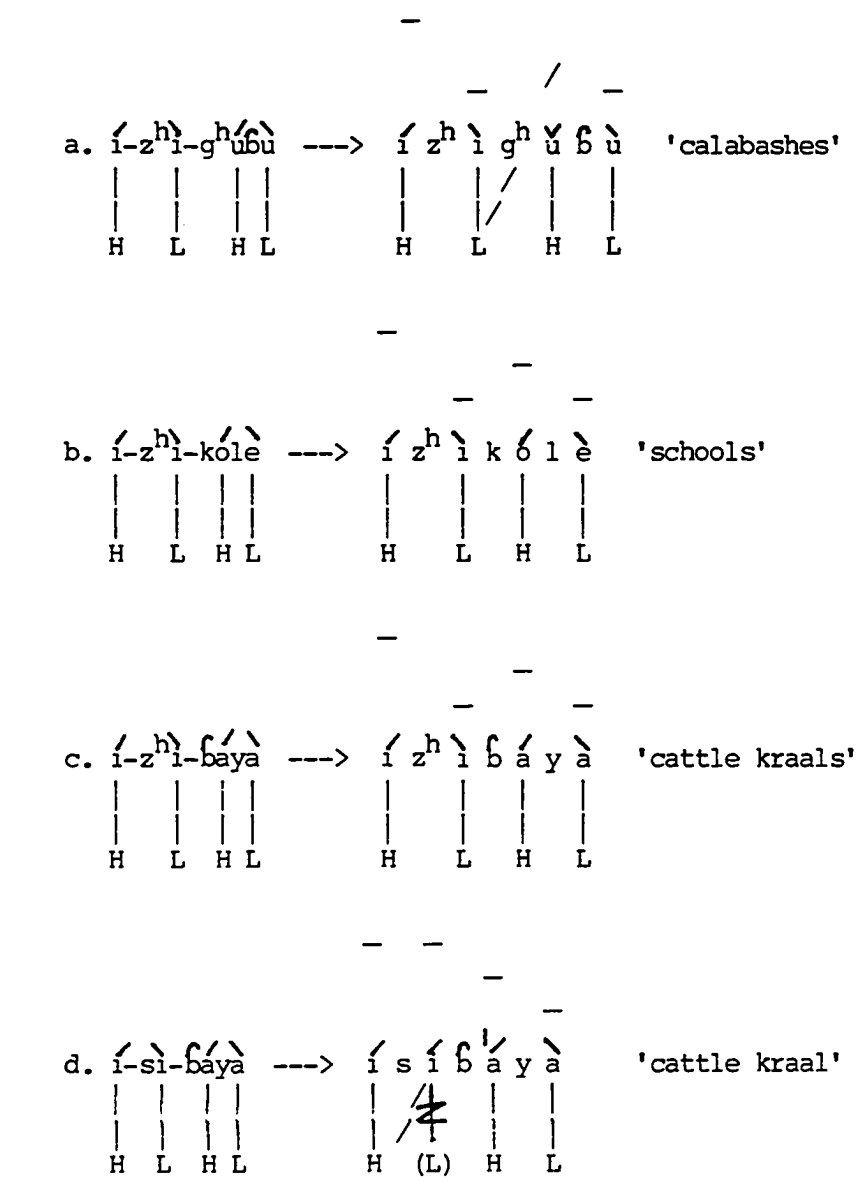
(3.3)



The initial consonant of the stem in /ízʰì-gʰúbù/ 'calabashes' in (3a) is breathy-voiced and it pulls down the beginning of the following high tone. The stem high tones are left unperturbed when the initial consonant is either voiceless (3b) or a implosive (3c,d). Breathy-voiced

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obstruents in Zulu also block the spreading of high tones from preceding syllables. Compare the singular of cattlekraal in (3d) with the plural in (3c): in (3d), a high tone spreads from the first syllable to the second across the voiceless fricative /s/, but the spreading of this high tone is blocked in (3c), where the breathy-voiced fricative /z^h/ intervenes. The low tone the second syllable bears underlyingly in (3d) is delinked by this spreading process, but the following high is still a half a step lower than the preceding highs, i.e. the floating low tone delinked by the spreading of the preceding prefix high still downsteps the following high; compare (3c) where the the low was not displaced. In this example, the high is also lowered, though after an attached low. Voiceless stops, ejectives, and implosives do not interfere with the lowering of following high tones by preceding lows (attached or floating), but they do prevent the low from spreading across them and turning the following high into a rising tone (compare (3c) with (3b)). Downstep is not sensitive to the glottal type of the intervening stop, only tone spreading is.

In the Chadic languages, Bade and Ngizim, both voiced and voiceless stops affect tone spreading (Schuh 1978). High tones spread through voiceless but not voiced stops,

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while voiced stops are transparent to low but not high tone spreading. Implosives behave like voiceless stops and allow high but not low tones to spread through them. Both high and low tones spread through sonorants.

(3.4)

Ngizim -- Low tone spreading

a. gubəs ɓai ---> gub s ɓai 'it's not a warthog'

Voiced - Low spreads

b. mari ɓai ---> mari ɓai 'it's not a beard'

Sonorant - Low spreads

c. təmaaku ɓai ---> təmaaku ɓai 'it's not a sheep'

Voiceless - Low does not spread

d. aaɗau ɓai ---> aaɗau ɓai 'it's not south'

Implosive - Low does not spread

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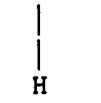
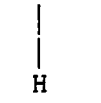
Bade -- High tone spreading

e. nən gafaw ---> nən gafaw 'I caught'



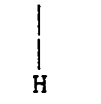
Voiced - High does not spread

f. nən lawaw ---> nən lawaw 'I ran'



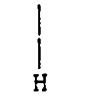
Sonorant - High spreads

g. nən kataw ---> nən kataw 'I returned'



Voiceless - High spreads

h. nən ɗamaw ---> nən ɗamaw 'I submerged'



Implosive - High spreads

The high tones following the lows displaced by spreading in (f,g,h) are downstepped.

(4a-d) illustrate spreading of a low tone. The low tone spreads through a voiced stop (4a) and a sonorant (4b), but not through a voiceless stop (4c) or implosive (4d). The high tone spreading rule illustrated in (4e-h) exhibits the opposite constraints. A voiced stop (4e) blocks the spreading of the high tone from the first syllable, but it spreads without impediment through a sonorant (4f), a voiceless stop (4g), and an implosive (4h).

All of these interactions between oral stops and tone are precisely what one would expect given the direction of

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Fo perturbations observed after voiced and voiceless stops. The tone which spreads through a stop is the one whose value is compatible with the perturbation caused by that stop and the tone whose spreading is blocked is the one which pulls the vowel in the direction opposite that which the stop is pulling it. Though tone spreading is generally perseverative, even in languages where the voicing distinction does not affect it (Hyman & Schuh 1974), the perturbation of Fo by a voiced or voiceless stop can only interact with a tone spreading across it from the preceding vowel since oral stops only perturb Fo on following vowels.

There appear to be no cases where an ejective has induced a tone or tone split on a following vowel. Both tonogenesis in languages like Lungchow and the synchronic tone spreading rules in Zulu, Bade, and Ngizim indicate that implosives elevate Fo on following vowels sufficiently to have phonological consequences. The failure of ejectives to contribute to tonogenesis on following vowels may not require a phonetic explanation, since ejectives are not found in any of the languages of Southeast Asia, where tone splitting under the influence of obstruent-induced Fo perturbations has been pervasive. In the Southern Bantu languages, ejectives behave like other voiceless stops in

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not depressing the beginning of following high tones and blocking low tone spreading.

Evidence is presented in section 3.2.3, which shows that ejectives are not phonetically identical in different languages; furthermore, the kinds of crosslinguistic differences which exist appear to be just the right sort to explain the opposing tone developments in Athabaskan discussed immediately below.

Like the oral stops, implosives appear to only perturb following vowels, though this may simply be an accidental consequence of their frequent failure to occur syllable-finally (ejectives are also rare in that position, but less so than implosives (Kingston 1982)). Furthermore, where implosives have been noted to induce tone splitting or affect tone spreading, they behave uniformly like voiceless stops, creating higher tones (Lungchow) and allowing high but not low tones to spread through them (Ngizim), i.e. there appears to be no phonological evidence for crosslinguistic differences in how implosives perturb Fo. However, Lindau (1984) has recently reported on significant phonetic differences in how implosives are articulated among a number of Nigerian languages, some of which could influ-

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ence the way in which an implosive perturbs Fo on a neighboring vowel. A more serious problem is explaining how it comes about that implosives elevate rather than depress Fo, given that they are usually voiced and are produced with a rapid and extreme lowering of the larynx.

3.2.2 Athabaskan tonogenesis[6]

3.2.2.1 Introduction

Ejectives, together with glottal stop, have given rise to tones in one notorious case, Athabaskan, but on the preceding not the following vowel (Krauss 1964, Leer 1979). In some Athabaskan languages, represented by Chipewayan in (3.5) below, a high tone has developed on the vowel preceding original syllable-final glottal stop and ejectives, while in others a low tone appears in cognate words, illustrated by the Navajo examples. In neither group are ejectives now found syllable-finally, though in some languages, glottal stops still occur in that position. The loss of a contrast between ejectives and oral stops at the end of the syllable in these languages, together with the fact that in two conservative groups of Athabaskan languages, the Pacific

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Coast group, represented by Hupa, and in Alaskan Athabaskan, represented by Ahtna, no tones have developed where glottalized consonants are retained syllable-finally, makes it clear that the ejectives are the source of the tones in the first two groups. Data is from Krauss (1979).

(3.5)

	Proto-Athabaskan	Chipewayan	Navajo	Hupa	Ahtna
'belly'	*-wət'	-bə́r	-bìd	-mət'	-bet'
'moss'	*-tLa:t'	-tLàr	-tLá:d	Lah	
'father'	*-ta?	-tá	-tà:?	-ta?	-ta?
'neck'	*-q^{w}'əs	-k'òθ	-k'òs	-q'os	-q'os
'rope'	*-tL'u:L	-tL'ùL	-tLó:L	-tLohL	-tLu:L
'water'	*-tu:	-tù	-tó	-to:	-to:

The symbol L represents a voiceless lateral fricative.

In Chipewayan, a high tone has developed before original glottal stop, */-ta?/ > /-tá/ 'father' and ejectives, */-wət'/ > /-bə́r/ 'belly' (Chipewayan syllable-final /r/ comes from Proto-Athabaskan */t'/) and a low tone elsewhere. Navajo represents the tonal developments of all of Apachean, low tone before glottalized consonants, /tà:?/ 'father' and /-bìd/ 'belly' (Navajo syllable-final /d/ comes from Proto-Athabaskan */t'/), and high tone elsewhere. Some other

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Athabaskan languages in Canada, for example Kaska and Chilcotin, have developed in the same way as Chipewayan, but others, including Sarcee and Kutchin, have low tones in syllables which originally ended in glottalized consonants, like Navajo and the rest of Apachean. No clear dialect grouping has been worked out for Canadian Athabaskan to explain this distribution of high and low tone languages (see Krauss & Golla 1981). Glottal stop and ejectives do not produce the same tone in syllables with long vowels as they do on short ones; generally, such syllables have the same tone as those ending in oral consonants, for example */tLa:t'/ 'moss' becomes /-tLàr/ with low tone in Chipewayan and /-tLá:d/ with high tone in Navajo; the same development as occurs when the syllable-final consonant is not glottalized, e.g. /-tL'u:L/ 'rope' which becomes /tL'ùL/ in Chipewayan and /tLó:L/ in Navajo. The crucial problem presented by Athabaskan is explaining how both high and low tones could develop from the same source. Somehow, syllable-final glottal stops and ejectives must be able to both elevate and depress Fo on preceding vowels.

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3.2.2.2 The case for tone reversal[7]

In the following discussion, languages which have developed high tone from final glottals will be called 'high-marked', while those which have developed low tone from this source will be said to 'low-marked', following Leer (1979) and Krauss (1979). In each language, the opposite tone, low in Chipewayan, and high in Navajo, for example, developed in stems which did not end in a glottal.

The difficulty in explaining the contrary tone developments in the various Athabaskan languages is compounded by the fact that neither the high- nor the low-marked languages form coherent subgroups; instead of a single innovation -- high for low and low for high (or vice versa) in a single branch -- it appears that high and low tone have reversed themselves at a number of times and places during the dispersal of the family (Krauss 1979).

The following sketch of the dispersal of the family (based on Krauss & Golla 1981, plus some additional details from Victor Golla, p.c.) is intended to illustrate the fact that tone reversals have recurred in this family of languages throughout its history.

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From a homeland in the southeastern interior of Alaska, covering the upper drainage of the Yukon River and perhaps stretching down into the northern part of British Columbia (where a number of conservative Athabaskan languages are still spoken), two major migrations issued. The first followed the interior mountains further south into British Columbia and eventually reached as far as Northern California, before 500 CE. At one time, this migration probably left a nearly continuous string of Athabaskan languages from Northern California back to the homeland, but this chain has subsequently been broken by the intrusion of other language groups along its length. What became the Pacific Coast group of Athabaskan languages, which survived into the historical period in Oregon and Northern California, were eventually isolated from the rest of Athabaskan. Phonologically, these outlier languages are extremely conservative, like those left behind in the homeland in Alaska. They preserve final glottalization and have not developed tone. A few languages from this first migration also survived in British Columbia, including Carrier, Chilcotin, Kwalhioqua-Tlatskanai, and Tsetsaut, though this last has recently become extinct.

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After 500 CE, another migration from the homeland began (or perhaps two), which brought Athabaskans down the drainage of the Mackenzie river and south along the eastern side of the Rockies. The southern extension of this second migration eventually reached the Southwest and later spread out onto the Plains. This is the Apachean branch of the family, which includes Navajo. It is in the languages of this second migration that tone has developed. The following table lists the languages which developed out of this migration and shows the distribution of high- and low-marked tone (the nontonal languages in the Alaskan and Pacific Coast groups are included for completeness):

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(3.6)

Pacific Coast group	nontonal
Upper Umpqua	
Tututni-Chasta Costa	
Galice-Applegate	
Chetco-Tolowa	
Hupa	
Mattole	
Sinkyone-Wailaki	
Cahto	
Kwalhioqua-Tlatskanai	nontonal (?)
Apachean	low-marked
Chiricahua	
Jicarilla	
Mescalero	
Navajo	
Western Apache	
Kiowa-Apache	
Lipan	

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Northern Athabaskan	
Tsetsaut	?
Babine	?
Carrier	?
Chilcotin	high-marked
Sarcee	low-marked
Sekani	low-marked
Tahltan	high-marked
Tagish	high-marked
Chipewayan	high-marked
Kaska	high-marked
Beaver	high-marked
Slavey	high-marked
Mountain	high-marked
Bearlake	high-marked
Hare	high-marked
Dogrib	low-marked
Northern Tutchone	high-marked
Southern Tutchone	low-marked
Kutchin	low-marked
Han	low-marked

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Alaskan	
Lower Tanana	low-marked
Upper Tanana	low-marked
Tanacross	high-marked
Ahtna	nontonal
Tanaina	nontonal
Upper Kuskokwim	nontonal
Holikachuk	nontonal
Ingalik	nontonal
Koyukon	vestigal tone

The groupings in this table are more geographical than linguistic.

As indicated above, all the Apachean languages have developed low tone from final glottalization, but further north the situation is more disparate. As in Apachean, low tone is found in Sarcee and Sekani, but high tone appears in Chipewayan, Kaska, and the Beaver-Slavey-Hare-Bearlake-Mountain dialect cluster. However, in Dogrib, which is closely related to this cluster and perhaps even part of it, low rather than high tone appears in stems which originally had final glottalization. The tonal divergence of Dogrib from its high-marked relatives suggests strongly that tone reversals have at least recently become part of the Northern Athabaskan scene.

Tonogenesis has apparently been creeping eastward

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toward the homeland from the Mackenzie River drainage area with Kutchin, Han, Southern Tutchone, Upper and Lower Tanana, and Upper Kuskokwim showing low tone, while Northern Tutchone, Tagish, and Tahltan have developed high tone. The split between Northern and Southern Tutchone with high tone on one side and low on the other is apparently as recent as that between Dogrib and the Mackenzie River dialect cluster. The shallowness of the tone isoglosses in these two cases makes tone reversal a more likely explanation than direct evolution of both high and low tone from the same phonetic source.

The pervasiveness of tonogenesis outside of the conservative Alaskan and Pacific Coast languages points to an early tendency to develop tone from final glottalization, beginning shortly after the initial breakup of Proto-Athabaskan, so it seems unlikely that final glottalization survived long enough for it to be the direct source for tone in Dogrib or the Tutchone dialects. Instead, tone developed in a much earlier ancestor of these languages and was later selectively reversed.

Although tone reversal seems to be the only plausible alternative for explaining the more recent isolglosses, it

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may be the case that the deeper ones, such as occur between low-marked Apachean (together with Sarcee and Sekani?) and the high-marked Mackenzie River languages (presently excluding Dogrib), do reflect direct, if divergent, developments from final glottalization. I have accordingly outlined what appears to be the most plausible way of getting opposing tones from the same source in the next section.

3.2.2.3 The phonetics of constriction

3.2.2.3.1 Introduction

In their analysis of Athabaskan tonogenesis, Leer (1979) and Krauss (1979) argue that tone developed as a result of a shift of glottalization from the stem-final consonant to the preceding vowel, a process they call "constriction". Constriction is simply one of a number of such shifts of features of this consonant to the stem vowel; the others include nasalization before an original final nasal and shifts in vowel quality before original glides. Though Krauss and Leer are quite vague about the phonetics of constriction, they imply that constriction makes tone reversals

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unnecessary, since once final glottalization has been replaced by constriction of the preceding vowel it can, in principle, develop into either high or low tone, independently in the various Northern Athabaskan languages. Their view of what constriction is phonetically seems to be that as a autonomous modification of the vowel it could either raise or lower Fo in different languages once they were relatively dispersed, a versatility which for unstated reasons they are unwilling to grant to the originally glottalized stops. It is phonetic plausibility of this hypothesis which is explored below.

The shift of glottalization from the final consonant of the stem to the preceding vowel is supposed to have taken place between a stage Leer and Krauss refer to as 'Pre-Proto-Athabaskan' and Proto-Athabaskan proper. In the languages which now have high or low tone in cognate stems, constriction eventually supplanted the glottalization of the stem-final consonant. Since the constriction initially developed as a redundant modification of the vowel preceding a stem-final glottal prior to the beginning of the breakup of Proto-Athabaskan, it must have been lost or ignored in the Alaskan and Pacific Coast languages which have failed to develop tone and which retain final glottalization in many

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cases. In fact, constriction was not lost entirely in the some of the nontonal languages, where it survives as vowel length.

This is a fairly direct piece of evidence supporting constriction as the transitional stage between the original final glottalization and the modern tones.

In some stems with marked tone in the tonal languages, no glottalization appears in cognate stems in the conservative Alaskan and Pacific Coast languages which normally retain final glottalization. A long vowel is found instead in some of these languages, among them Ahtna, spoken in Alaska. In other stems, unmarked tone corresponds to a long vowel in the nontonal languages. These corresposndences point to a stage in the protolanguage when a long vowel contrasted with a constricted vowel. This contrast has merged to a long vowel in languages such as Ahtna, while in languages such as Chipewayan and Navajo, the constricted vowel has developed into marked tone. The correspondence between Chipewayan and Navajo unmarked tone to a long vowel in Ahtna goes back to unconstricted long vowel in the protolanguage. These correspondences are illustrated in noun stems below (examples from Krauss 1979. Constriction is

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represented in Proto-Athabaskan as a /?/ following the vowel.):

(3.7)

	Proto-Athabaskan	Chipewayan	Navajo	Ahtna
a. 'wife, female'	* -?a:d	-?à	?á:d	-?a:d
b. 'rope'	* -tL'o:L	-tL'ùL	-tL'ó:L	-tL'u:L
c. 'inside of mouth'	* -za?d	-ǾÁ	-zà:d	-za:
d. 'fore-arm'	* -te?L	-tél(é)	-tè:L	-te:L
e. 'belly'	* -wət'	-bər	-bìd	-bet' **
f. 'knee'	* -G^{w}ət'	-gór	-gòd	-Got' **
g. 'scar'	* -Lu:t'	-Lùr	-Ló:d	-Lu:t' **
h. 'crusty snow'	* -ci:tL'	-cìL	-cí:l	-ci:tL' **

** Ahtna final ejectives are realized as preglottalized lenis stops, i.e. [?d], etc. (Kari 1979).

The first pair of examples show the unmarked tone:long vowel correspondence, while in the second pair, marked tone appears in Chipewayan and Navajo without there being any trace of glottalization in Ahtna; only vowel length in Ahtna points to the original constriction of these forms, represented here as a nucleus of the form V?. The last two

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pairs of examples show the normal tone:glottalization correspondences for these languages: marked tone in the third pair when the stem vowel is short (reduced), but unmarked tone in the last pair when the stem vowel is long (full). In all of these last four forms, Ahtna shows final glottalization.

Even more direct evidence for constriction is provided by Eyak, the closest relative to Athabaskan within Na-Dene, which retains a contrast between an unmodified long stem vowel and a constricted one. Eyak cognates for the examples above are given below, beside the Proto-Athabaskan forms (examples again from Krauss (1979)):

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(3.8)

	Proto-Athabaskan	Eyak
a. 'wife, female'	* -?a:d	-?ehd
b. 'rope'	* -tL'u:L	-tL'i?L
c. 'inside of mouth'	* -za?d	-sa?d
d. 'forearm'	* -te?L	-te?L
e. 'belly'	* -wət'	-wət'
f. 'knee'	* -Gwət'	-Guhd
g. 'cradle'	* -c'a:tL'	-c'a:tL'
h. 'spit'	* -$\check{s}$we:q'	-$\check{s}$ahG

(The forms in (g) and (h) were substituted for 'scar' and 'crusty snow' in (3.7g,h) because Eyak lacks cognates for those words in the material available to me.) There is a disconcerting variability in the correspondences between the Eyak vowel modifications: constricted V?, breathy Vh, and simply long VV (= V: in examples above) and Proto-Athabaskan nuclei, but, nonetheless, Eyak does modify its vowels in ways which are analogous, if not always precisely correspondent, to the constriction proposed by Leer and Krauss for Proto-Athabaskan (the significance of the two pieces of evidence just presented is entirely ignored by Cook (1981) in his criticism of the constriction hypothesis).

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To briefly recapitulate the points made above, it is clear that the erosion of stem-final consonant contrasts which led to constriction began quite early in the breakup of Proto-Athabaskan, presumably just after the first migration. Therefore, it is highly unlikely that final glottals survived long enough to directly induce tones at the time that Mackenzie River dialect cluster or the Tutchone dialects began to diverge from one another tonally. The tone isoglosses in these groups must, therefore, be the result of tone reversals in already tonal languages, with low-marked Dogrib and Southern Tutchone being the likely innovators in their respective groups. This argument does not, of course, rule out the possibility that much deeper splits, such as that between low-marked Apachean and the high-marked Canadian languages, might be the result of independent and opposing mutations of the phonetic substance of constriction. Accordingly, the phonetic paths to this divergence are laid out in the next section.

3.2.2.3.2 A phonetic explanation for the evolution of opposing tones from the same source

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It has often been observed that post-vocalic glottal stop varies freely in some languages with creaky voice. This voice quality is characterized by irregular, at times nearly aperiodic, vocal fold vibration, often at extremely low rates. On the other hand, glottal stop, when present, may induce a tense voice quality on neighboring vowels. Tense voice differs from creak primarily in having a higher fundamental frequency. In both voice qualities, the closed phase of a glottal cycle is longer relative to the open phase than in other voice qualities (Laver 1980: 122-26, 141-49) because of medial compression of the folds. The principal acoustic result of lengthening the closed phase of a glottal cycle is to tilt the spectrum up: there will be more energy at high frequencies with tense and creaky voice than during modal voice. (Breathy and lax voice, which have a lengthened open phase, show a more rapid decline in energy at higher frequencies than does modal voice.) The two voice qualities which derive from glottal stop (and presumably also ejectives), tense and creaky voice, are similar then in spectral properties but potentially quite different in fundamental frequency: tense being high and creaky low.

What became the low-marked Athabaskan languages could have selected the creaky voice quality with its low

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fundamental frequency as the realization of constriction, while those that became high-marked selected the high frequency, tense variant.

Unfortunately, this explanation has a potentially fatal difficulty. It predicts that in the low-marked languages, creaky voice would replace final glottalization, since if the glottal survives, a tense voice quality would be more likely to result. This prediction is not borne out: a final glottal stop is as stable in the low- as high-marked languages. For example, in the words for 'father' from Proto-Athabaskan */-ta?/ and 'beaver' from */ca?/, the glottal stop survives in eight of nine low-marked languages (only Dogrib loses it) and nine of ten high-marked ones (only Chipewayan lacks it).

If one looks outside of Athabaskan to other cases where a final glottal stop has influenced tone developments, for example in the Loloish languages described by Matisoff (1972) and Wheatley (1982), it is clear that a final glottal stop has survived more often in syllables which have developed a lower tone (from the initial consonant) than in syllables which have developed a higher tone. This is illustrated by the following cognate sets (taken from Matis-

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off 1972):

(3.9)

	Proto-Lolo-Burmese	Lahu		Sani	
a. 'village'	* kak	qha?	54s	tšhe	44
b. 'crooked, bent; return, go back'	* gok	qo?	21s	qu?	22s
c. 'rope, string'	* ?kyak	ca?	54s	tše	44
d. 'to boil'	* ?gyak	ca	45	tse	55
e. 'hand'	* lak	la?	21s	le?	22s
f. 'eight'	* ?rit	hi	45	he?	22s

The s following the tone numbers indicates a stopped syllable, also marked segmentally with /?/.

In these languages, a tone split has occurred as a result of the merger of initial consonants (as in Lungchow). After an original Proto-Lolo-Burmese voiceless stop or preglottalized consonant higher tones have developed in both Lahu and Sani, while after an original voiced stop or simple sonorant, a lower tone appears. In Lahu, with one exception, a syllable which was closed by a stop in the protolanguage still has a final stop (always /?/) after both the new higher and lower

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tones, but in Sani, a stop is only retained after the new lower tone. The exception in Lahu is words which originally began with a preglottalized voiced stop or sonorant, i.e. 'to boil' */?gyak/ > /ca/ and 'eight' */?rit/ > /hi/, both with open, high rising 45 tone in Lahu. Matisoff describes this as a "glottal dissimilation", i.e. the final glottal stop is lost when an initial which would induce a lower tone is preglottalized. This dissimilation would be unexpected if the voiced stop or sonorant still lowered the tone of the following syllable, as it does when not preglottalized, since final glottal stop should be retained after a lower tone. The tone which has developed in such cases is high rising 45 rather than low falling 21s, however. The voiced stop or sonorant has only managed to slightly depress the beginning of this tone, which reaches the top of the range by the end of the syllable. Loss of the final glottal stop is, therefore, expected. Note also that preglottalized voiced stops induce a high level 55 tone in Sani which is not stopped either.

These Loloish developments confirm the suspicion raised by the Athabaskan data that final /?/ is likely to be as stable, if not more so, after lower than higher tones. The Loloish facts can be explained, I think,by appealing to the

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notion of camoflauge, introduced by Ohala (1981) and exemplified in Kawasaki (1982). If syllable-final glottal stops in these languages tended to elevate the fundamental frequency of the preceding vowel and if this elevation was one of the principal perceptual cues to the presence of the glottal stop, then in a syllable where the initial consonant has induced a higher tone, it is possible that the high fundamental frequency of the syllable would be attributed by listeners to the initial or the vowel rather than the final glottal stop. These listeners would accordingly fail to produce the final glottal stop when they in turn acted as speakers. Final glottal stops would be retained in syllables where a low tone was induced by the initial consonant because whatever raising of the fundamental frequency of the vowel occurs could only be attributed to the final glottal stop. If invoking camoflauge to explain the retention of final glottal stops in newly low Loloish syllables has any merit, then it can in turn be applied to explain why final glottal stops were not lost in the low-marked Athabaskan languages, though one might now ask why glottal stops were not lost from syllable-final position in the high-marked languages in that family. Since this discussion threatens to swing endlessly back and forth between a situation where

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the low-marked languages are the problem and one where the high-marked languages are, I will not tax my phonetic ingenuity or the reader's patience any longer with this matter.

Though tone reversal cannot be ruled out for the earliest splits between high- and low-marked languages in Athabaskan, the discussion above suggests that is possible that opposing tones could have developed on constricted vowels, realized in the low-marked languages as creaky voice and in the high-marked as tense voice. Because tone clearly arose soon after the breakup of Proto-Athabaskan, tone reversal remains, however, the most likely source of the shallower splits in the family. In the last section of chapter 4, tonogenesis in Athabaskan will be taken up again.

3.2.3 Mechanisms for perturbing Fo

3.2.3.1 Perturbation by oral stops

The perturbations of Fo by voiced and voiceless oral stops have three essential features. First, only obstruents perturb Fo. Though Fo is generally low after sonorants

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(Hombert 1978) this perturbation apparently does not cause tone splitting nor interfere with tone spreading unless the obstruents do. Note that the reverse implication does not hold; i.e. the perturbation of Fo by obstruents may have phonological consequences without any participation of the sonorants. For example, recall that in Bade and Ngizim, (voiced) sonorants allow both high and low tones to spread through them; sonorants are similarly transparent in Nupe (Hyman & Schuh 1974). In the rare circumstance where there are voiceless as well as voiced sonorants, as in Lungchow, voiced sonorants behave like voiced stops and induce lower tones, while voiceless sonorants behave like voiceless stops, creating higher tones. Since sonorants seldom participate in the voicing contrast, no difference in Fo normally appears on the following vowel, so sonorants will usually be neutral with respect to tonogenesis or tone spreading processes; as they are in Bade and Ngizim. The genesis of lower tones after voiced sonorants as well as obstruents in Lungchow is probably analogical; the analogy based on the occurrence of (redundant) voicing in the sonorants. No evidence regarding the phonetic effect of a voiceless sonorant on the fundamental frequency of a following vowel is available; they probably would raise Fo by the same mechanism as

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voiceless obstruents do.

The second general feature of Fo perturbations is that they are large enough to be reliable secondary cues for discriminating voiced from voiceless obstruents (Haggard, Ambler, & Callow 1970, Fujimura 1971, Massaro & Cohen 1976, 1977, Haggard, Summerfield, & Roberts 1981).

Third, whatever mechanism changes glottal tension during oral stops is invariably active during the production of these stops and it is slow enough to revert to a rest state that the following vowel is invariably perturbed.

Two plausible mechanisms have already been introduced to account for the perturbations of Fo by voiced and voiceless stops: the horizontal tension hypothesis of Halle and Stevens (1971) and the vertical tension hypothesis of Hombert, Ohala, and Ewan (1979).

Recall that Halle and Stevens suggest that in order to inhibit voicing during the stop closure of a voiceless stop, horizontal vocal fold tension is increased by contracting the cricothyroid and stretching the folds. As noted in earlier discussion in chapter 1, voicing is probably precluded in voiceless stops by drawing the folds too far apart to

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vibrate, so stretching the vocal folds would only delay the onset of voicing after the release of the closure, until the folds are relatively closely adducted. This stretching of the vocal folds would inadvertantly elevate Fo next to voiceless stops. A reduction in vocal fold tension during voiced stops produces slack folds which will vibrate more easily in response to weak air flow between them (as noted in chapters 1 and 2, the higher transglottal volume velocity which slack folds allow will elevate intraoral air pressure faster and thus will eventually threaten voicing). This slackness would also result in a lowering of Fo on the following vowel. Both of these systemic adjustments are conceived by Halle and Stevens as attempts to prevent or encourage vocal fold vibration, though the perturbation of Fo itself is inadvertant.

Hombert, Ohala, and Ewan note that the activity of the cricothyroid, the muscle whose contraction increases horizontal tension on the vocal folds by tilting the thyroid cartilage, does not usually increase during the production of voiceless stops. As noted above, the activity of this muscle is suppressed during the production of both voiced and voiceless stops (Hirose & Gay 1972, Hirose & Ushijima 1978, Hirose, Yoshioka, & Niimi 1978, cf. Dixit & MacNeilage

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1980). Though slightly more suppression is often noted for voiced than voiceless stops, this cannot easily explain the differences in Fo which appear on the following vowel, since cricothyroid activity begins to increase before the oral release of both voiced and voiceless stops. This increase in activity might explain the initially low and slowly rising Fo contour which follows voiced stops, but it would not by itself produce the initially high and falling contour observed after voiceless ones.

The second problem with the horizontal tension hypothesis is that it would predict the same Fo perturbations should occur on the preceding as the following vowel, since the adjustments of vocal fold tension are part of a set of adjustments designed either to turn voicing off and keep it off or to keep it going. No differences in Fo at vowel offset are observed before voiced and voiceless stops.

Because of these problems with the horizontal tension hypothesis, Hombert, Ohala, and Ewan suggest that vertical movement of the larynx during stop articulations may be the source for the Fo perturbations. During vowels, the larynx rises and falls with Fo and it is usually found to be higher during the production of voiceless than voiced stops. They

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argue that lowering the larynx would reduce vertical tension on the folds. Riordan (1980) has shown that during a voiceless stop the larynx reaches its highest point just before the oral release and that during a voiced stop it reaches it lowest point at the same time. If changes in larynx height do bring about changes in the vertical tension applied to the folds, this synchronization of the greatest vertical displacement of the larynx with the oral release would result in perturbations of Fo occurring on the following but not the preceding vowel. Halle and Stevens' proposal would have to be modified so as to require progressive stiffening or relaxation of the vocal folds during the closure interval of voiceless and voiced stops, respectively, to explain the absence of Fo perturbations on preceding vowels. The problem remaining with the vertical tension hypothesis is that there has been no direct demonstration that changing the vertical position of the larynx does change the vertical tension applied to the folds. All that has been demonstrated is that larynx height correlates positively with Fo and the timing of larynx movement is appropriate to explain the fact that only following vowels are perturbed.

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3.2.3.2 Perturbation by ejectives

Given the correlation between larynx height and Fo observed for oral stops, one would expect Fo to be elevated after ejectives and depressed after implosives. Measurements (Kingston 1982) taken of Fo of vowels following ejectives produced by one speaker each of Tigrinya, a Semitic language of Ethiopia, and Quiché, a Mayan language of Guatemala, show that Fo can be both elevated and depressed after ejectives. In fact, the ejectives of these two languages are different in many respects, illustrated with representative waveforms of alveolar and velar ejectives in these languages in Figure 3.1:

Figure 3.1.

a. Alveolar ejectives. Arrow indicates creaky voice in Quiché.

b. Velar ejectives

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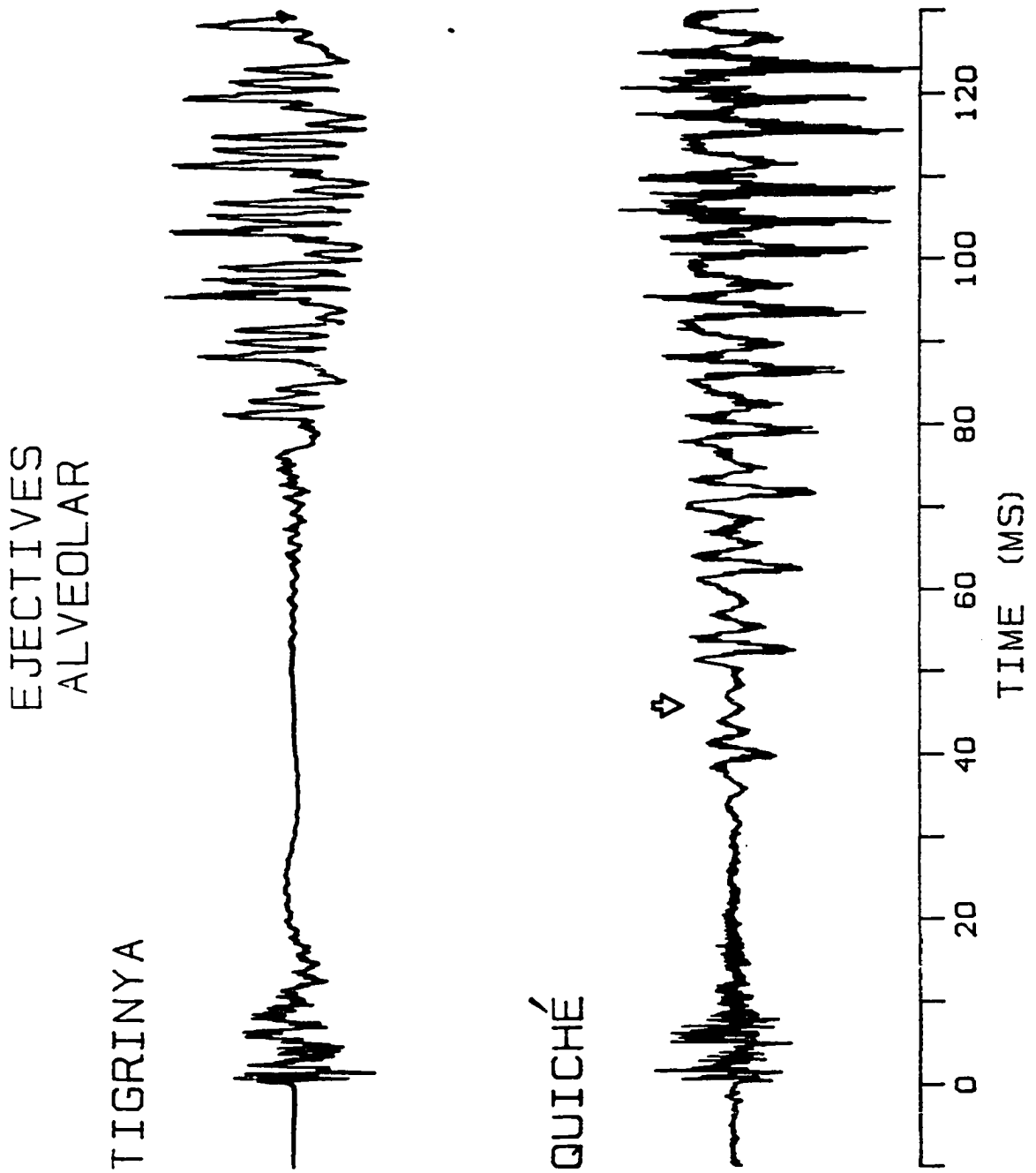

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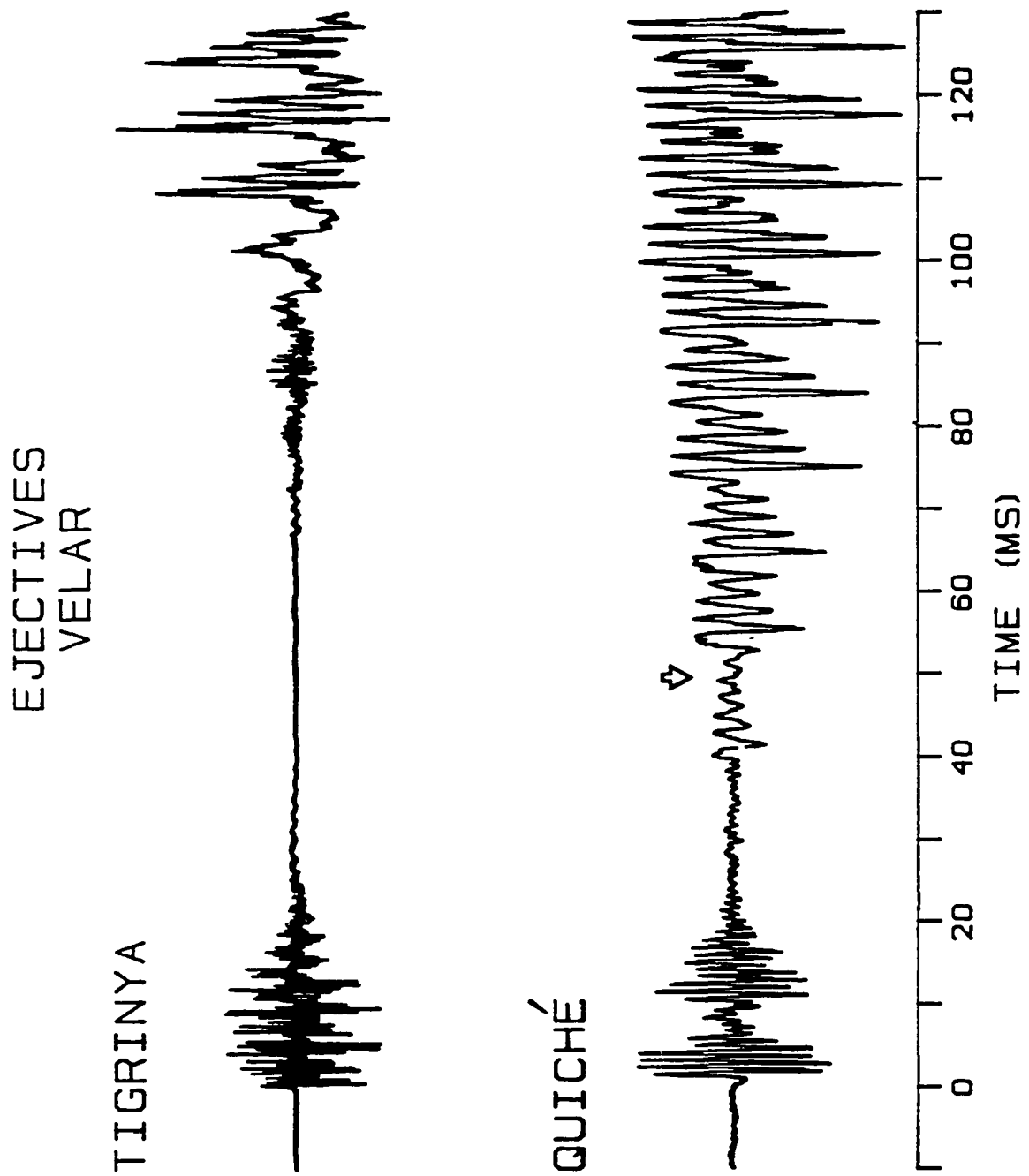

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The important differences between the ejectives in these two languages are listed below:

(3.10)

	Tigrinya	Quiché
i)	Fo of following vowel is elevated	Fo of following vowel is depressed
ii)	Long voice onset time	Short voice onset time
iii)	Intense burst followed by silence until vowel onset	Weaker burst followed by low intensity noise until vowel onset
iv)	Abrupt voice onset with rapid rise to maximum amplitude	Gradual voice onset with slow rise to maximum amplitude
v)	Modal voice at voice onset	Significant interval of creaky voice before transition to modal voice

The long silent interval following the intense burst of the oral release in Tigrinya indicates that the glottal release is significantly delayed. Once it occurs, there is a quick transition from the tightly adducted state of the vocal folds to the moderately stretched state characteristic of modal voice. The elevation of Fo indicates the vocal folds only lose their stiffness gradually. In Quiché, after an earlier glottal release, nearly simultaneous with the oral one apparently, the vocal folds must not be terribly stiff to create the irregular, weak, low frequency creaky voice observed after ejectives in this language. For convenient reference, ejectives of the Tigrinya type will be called

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'tense' and the Quiché type 'lax'.

If larynx raising is one of the maneuvers which elevates Po during the closure interval of ejectives in both Tigrinya and Quiché to levels significantly above those observed during voiceless stops (Pinkerton (1980) shows that Po is higher during ejectives than voiceless stops in Quiché) and larynx raising elevates Fo, how can Fo at the following vowel onset be high in Tigrinya and low in Quiché? This paradox suggests that larynx movement either does not perturb Fo at all or its effects are masked by more direct manipulation of vocal fold tension in these languages. More specifically, this paradox suggests replacing larynx movement with a variant of Halle and Stevens' hypothesis where a progressive increase in vocal fold stiffness brought about by the contraction of the vocalis and lateral cricoarytenoid occurs during the closure, rather than an increase in stretch by the contraction of the cricothyroid of the sort suggested by Halle and Stevens. The folds must be compressed medially during ejective articulations to prevent air flow through the glottis.

Independent support for this kind of manipulation of vocal fold stiffness is found in Korean, where there is

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a contrast between what have been called 'tense' and 'lax' stops which resembles that found between Tigrinya and Quiché ejectives, except for the VOT differences.[8] Though the tense stops in Korean usually have shorter VOTs that the lax ones, the two series are not reliably distinguished by VOT alone (Lisker & Abramson 1964, Kim 1965, Abramson & Lisker 1971). Instead it is the nature of the following vowel onset which is distinctive. After the tense stops, the vowel has a rapid rise time and Fo is elevated, but after the lax stops, the vowel's amplitude increases more slowly and Fo is quite low (Han & Weitzman 1970, Hardcastle 1974, Kagaya 1974, Hirose, Park, Yoshioka, Sawashima, & Umeda 1981). Han and Weitzman (1970) also observed spectral differences between the two series: higher frequency cavity resonances were more intense at vowel onset after the tense stops than the lax ones, an indication of a firmer adduction of the folds. Fo after the aspirated stops of Korean, which have exceptionally long VOTs, is usually elevated about as much as it is after the tense stops.

Kagaya's (1974) observations through a fiberscope revealed that the glottis closes considerably before the oral release in the tense stops, but in spite of the lack of separation of the folds, voicing does not begin until

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shortly after the oral release. For both the lax (unaspirated) and aspirated stops, voicing begins as soon as the glottal aperture gets sufficiently narrow. The long delay in voice onset after glottal adduction in the tense stops must be a product of some stiffening or compression which increases the glottal resistance enough to prevent any vibration of the vocal folds during the stop itself.

Evidence for such stiffening in the articulation of the tense stops is found in the increase in the activity of the vocalis and lateral cricoarytenoid muscles just before the oral release (Hirose, Lee, & Ushijima 1974, Hirose, Park, Yoshioka, Sawashima, & Umeda 1981). Though these muscles are often lumped together with the interarytenoid as muscles which close the glottis, their role here seems to be to increase vocal fold stiffness sufficiently to prevent voicing. Kim (1967) shows that Po is never greater than Ps in the tense stops, and since Po remains dependent on Ps, the glottis cannot be completely airtight.

The same level of activity is observed in the interarytenoid for both tense and lax stops, so it cannot be the muscle that causes the differences between the two stop series; nor is it the cricothyroid, which shows the same

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pattern of suppression for all three stop series in this language. Electromyogrpahic investigations of glottal stops (Hirose & Gay 1972) and Danish stød (Fischer-Jorgensen & Hirose 1974), also demonstrated no increase in interarytenoid activity, but a sharp rise for the vocalis and in articulating a glottal stop, the lateral cricoarytenoid. Finally, these observations suggest that Dent's (1981) demonstration of elevated levels of vocalis activity in her imitations of Quechua ejectives is at least plausible, though nagging doubts remain about whether to accept physiological data taken from someone who is not a native speaker. This electromyographic data makes it reasonable to conclude that the adduction of the folds during an ejective is maintained by an increase in the level of activity of the vocalis and perhaps also the lateral cricoarytenoid, much like the stiffening that inhibits voicing after glottal adduction in the Korean tense stops.

The fact that the tense and lax stops of Korean have overlapping VOTs shows that the contrast between Tigrinya tense ejectives and Quiché lax ones does not depend on the differences in the timing of the glottal release between the two languages. The Korean data also shows that if the vocalis and lateral cricoarytenoid are active, voicing will

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not occur even when the vocal folds are closely adducted. As Kim (1965) emphasized, the changes in vocal fold stiffness controlled by these muscles is manipulated orthogonally to VOT, which suggests that a fourth type of language, with long VOTs after its ejectives but depressed Fo on the following vowel, should exist, filling the gap in the chart below:

Table 3.4

		VOT	
		Short	Long
Fo	High	Korean tense stops	Tigrinya ejectives
	Low	Quiche ejectives	?

Observed combinations of voice onset time (VOT) and Fo perturbations

This fourth type of language may not exist, however. If it turns out to be impossible to prevent voicing from starting soon after the oral release when only moderately stiff vocal folds are adducted at the oral release, then the contrast between tense and lax ejectives reflects quantitative differences in the degree of stiffening induced by the contraction of the vocalis and lateral cricoarytenoid. Otherwise, it is difficult to understand how an increase in

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stiffness in the vocal folds can depress Fo in Quiché and elevate it in Tigrinya. Tigrinya ejectives would be produced with the folds in a relatively stiff state with considerable medial compression, the Korean tense stops with stiff folds but without much medial compression, and in Quiché ejectives the folds would be compressed medially without appreciable stiffening. In this description, medial compression but not stiffening is characteristic of all ejectives. It remains an open question just what muscles are responsible for the medial compression, however. We have already seen that it cannot be the interarytenoid, since this muscle is not especially active in glottal stops. In a discussion of creaky voice, Laver (1980), citing Hollein, Moore, Wendahl, and Michel (1966), Hollein, Coleman, and Moore (1968), and Hollein and Colton (1969), suggests that marked medial compression can be produced by bringing the false vocal folds together and pressing them down on the true folds. This creates a thick mass of tissue in which vibration is very quickly damped. Furthermore, it is apparently possible to cause the folds to vibrate at different rates when they are in this state without changing their length by contracting the cricothyroid. It would appear that differences in fundamental frequency between

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tense and creaky voice are then a matter of how stiff the folds are, the stiffer the higher the fundamental frequency. The fact that considerable medial compression occurs in the production of both tense and creaky voice is especially interesting since it appears that these two voice qualities differ in fundamental frequency in precisely the same way that the tense ejectives of Tigrinya and the lax ejectives of Quiché do. These facts also suggest that the amount of stiffening the folds are subject to is independent of the amount of medial compression.

3.2.3.3 Perturbation of Fo by implosives

In section 3.2.1 evidence was presented that implosives, like voiceless stops, create higher tones in Lungchow, fail to depress the beginning of high tones in Zulu, and allow high but not low tones to spread through them in Bade and Ngizim. These facts suggest that implosives elevate Fo on following vowels, in spite of the fact that they are produced with a rapid lowering of the larynx and are usually voiced -- voiceless implosives have been reported for Igbo (Ladefoged 1976), Quiché (Pinkerton 1980), and for some speakers of Hausa (Lindau 1982), but they are

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rare. If implosives do in fact elevate rather than depress Fo as Painter (1978) has shown, then they provide even stronger proof than the Fo depression after Quiché ejectives that larynx movement is not the principal mechanism for perturbing Fo in glottalic consonants.

The small amount of phonetic information available on implosives shows that they are not at all the same thing phonetically in all the languages they occur in; Lindau (1982), for example, describes striking differences in how implosives are articulated among a number of Nigerian languages. Two types of implosives are distinguished in her material: the first found in Niger-Congo languages and the second in Hausa, a Chadic language. Closure durations are relatively longer (> 100 ms) in the Niger-Congo languages than in Hausa (< 75 ms); however, in Hausa the amplitude of voicing increases more from the center of the closure to the end than it does in the Niger-Congo languages. Lindau interprets the relatively greater change in amplitude as an indication of greater cavity expansion in Hausa compared to the Niger-Congo languages. Even more interesting are differences in periodicity and spectral shape. In the Niger-Congo languages, the waveform during the closure is relatively periodic and its spectrum shows evidence of

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higher frequency cavity resonances. In Hausa, on the other hand, the waveform is comparatively aperiodic and there is no evidence of higher frequency cavity resonances. These differences suggest that the folds are more tightly adducted, i.e. stiffer, in the Niger-Congo languages than they are in Hausa. If there is a difference in fold stiffness among these languages, then it is possible that their implosives would differ in how they perturb Fo. If they are produced with slacker folds, Hausa implosives should not elevate Fo; if anything, they should depress it, while in the Niger-Congo languages Fo elevation is quite likely. However, Bade and Ngizim, whose implosives clearly elevate Fo, belong to the same family as Hausa i.e. Chadic, so it seems unlikely that the Hausa implosives would not also elevate Fo. What is startling about the difference in the nature of vocal fold vibration during implosives in the Niger-Congo languages compared to Hausa is that it exactly parallels the difference observed after the glottal release between the tense ejectives of Tigrinya and the lax ones of Quiché as well as the difference between the tense and lax stops of Korean. The recurrence of this contrast strongly suggests that vocal fold stiffness is an independently manipulated parameter in the articulation of glottalic con-

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sonants. The evidence presented in this section and section 3.2.3.2 does not, however, demonstrate that fold stiffness rather than larynx movement is the mechanism which perturbs Fo after oral stops, though one mechansism would be more parsimonious than two.

Unfortunately, I have not been able to collect phonetic data from a language with implosives to resolve the questions posed by this class of consonants.

3.3 Larynx movement and Fo perturbations in Tigrinya

3.3.1 Introduction, materials, and methods

In the next section, the relationship between larynx movement and the perturbation of Fo after stops in Tigrinya is illustrated.

3.3.1.1 Speakers

The same speakers who provided data on air pressure changes during stops in this language also provided the data

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described in the next section.

3.3.1.2 Vocabulary recorded

Word-initial dental and velar stops were recorded from the Tigrinya speakers: /tə̈lə̈lə̈/ 'sketch', /də̈lə̈lə̈/ 'deal', /t'ə̈lə̈lə̈/ 'wet', /kə̈lə̈lə̈/ 'enclose', /gə̈lə̈lə̈/ 'separate', /k'ə̈lə̈lə̈/ 'easy', as well as a bilabial nasal /manana/ 'become a monk or nun' and a glottal stop /ʔalama/ 'weave'. These are third person masculine singular forms of the perfect of the verbs indicated in the glosses. Five repetitions of each word were obtained from each speaker.

3.3.1.3 Analysis procedures

As with the air pressure data presented in chapter 2, the reference point for larynx movement was taken to be the minimum point within the portion of the utterance containing the word of interest, including the vowels of the preceding and following frame words.

Fo was extracted from the waveform using a combination of a cepstral technique and measuring the duration of

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individual periods at the edge of the vowel. In this region, the cepstral technique occasionally produced unreasonably high values for Fo, apparently because its window had not yet moved far enough into the vowel for the fundamental frequency to dominate the spectrum.

Two kinds of data are reported. As was done for the Po and larynx height curves in chapter 2, Fo and larynx height curves have been averaged here and are displayed over the amplitude curve in the figures. Each token was linearly time-warped before averaging so that the following points were aligned: the stop closure (OC), the release (OR), and the end of the word. For reasons discussed below, the beginning of the vowel, though marked in the figures (BV) as a reference point, was not an alignment point in the time-warping. Dental and velar stops of each type, /t, k/, /d, g/, and /t', k'/ wee pooled in the averaging, so 8 to 10 tokens of each stop type were available from each speaker. In addition, moment-by-moment correlations, at 4.8 ms intervals between the position of the larynx and the fundamental frequency of the vowel following the various consonants have been calculated. If larynx movement is responsible for the perturbation of Fo after these consonants, then the two parameters should covary and the correlation coefficient

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should be positive; how positive depends on the extent of the covariance. No correlations were done for /m/ or /?/.

For the six words analyzed, two separate correlations between Fo and larynx height were calculated: one for the first 100 ms of the vowel following the initial consonant of the word and the other for the entire word -- barring the initial consonant, these six words consist entirely of sonorant segments, so a continuous Fo contour could be obtained. The correlation over the smaller interval at the beginning of the vowel represents the perturbatory effect, if any, of the movement of the larynx away from the position it assumed during the preceding consonant to its vocalic position. The second correlation subsumes this local effect within an expression of the longer term relationship between larynx movement and the entire Fo contour of the word.

3.3.2 The results

In the following three sections, the relationship between larynx height and Fo is examined for each speaker individually before the speakers are compared and conclusions drawn about this relationship.

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3.3.2.1 Speaker T1

In figures 3.3.1.1-8, averaged Fo contours are displayed over curves representing larynx movement for voiceless /t k/, voiced /d g/, and ejective /t' k'/ stops.

Table 3.3.1

Fo and larynx height in Tigrinya stops - Subject T1

Figure #	Figure description
3.3.1.1	Voiceless dental and velar stops. Fo, larynx height and amplitude. Means (solid lines) and standard deviations (dashed lines).
3.3.1.2	Voiced stops -- same format as 3.3.1.1.
3.3.1.3	Ejectives -- same format as 3.3.1.1.
3.3.1.4	Composite of voiceless (dotted line), voiced (dashed line), and ejective (solid line) stops -- same format as 3.3.1.1., otherwise.
3.3.1.5	Closeup of figure 3.3.1.1 -- same format, otherwise.
3.3.1.6	Closeup of figure 3.3.1.2 -- same format, otherwise.
3.3.1.7	Closeup of figure 3.3.1.3 -- same format, otherwise.
3.3.1.8	Closeup of figure 3.3.1.4 -- same format as in that figure.

A pair of figures is presented for each kind of stop: one representing the entire word and the other a closeup centered on the release of the stop. The dotted lines above and below the Fo and larynx height curves represent one

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standard deviation. In figures 3.3.1.7 and 3.3.1.8, the averaged Fo and larynx height curves for the three varieties of stops are plotted against one another for comparison (the same format is used in the presentation of the data for the other two speakers in the next two sections).

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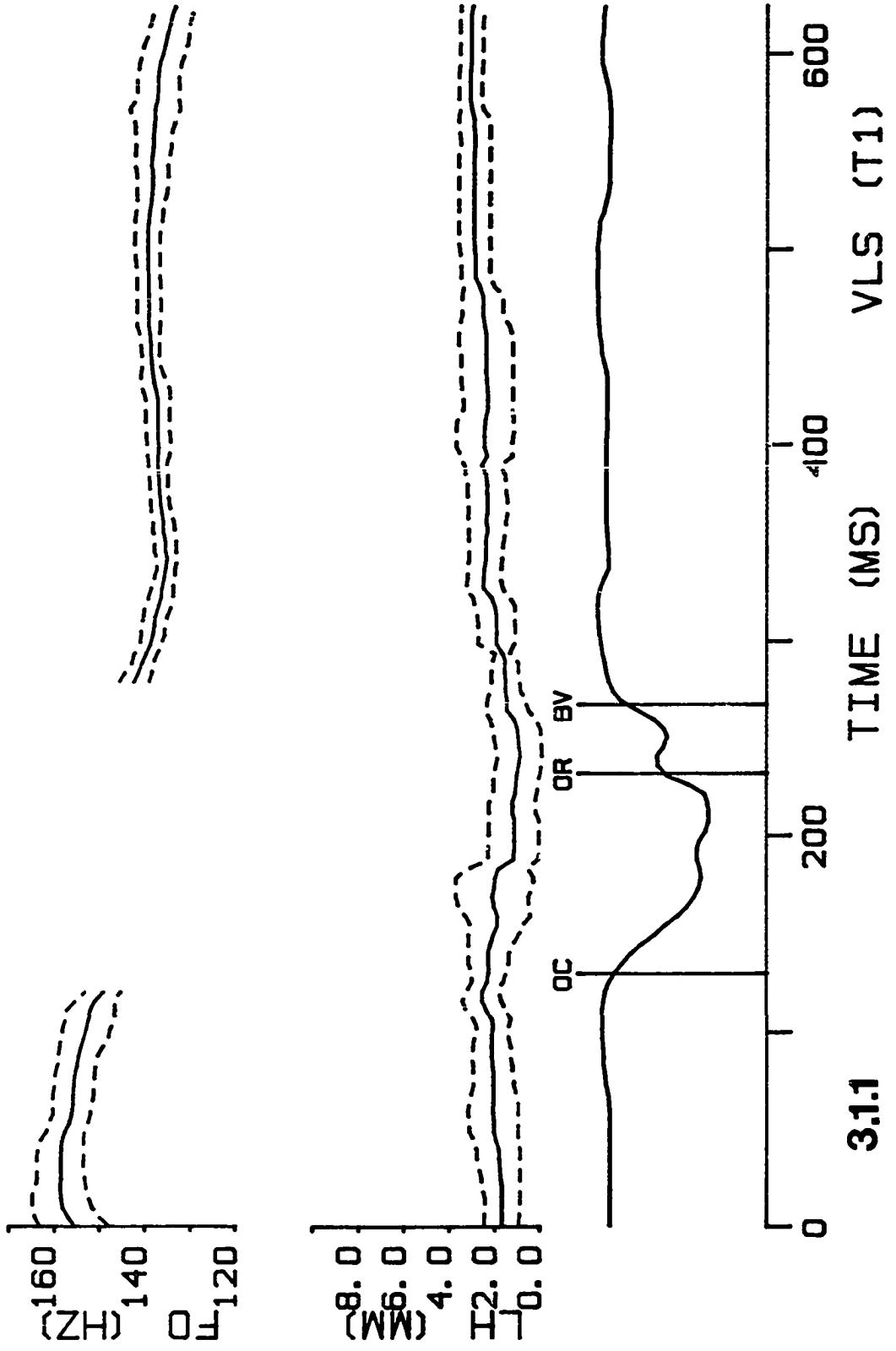

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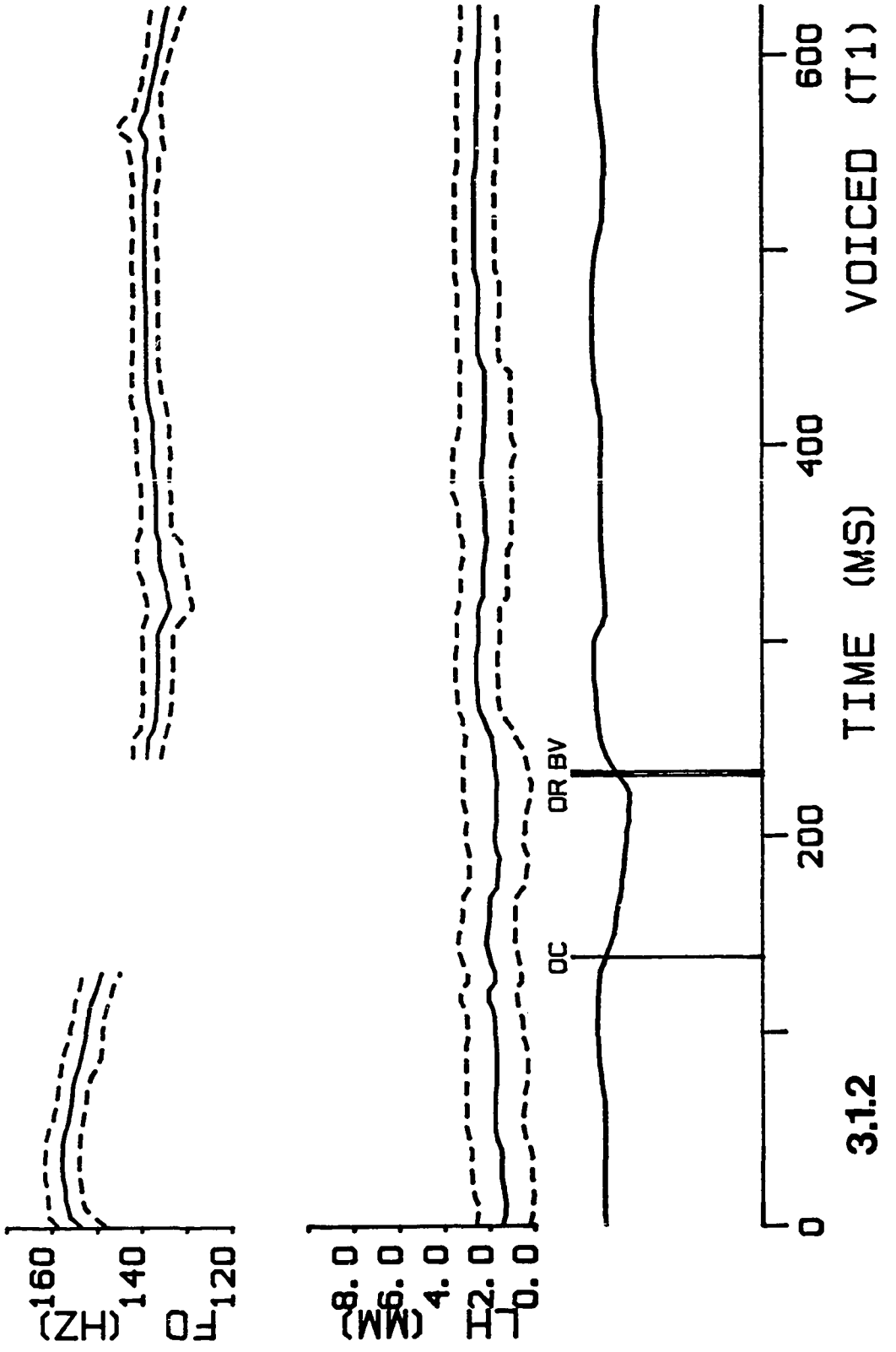

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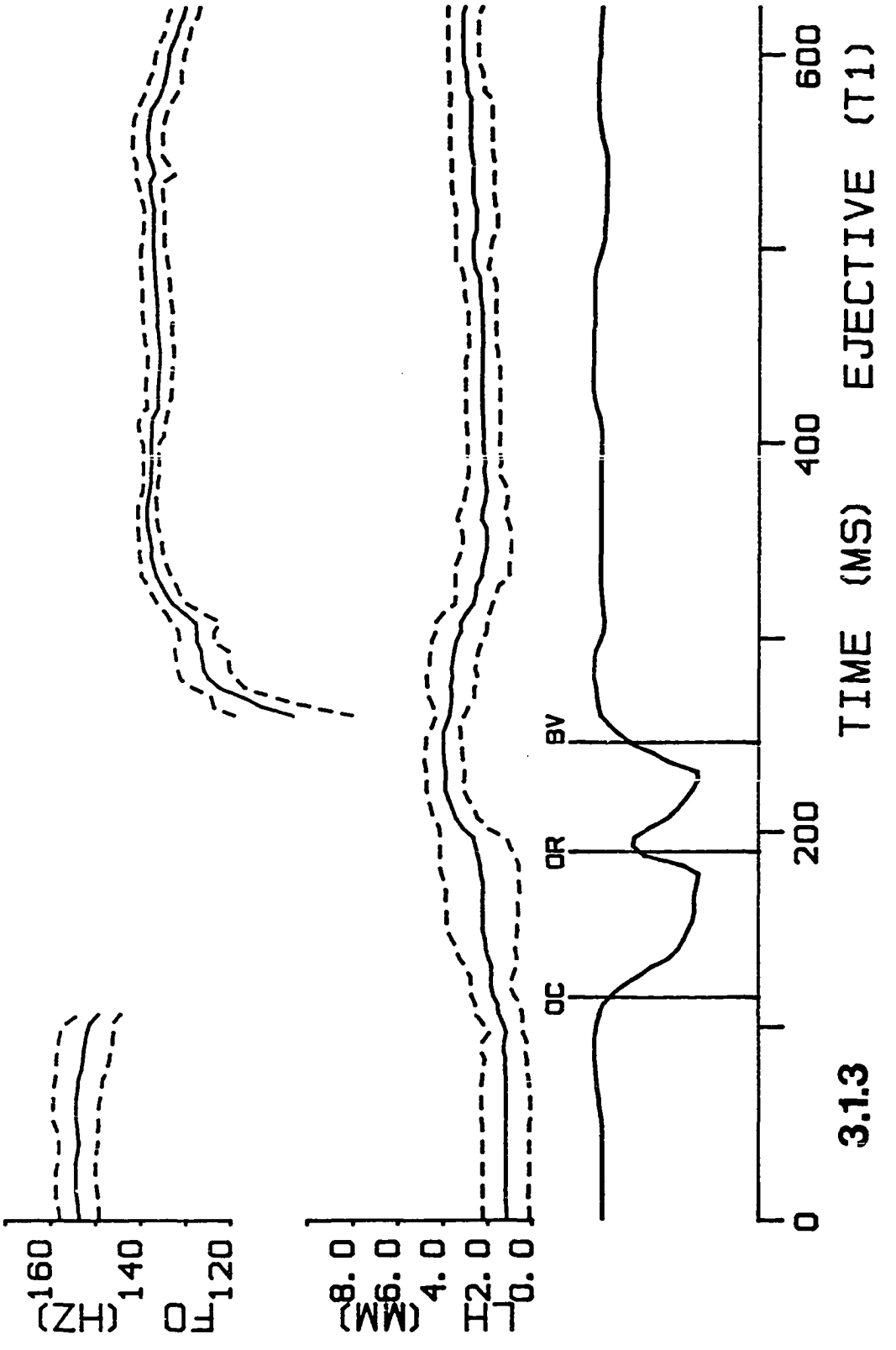

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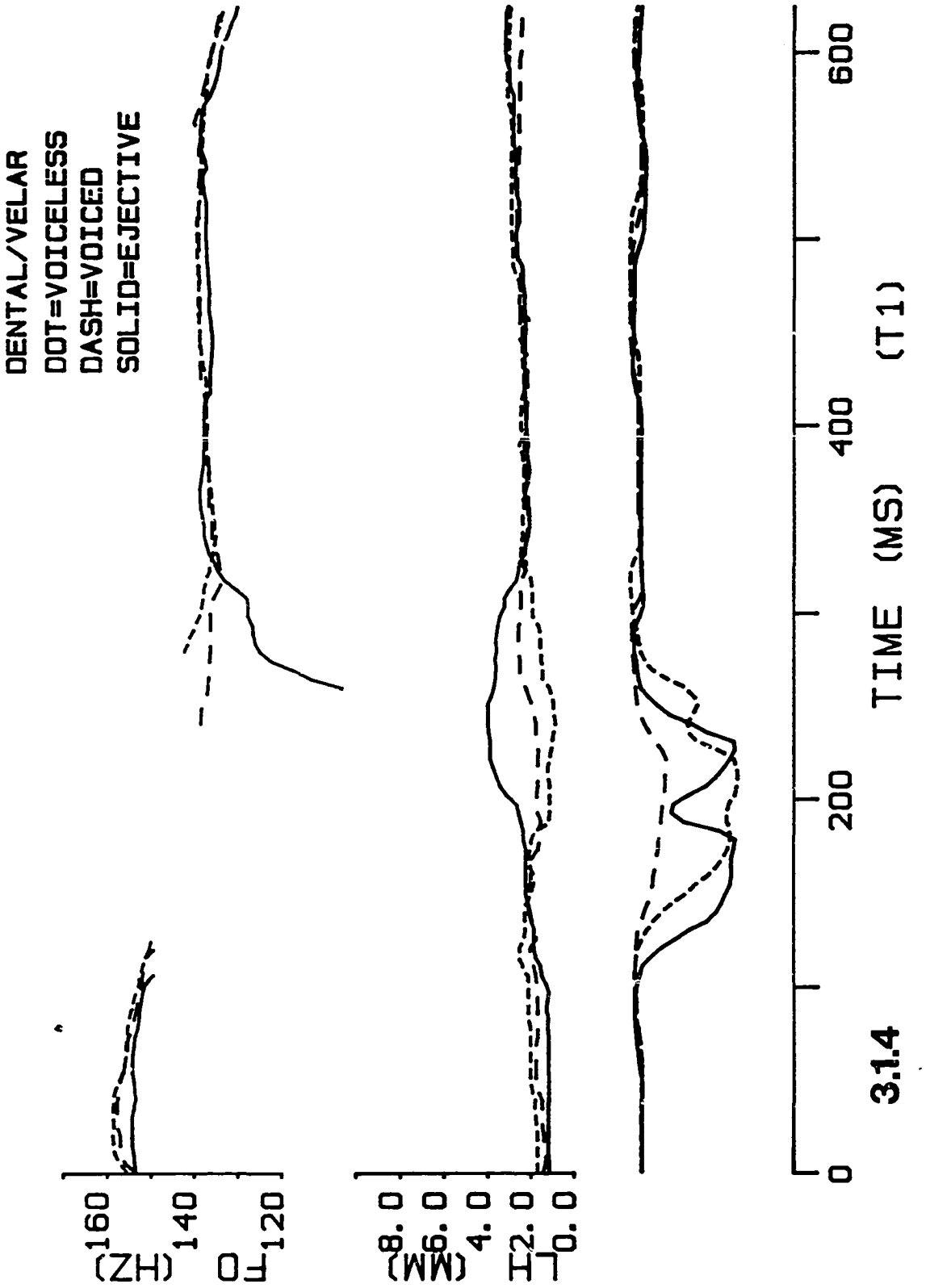

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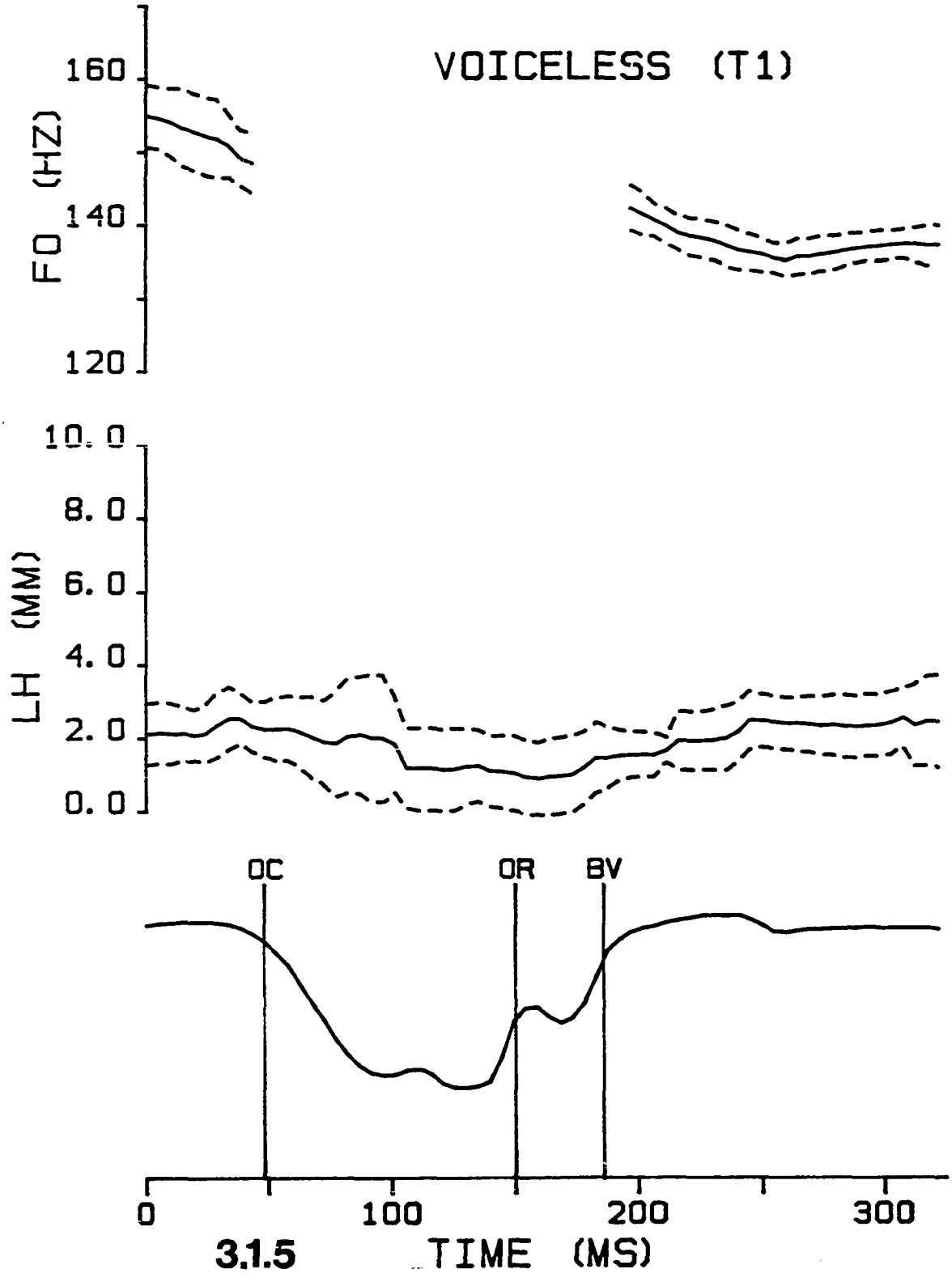

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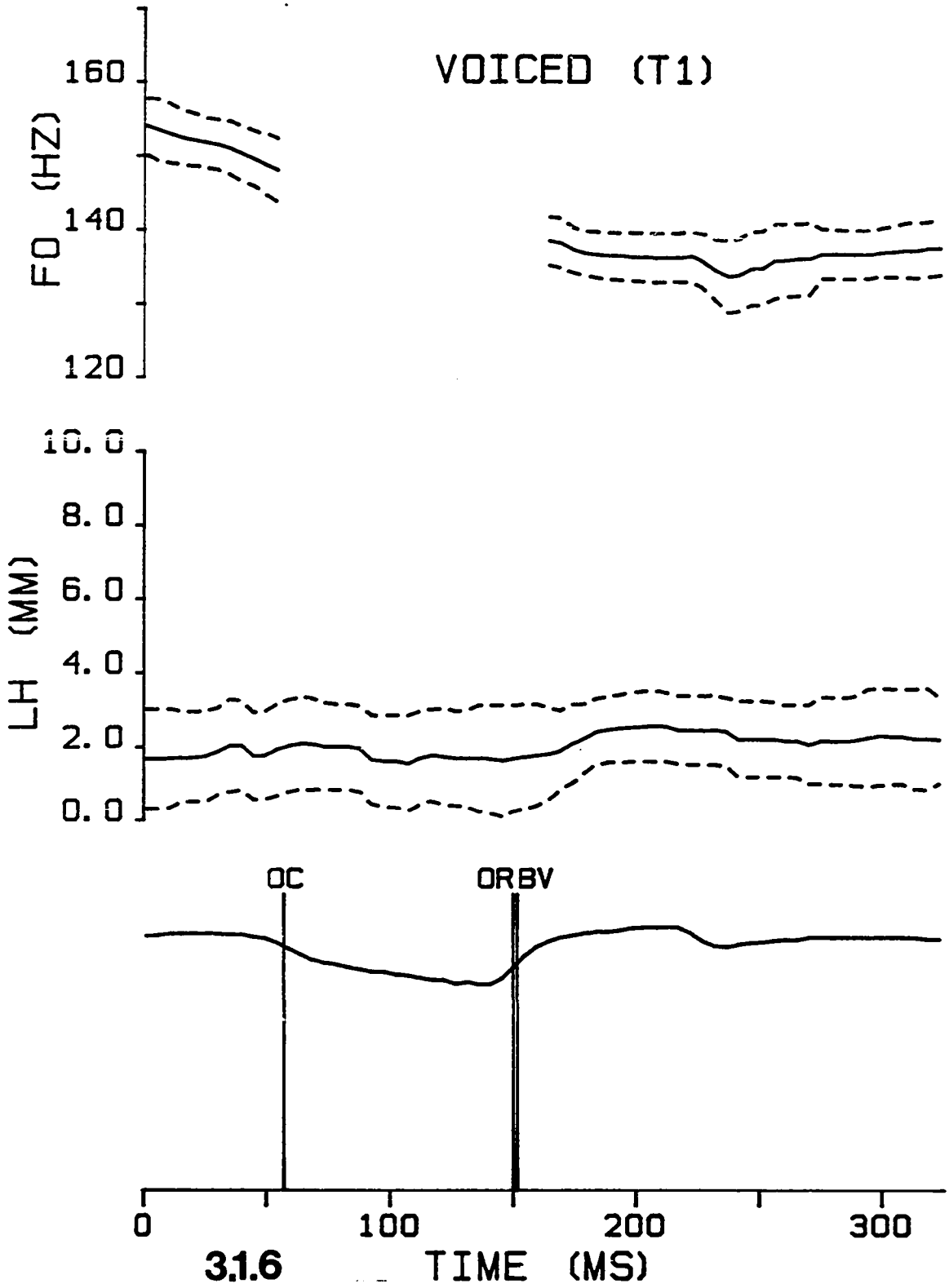

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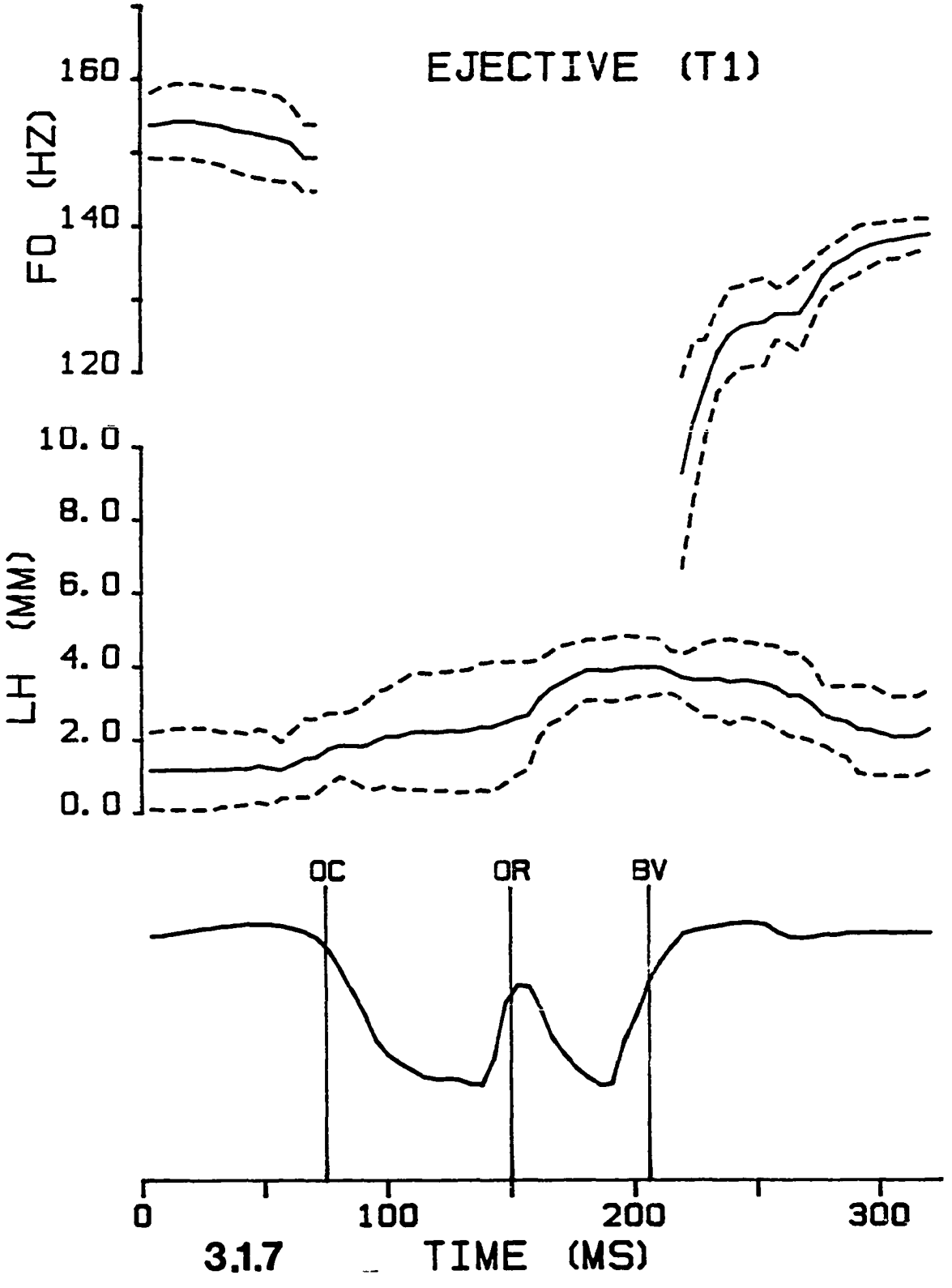

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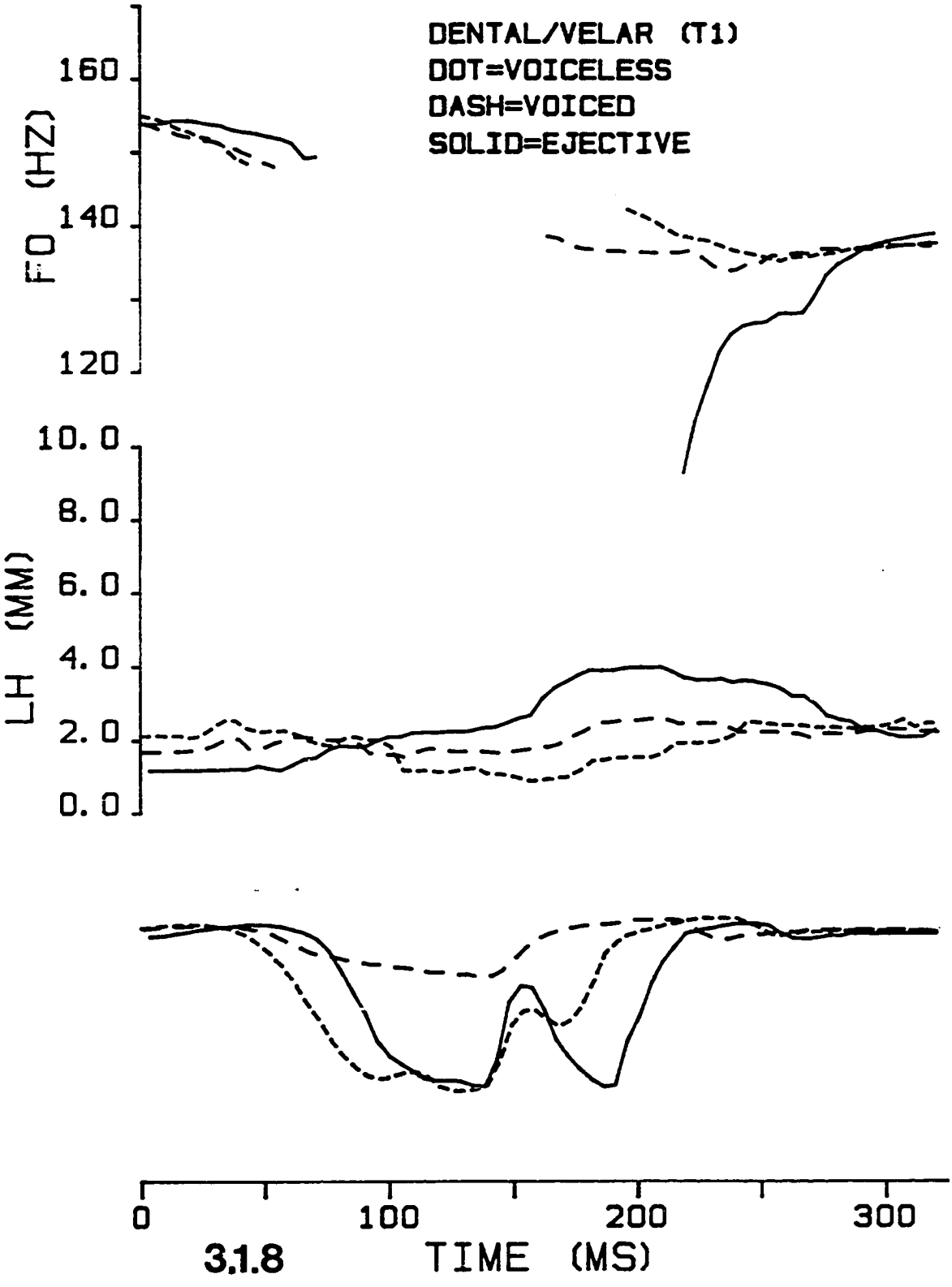

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Figure 3.3.1.4 shows that the larynx is noticeably higher during the stop closure and the early part of the following vowel for ejectives than it is for either voiced or voiceless stops, between which there is little difference in larynx height. Despite the elevation of the larynx during the ejectives, Fo is markedly depressed following this class of stops. This difference is particularly clear in the composite closeup in figure 3.3.1.8. This figure also shows that Fo is only slightly lower after voiced stops than voiceless ones. The depression of Fo after ejectives occurs during an interval of creaky voice at the beginning of the vowel which does not grade into modal voice until nearly 100 ms after the vowel begins. Since the larynx is elevated throughout this interval, it is clear the Fo after an ejective is not dependent on larynx height for this speaker. That Fo is higher after voiced and voiceless stops than after ejectives, though the larynx is lower provides further support for this conclusion. Nor is Fo related to the direction of movement of the larynx, since it rises after an ejective as the larynx falls.

The Fo contours in these figures (and in all the others presented in this chapter) have been aligned with respect to the release of the stop closure rather than the onset of the

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vowel, the lineup point used in most other studies (e.g. Hombert 1978, but see Riordan 1980, who aligns her Fo and larynx height curves with respect to the stop closure rather than the vowel onset). The procedure used here has the effect of shifting the vowel onsets of the stops with longer vowel onset times -- the voiceless stops and ejectives -- to the right with respect to the voiced stops, whose vowel onset time is taken to zero. My shift of the Fo contours reduces the difference in Fo after voiced and voiceless stops by aligning a point well after the release of the voiced stop with the point of vowel onset following a voiceless stop. By this time, Fo after the voiced stop has had a chance to rise to the level that it begins at following a voiceless stop. This procedure is based on the notion that if the Fo contour at the beginning of a vowel following a stop is determined by changes in the tension of the vocal folds which only occur once the stop is complete, then the stop's termination point, its release, rather the onset of the following vowel should be the lineup point for comparing Fo contours after different kinds of stops. This point is explored further below.

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3.3.2.2 Speaker T2

Figures 3.3.2.1-8 show that the larynx moves relatively little for this speaker during all three kinds of stops, much as we saw in chapter 2.

Table 3.3.2

Fo and larynx height in Tigrinya stops -- Subject T2

Figure #	Figure description
3.3.2.1	Voiceless dental and velar stops. Fo, larynx height, and amplitude. Mean (solid line) and standard deviation (dashed line).
3.3.2.2	Voiced stops -- same format as 3.3.2.1.
3.3.2.3	Ejectives -- same format as 3.3.2.1.
3.3.2.4	Composite of voiceless (dotted line), voiced (dashed line), and ejective (solid line) stops -- same format as 3.3.2.1, otherwise.
3.3.2.5	Closeup of figure 3.3.2.1 -- same format, otherwise.
3.3.2.6	Closeup of figure 3.3.2.2 -- same format, otherwise.
3.3.2.7	Closeup of figure 3.3.2.3 -- same format, otherwise.
3.3.2.8	Closeup of figure 3.3.2.4 -- same format as in that figure, otherwise.

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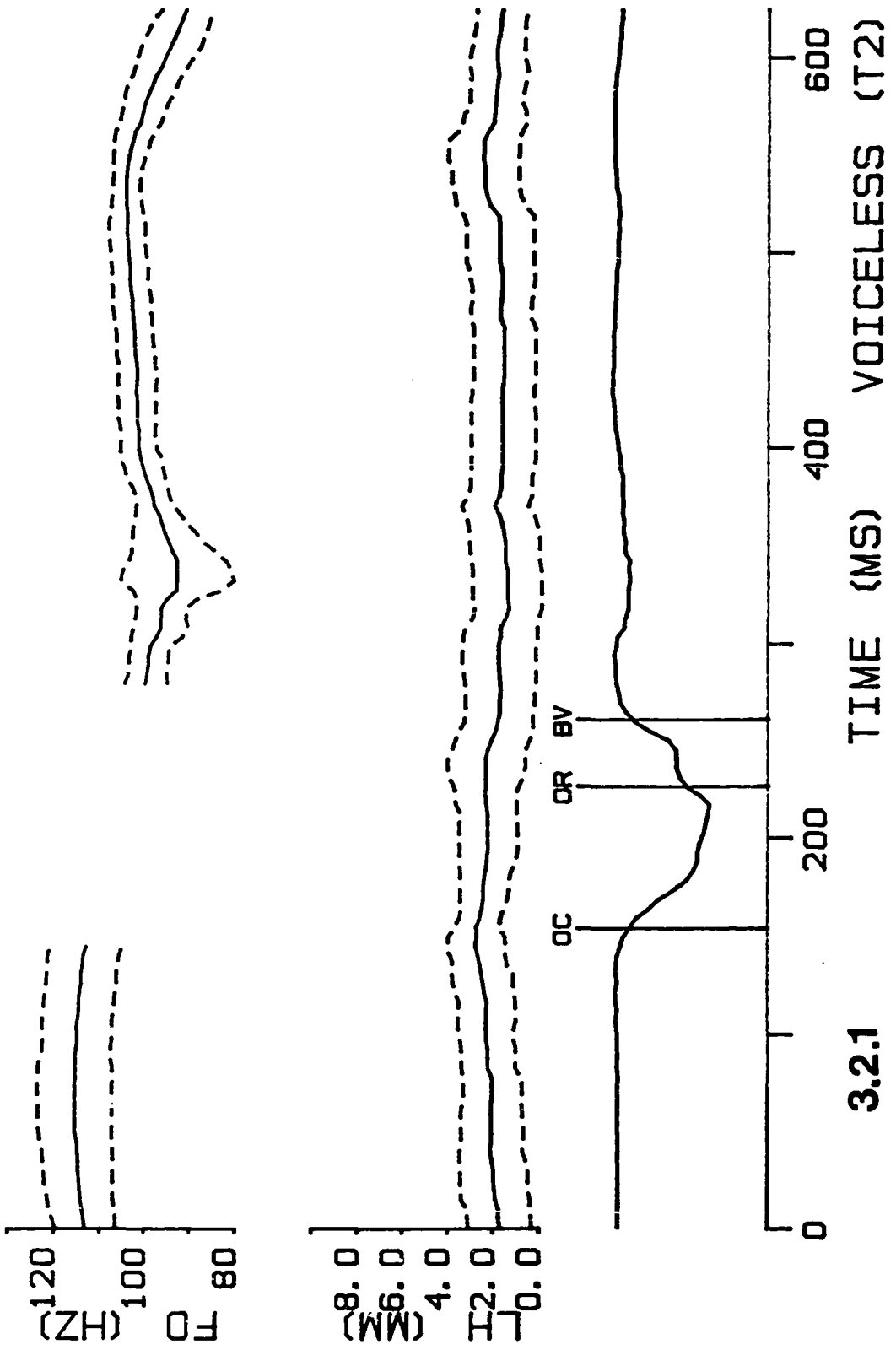

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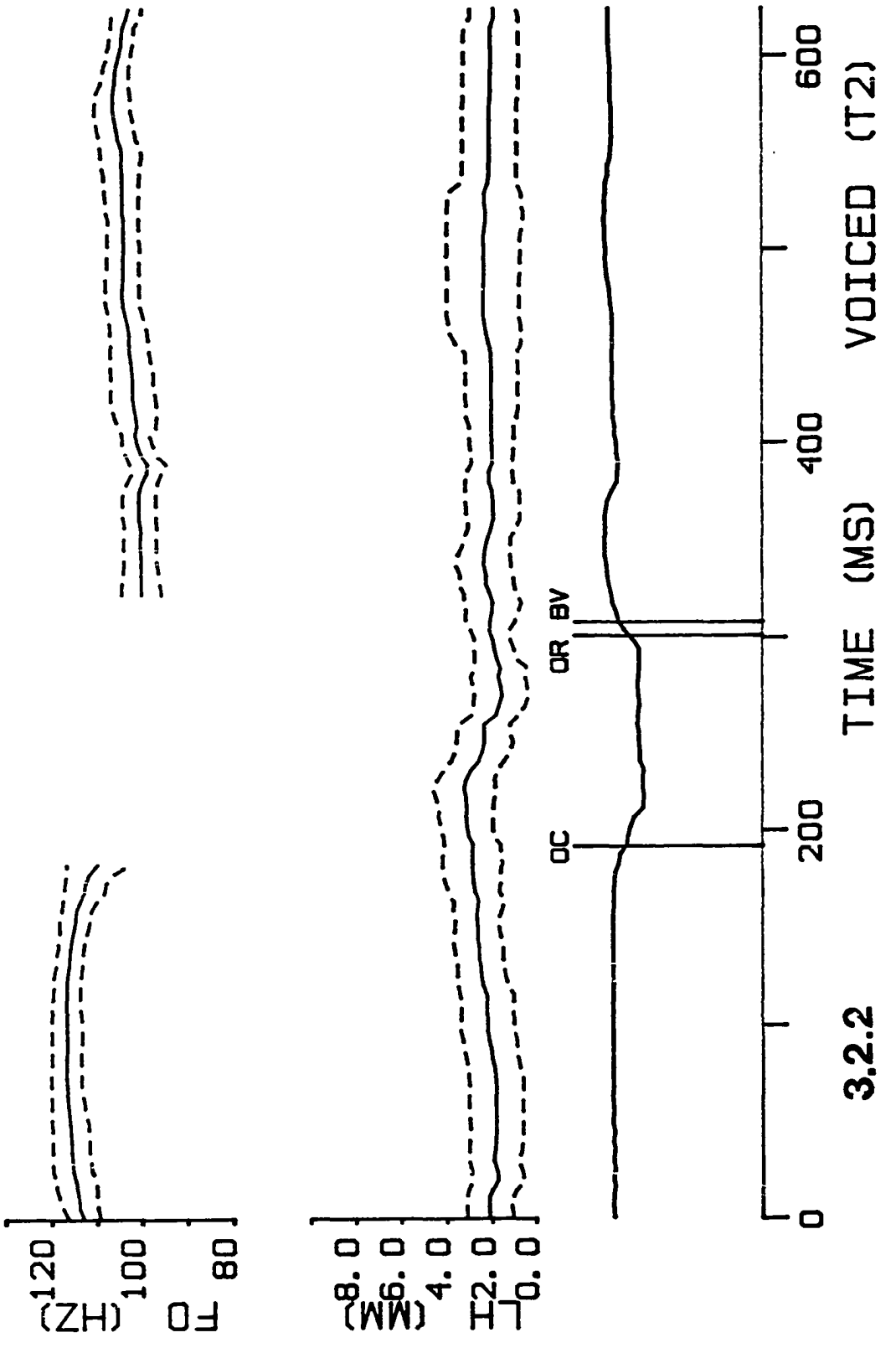

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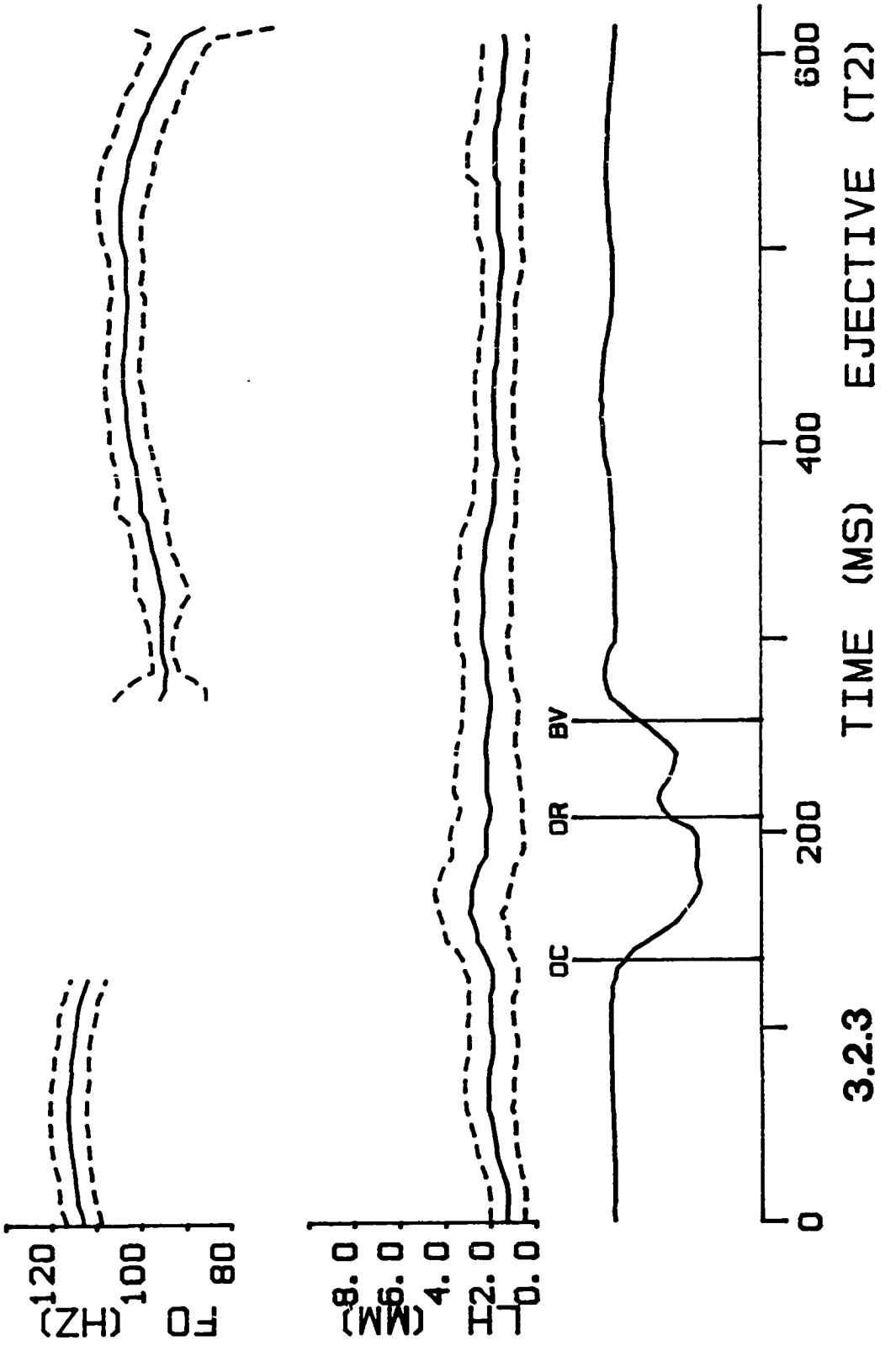

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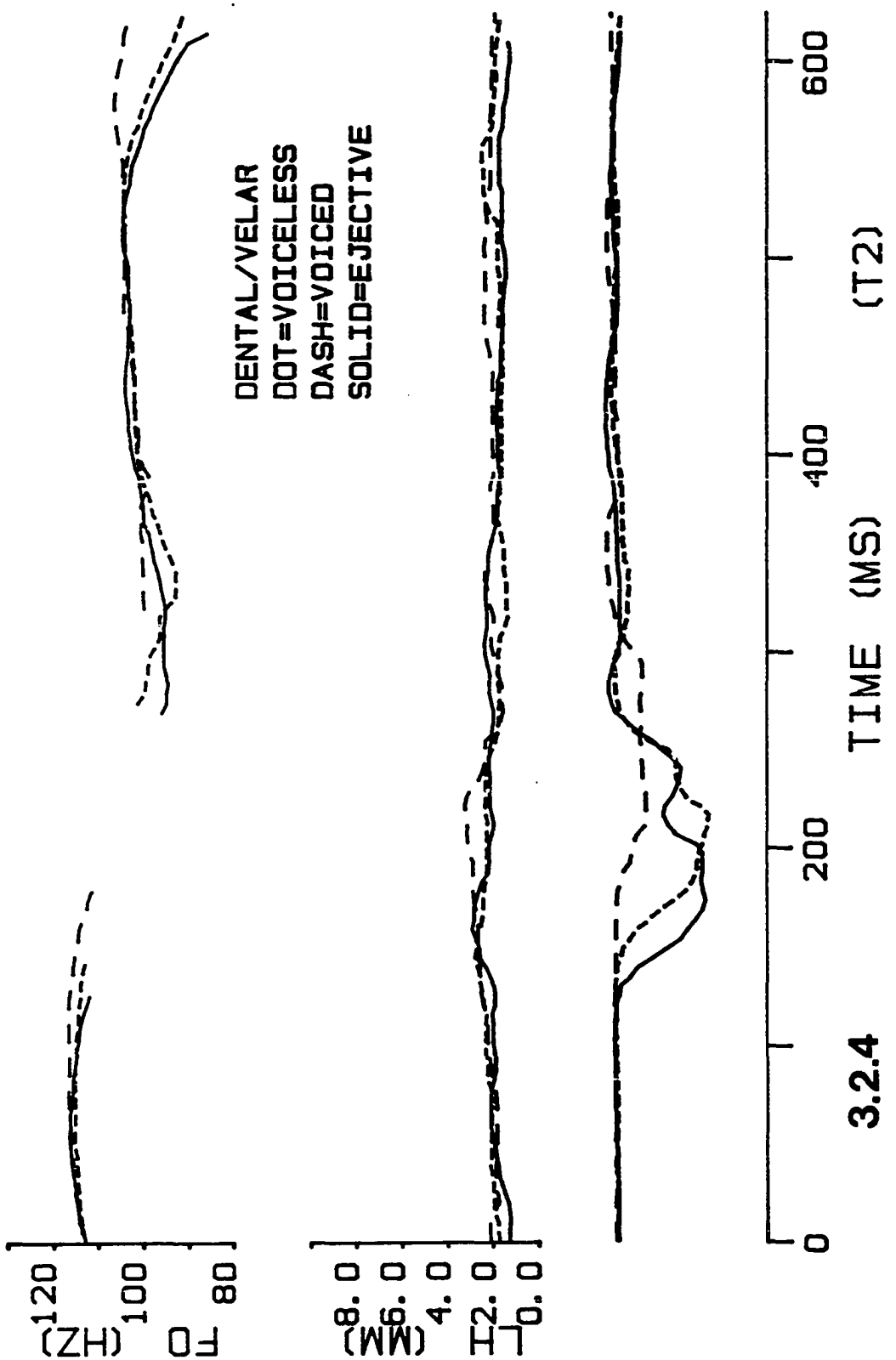

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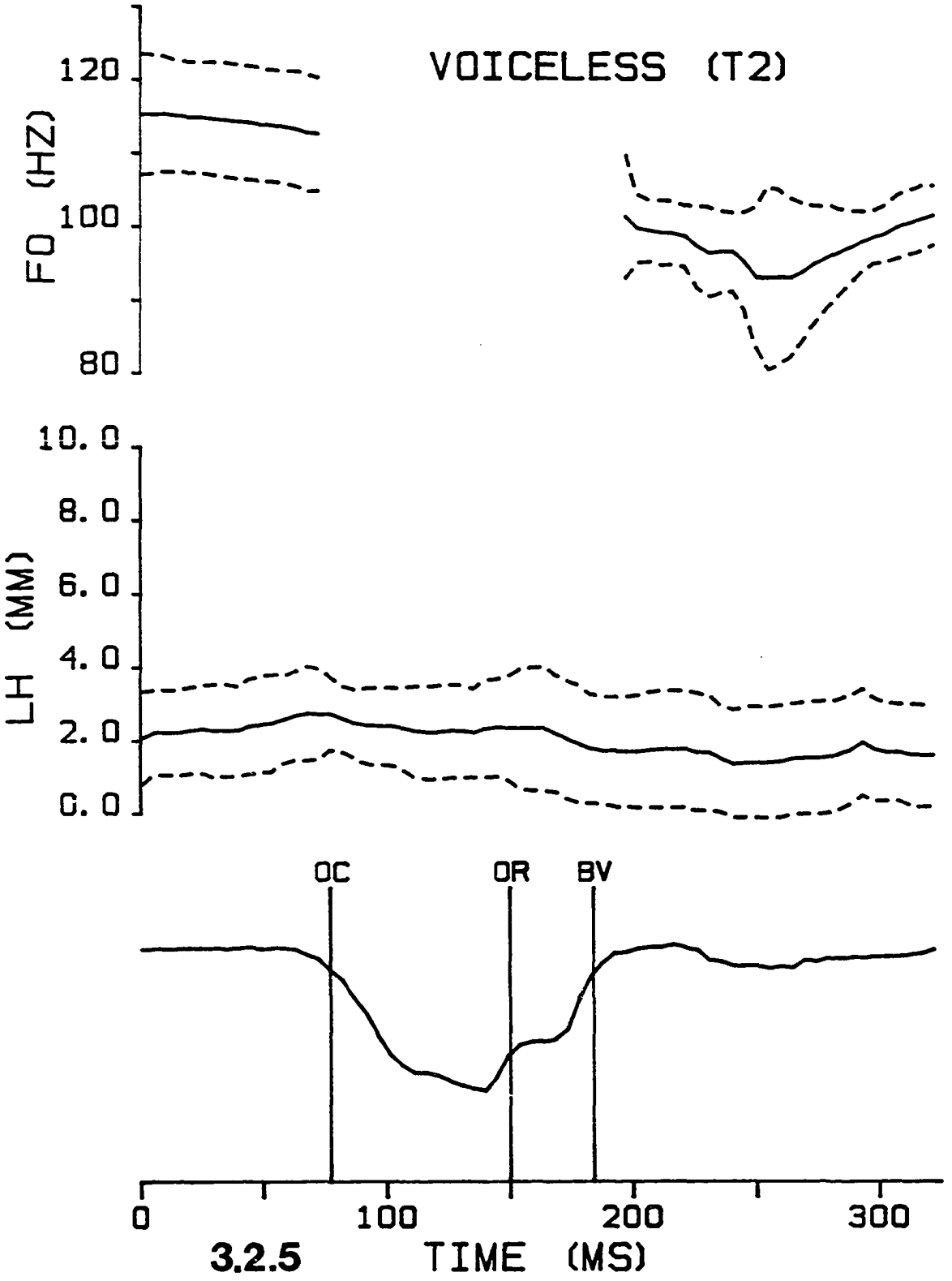

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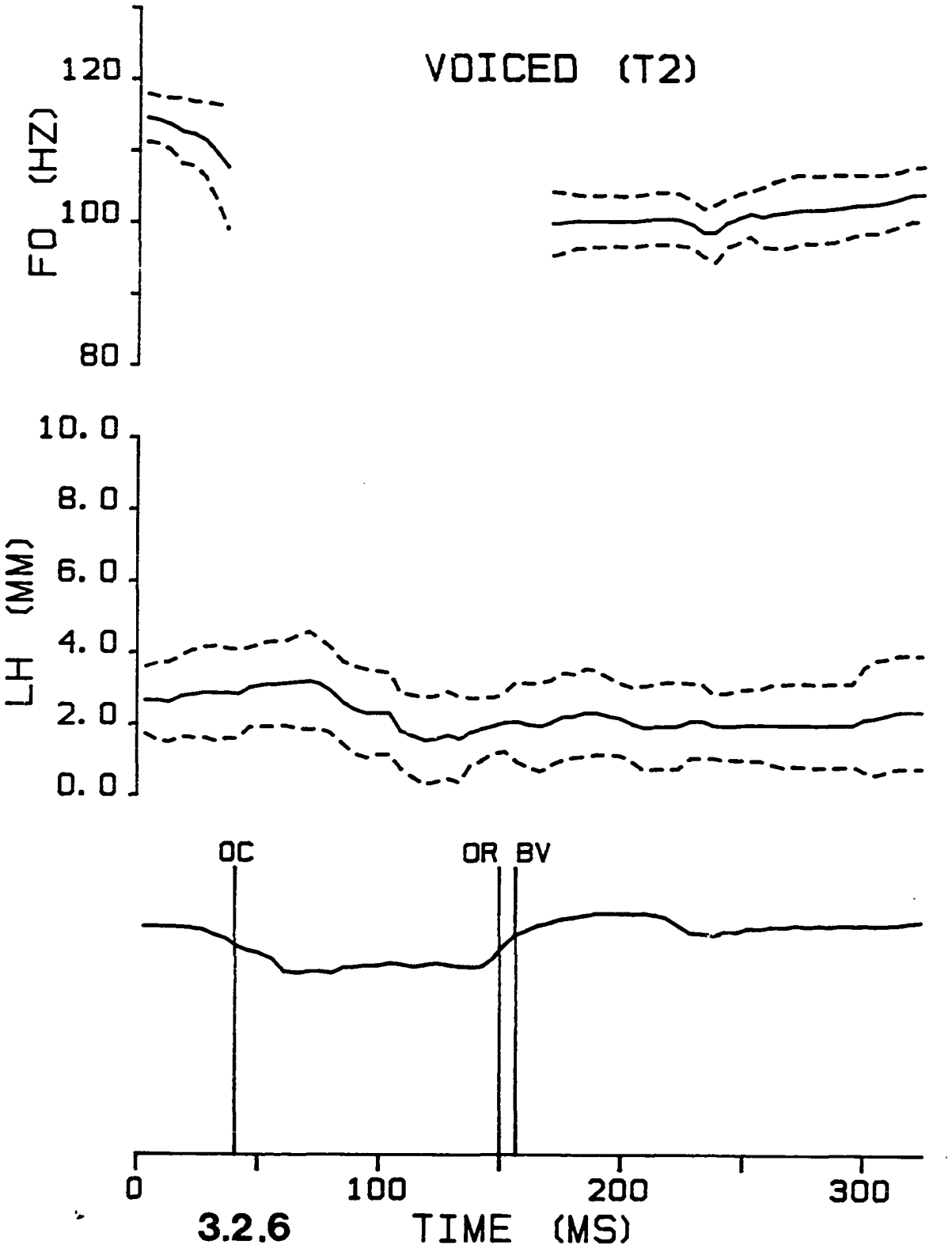

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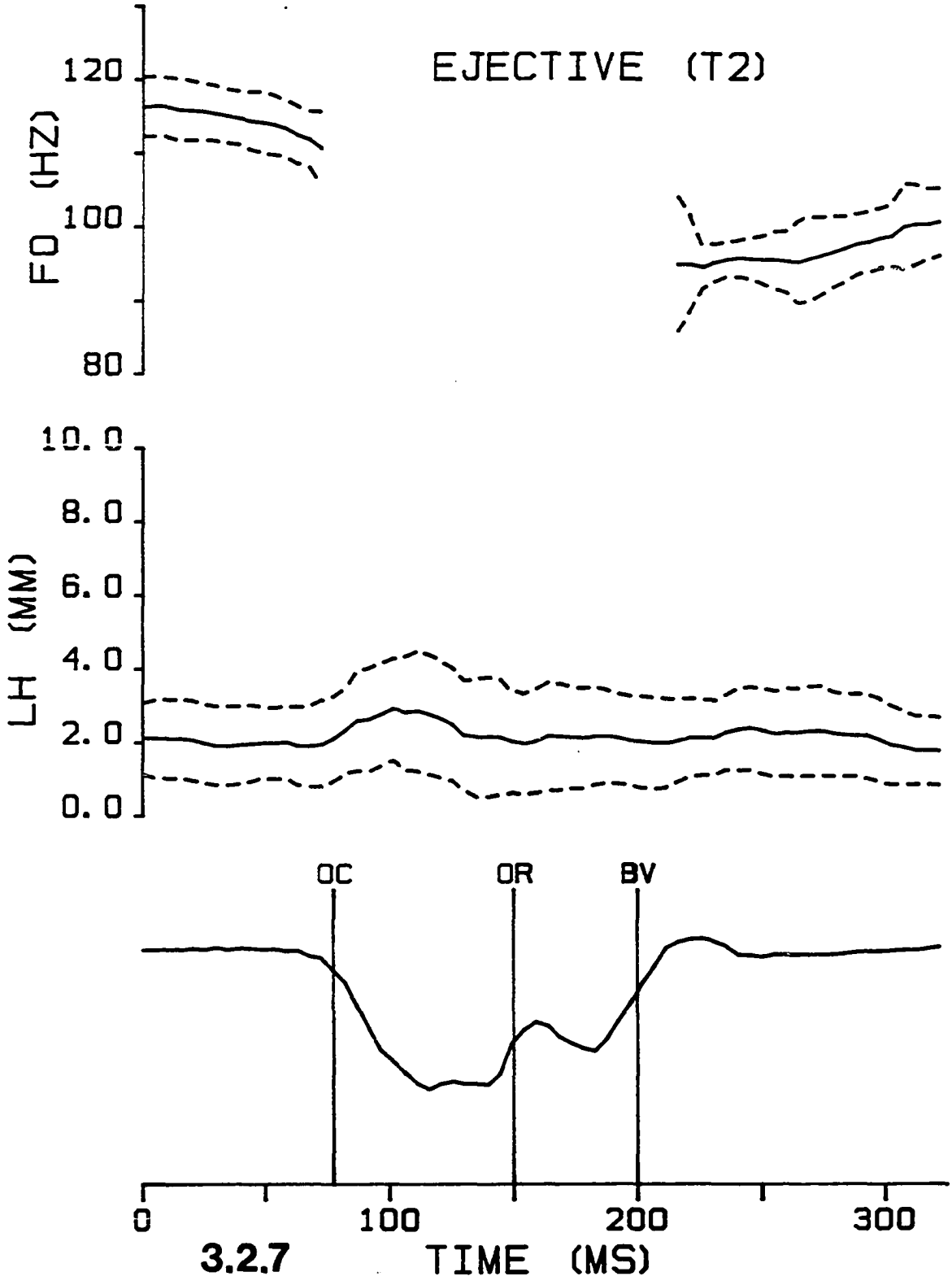

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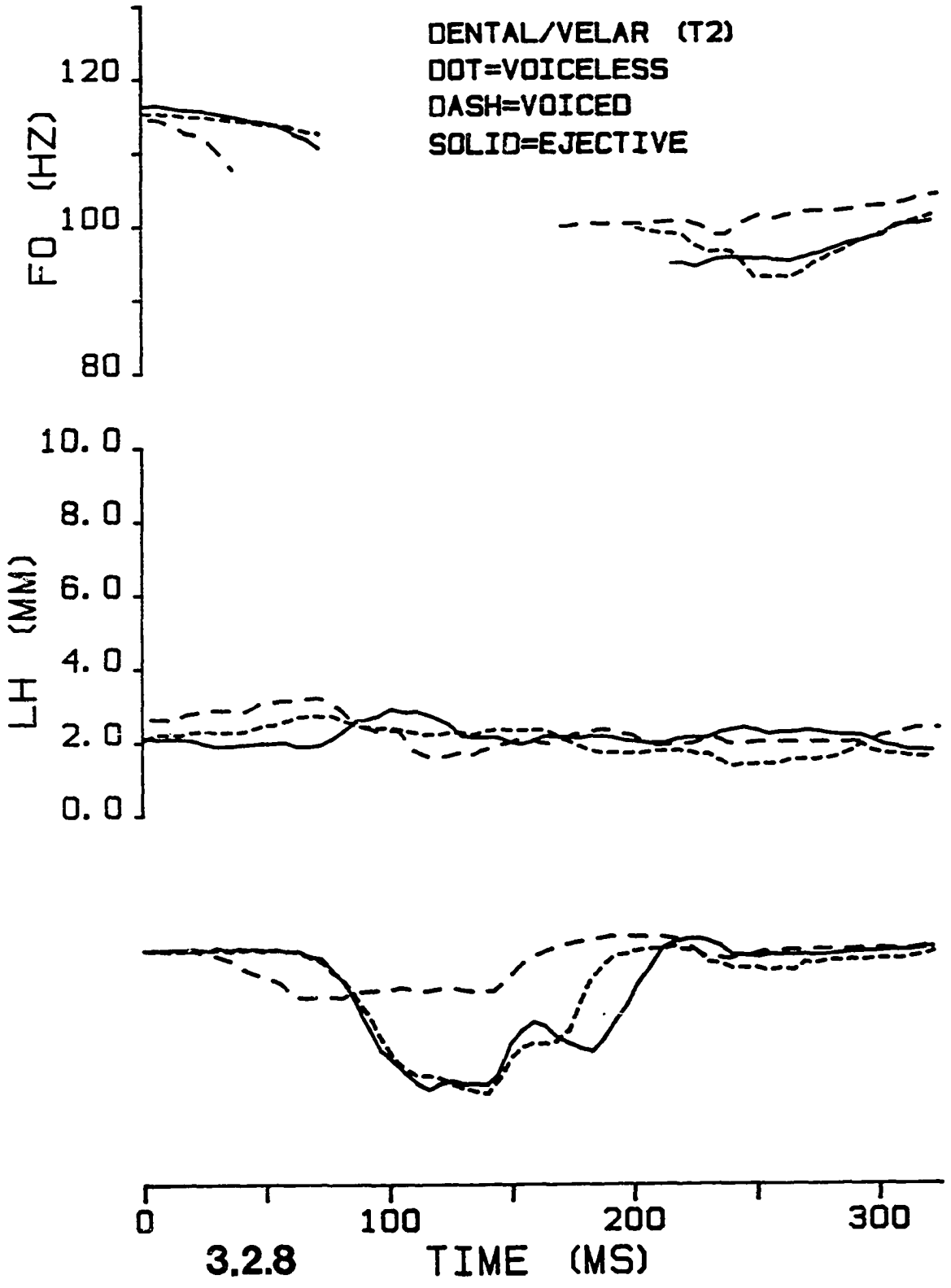

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In addition, no significant difference in larynx height is discernable among the voiced or voiceless stops or ejectives (see in particular the composite closeup in figure 3.3.2.8), nor are the Fo contours following any of the three kinds of stops noticeably different.

3.3.3.3 Speaker T3

In figures 3.3.3.1-8, it can clearly be seen that the larynx of T3 again moves more than it does for either T1 or T2, rising much higher after voiceless than voiced stops and higher still after ejectives.

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Table 3.3.3

Fo and larynx height in Tigrinya stops -- Subject T3

Figure #	Figure description
3.3.3.1	Voiceless dental and velar stops. Fo, larynx height, and amplitude. Mean (solid line) and standard deviation (dashed line).
3.3.3.2	Voiced stops -- same format as 3.3.3.1.
3.3.3.3	Ejectives -- same format as 3.3.3.1.
3.3.3.4	Composite of voiceless (dotted line), voiced (dashed line), and ejective (solid line) stops -- same format, otherwise.
3.3.3.5	Closeup of figure 3.3.3.1 -- same format, otherwise.
3.3.3.6	Closeup of figure 3.3.3.2 -- same format, otherwise.
3.3.3.7	Closeup of figure 3.3.3.3 -- same format, otherwise.
3.3.3.8	Closeup of figure 3.3.3.4 -- same format as in that figure, otherwise.

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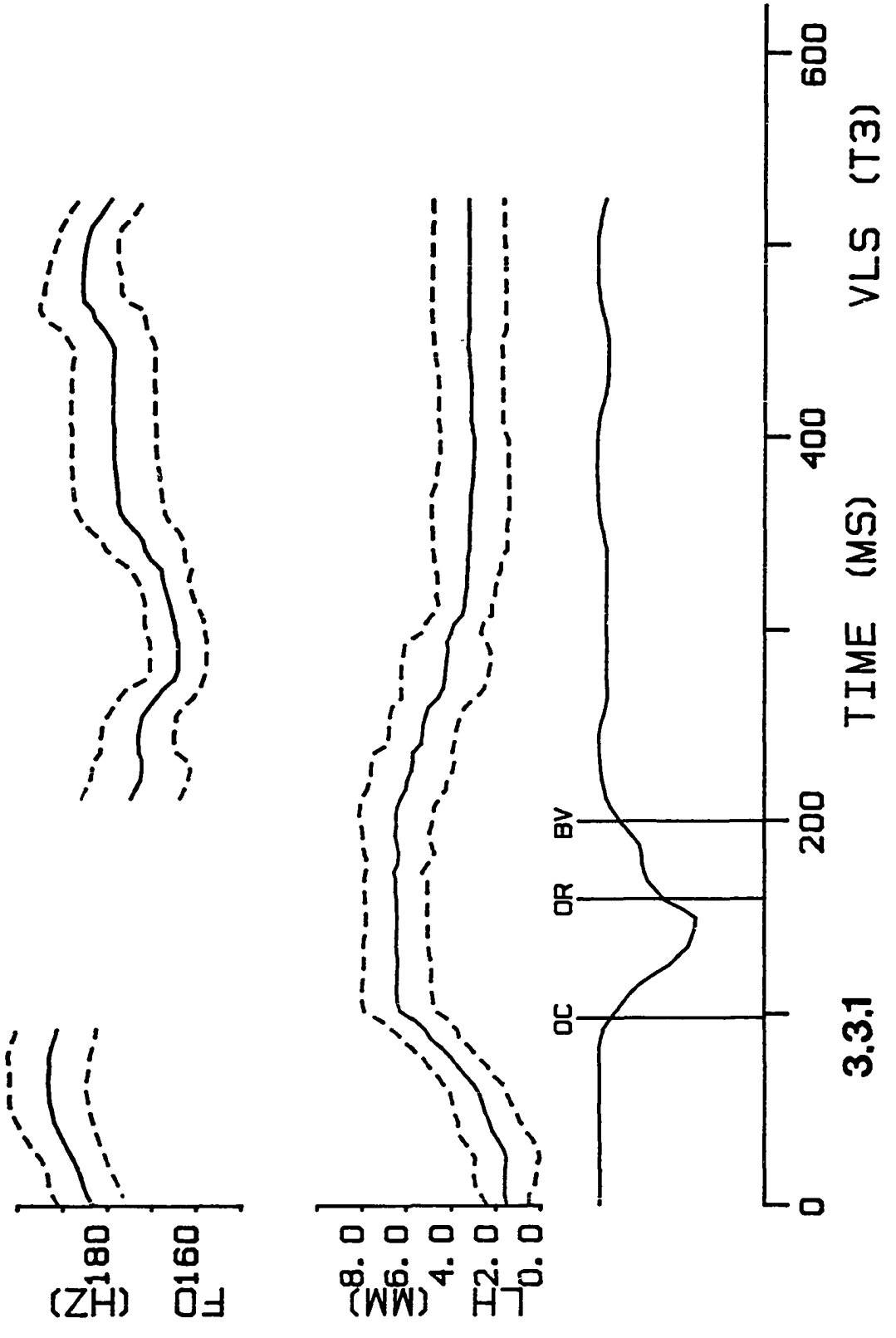

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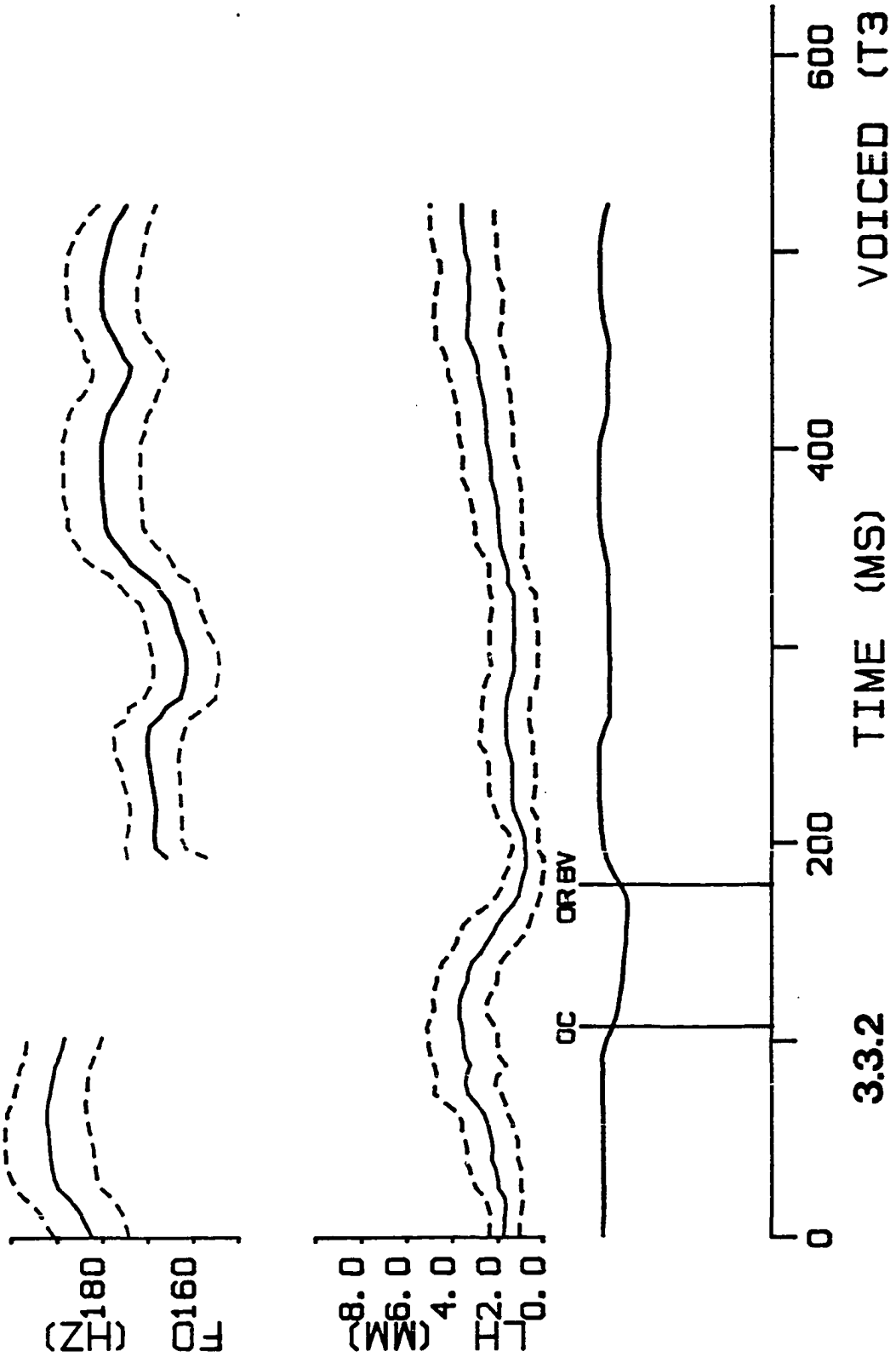

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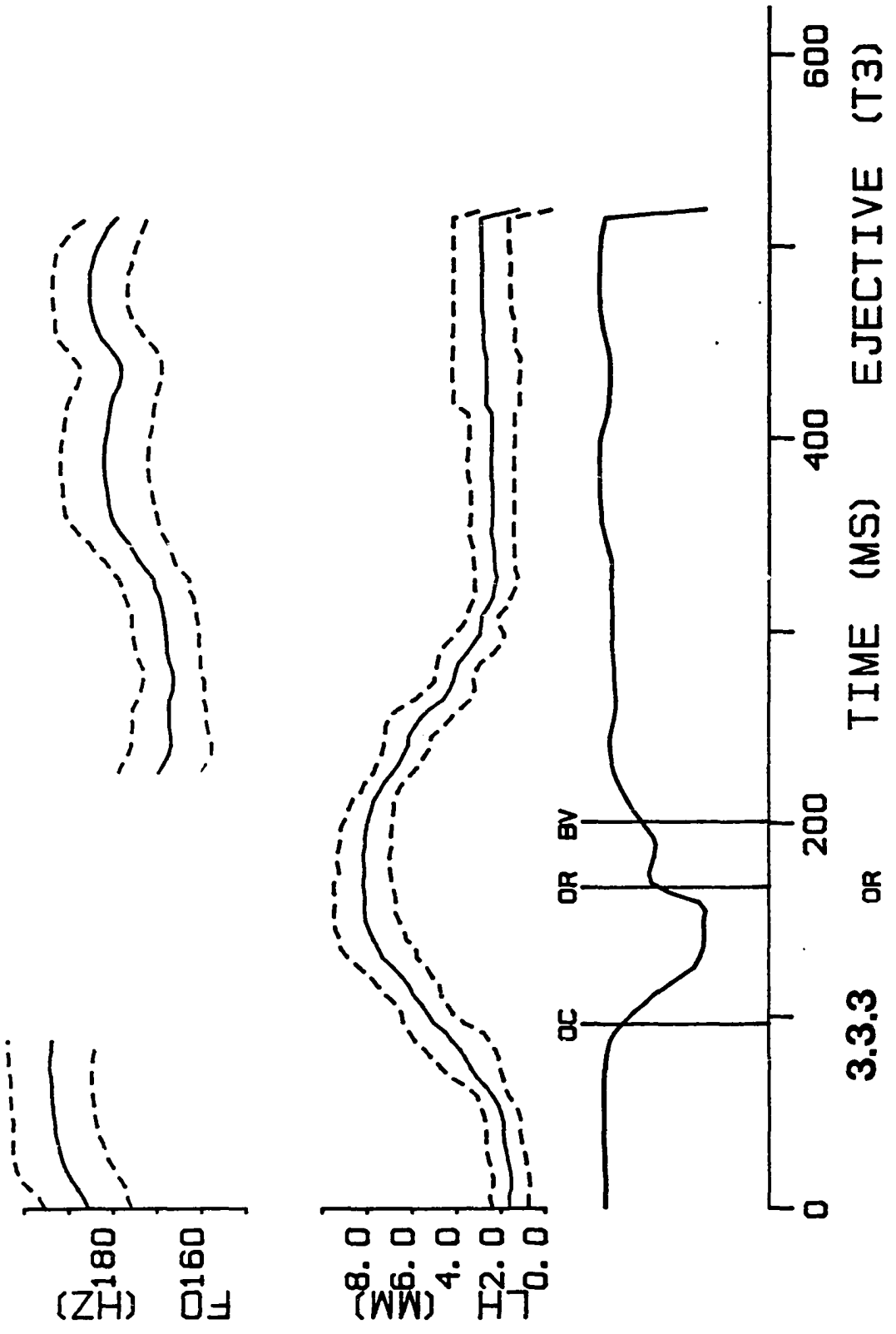

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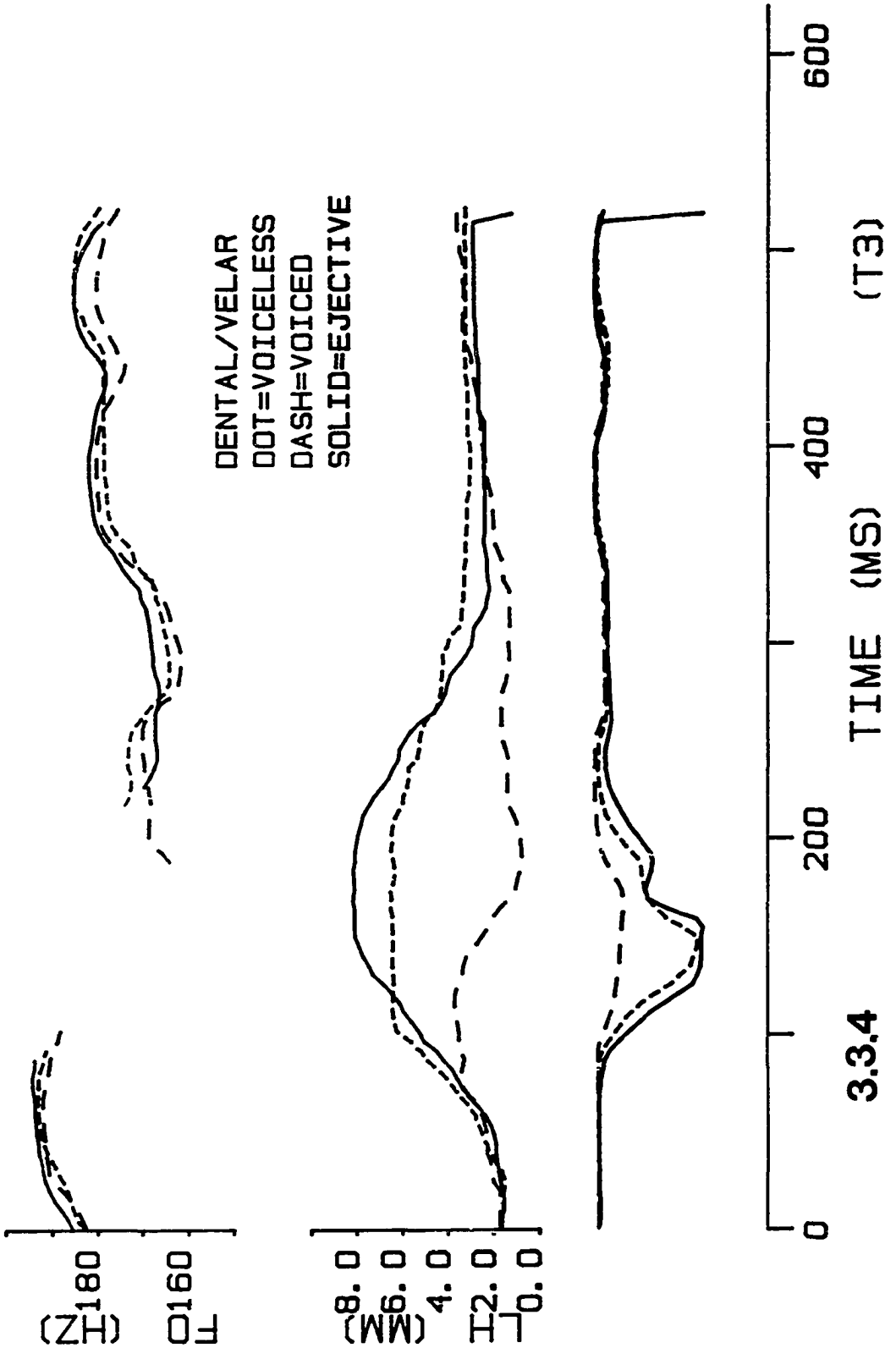

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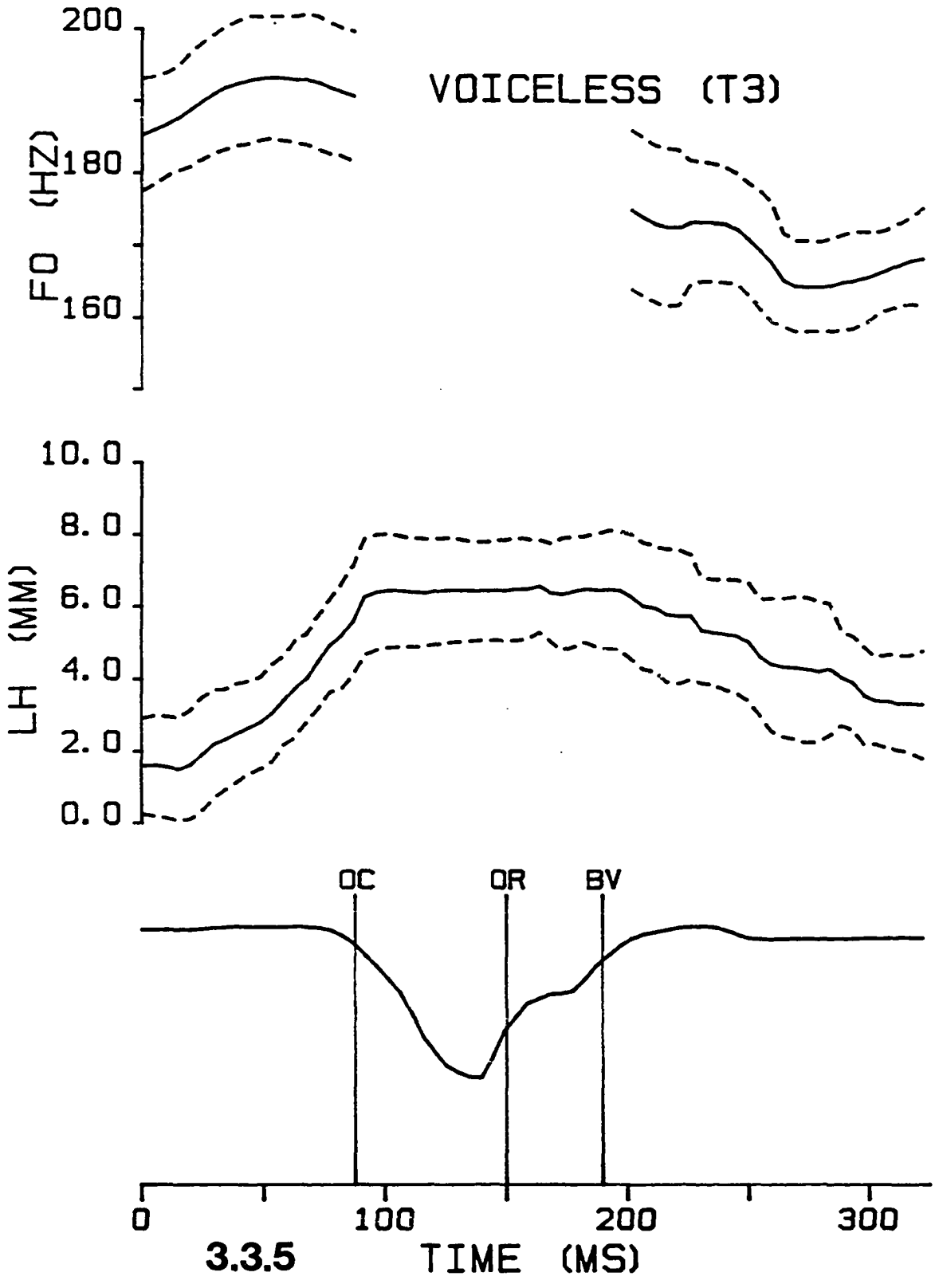

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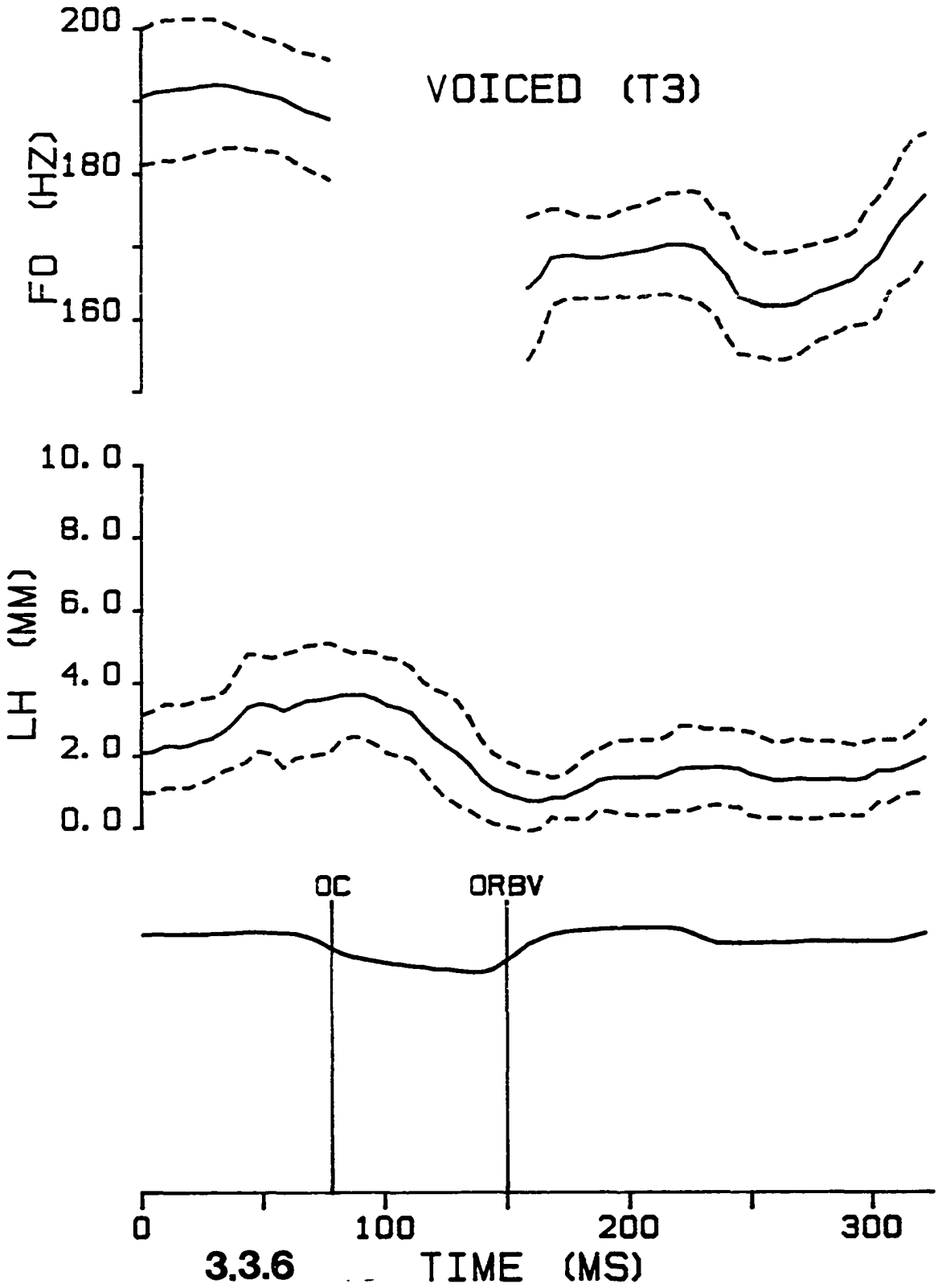

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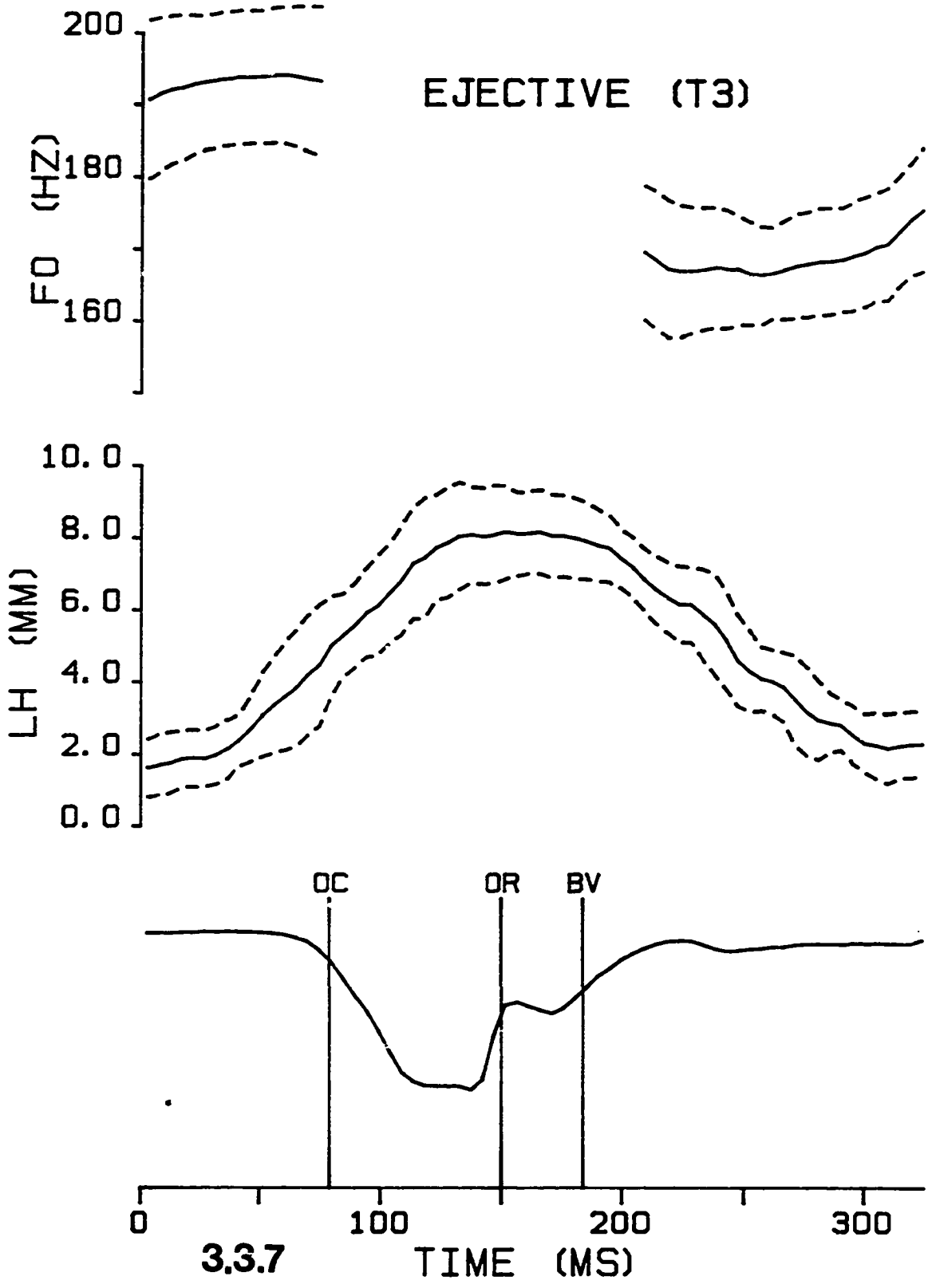

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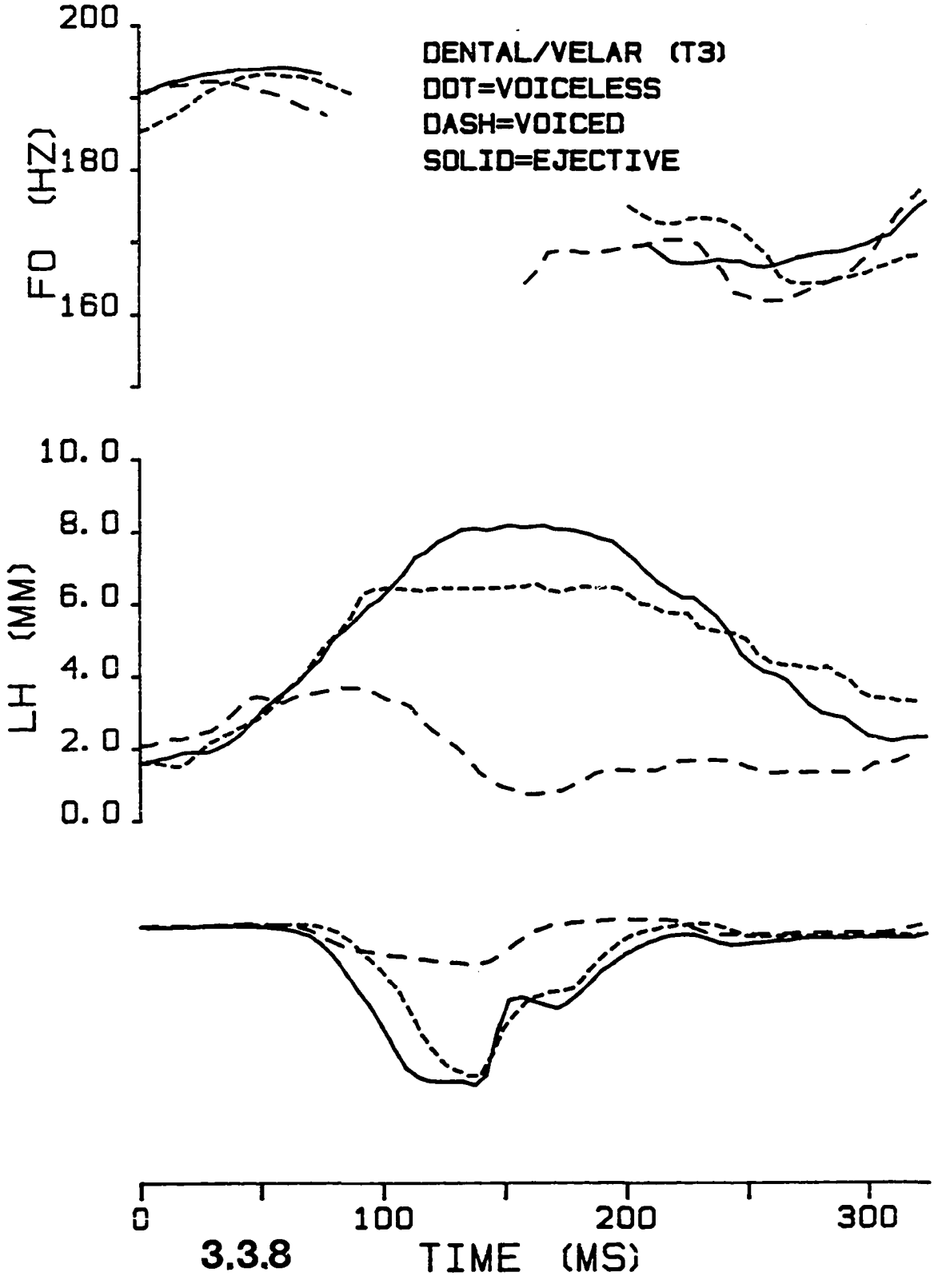

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Furthermore, these differences last well into the following vowel. One would expect, then, if the height or movement of the larynx is responsible for the perturbation of Fo, that this speaker would produce the most marked differences in Fo as well. However, since the differences in Fo after the three kinds of stops are instead quite small, the data from this subject conclusively proves instead that the Fo contours following stops are not determined by the height of the larynx. Note also that the direction of movement of the two curves for ejectives and voiceless stops is, if anything, opposite. Fo rises steadily after a brief initial fall following all three kinds of stops, while the larynx falls after ejectives and voiceless stops. It is only after voiced stops that the two curves appear to move in the same direction, upward.

3.3.4 Larynx movement and Fo perturbation after a nasal and glottal stop

The following six figures show that except for T3 (again) the larynx moves relatively little during either a nasal or glottal stop; it instead remains close to the bottom of its range during both types of consonants. Fo is also relatively low after both a nasal and glottal stop, and

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is noticeably lower after glottal stop than a nasal for subjects T1 and T3.

Table 3.3.4

Fo and larynx height for nasals and glottal stop

Figure #	Figure description
3.4.1	Fo and larynx height for the nasal /m/ -- subject T1.
3.4.2	The nasal /m/ -- subject T2.
3.4.3	The nasal /m/ -- subject T3.
3.4.4	Fo and larynx height for glottal stop /?/ -- subject T1.
3.4.5	Glottal stop /?/ -- subject T2.
3.4.6	Glottal stop /?/ -- subject T3.

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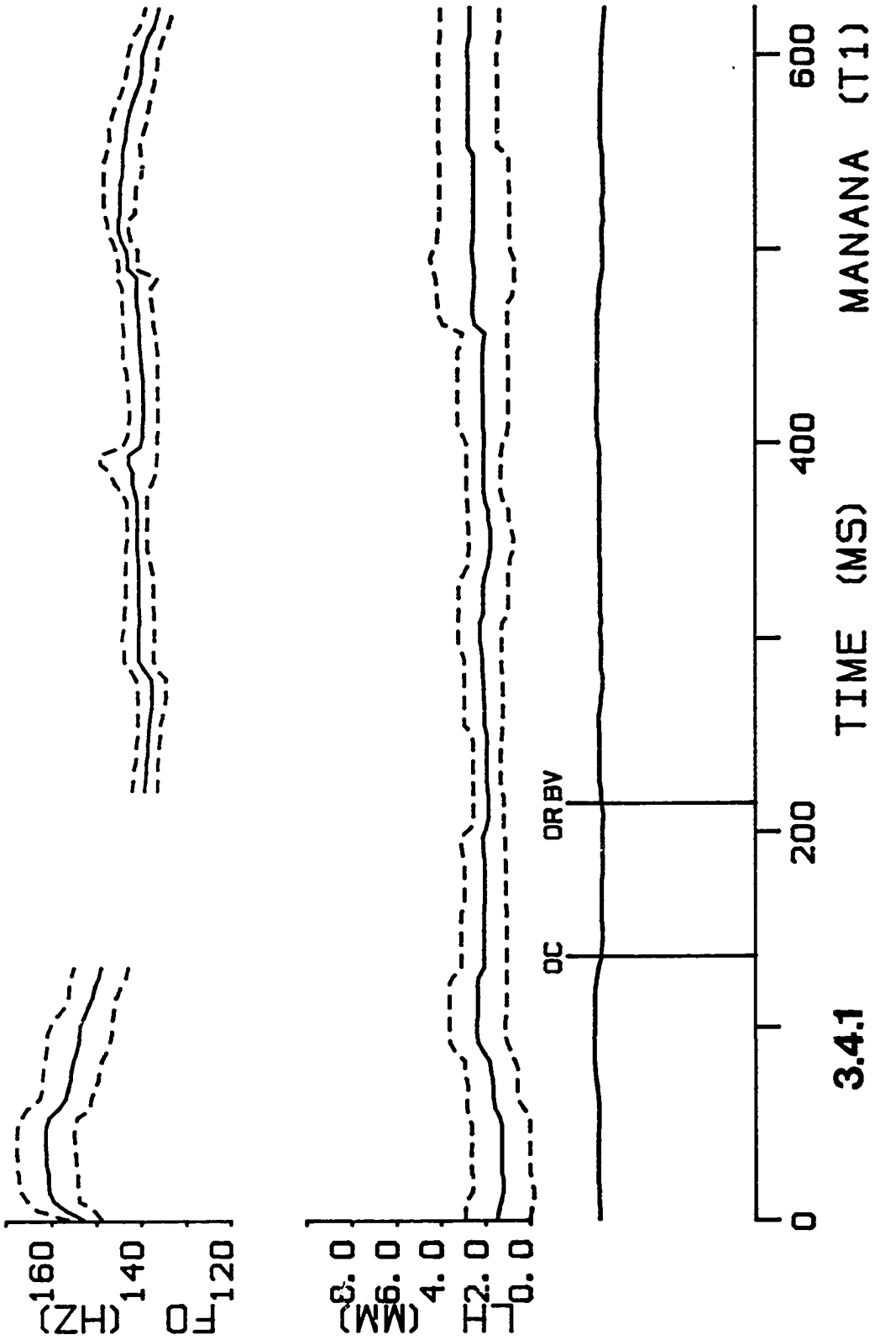

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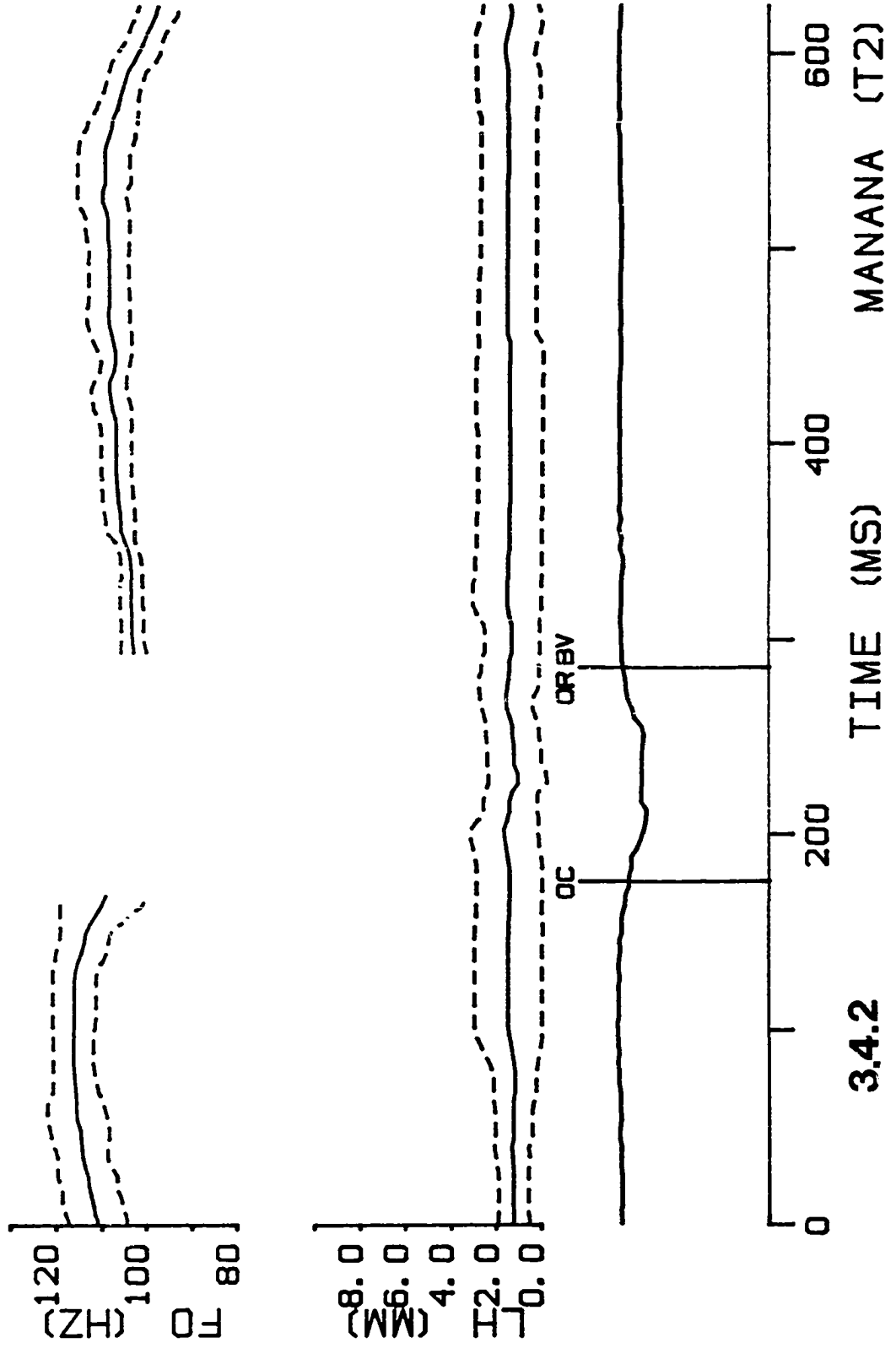

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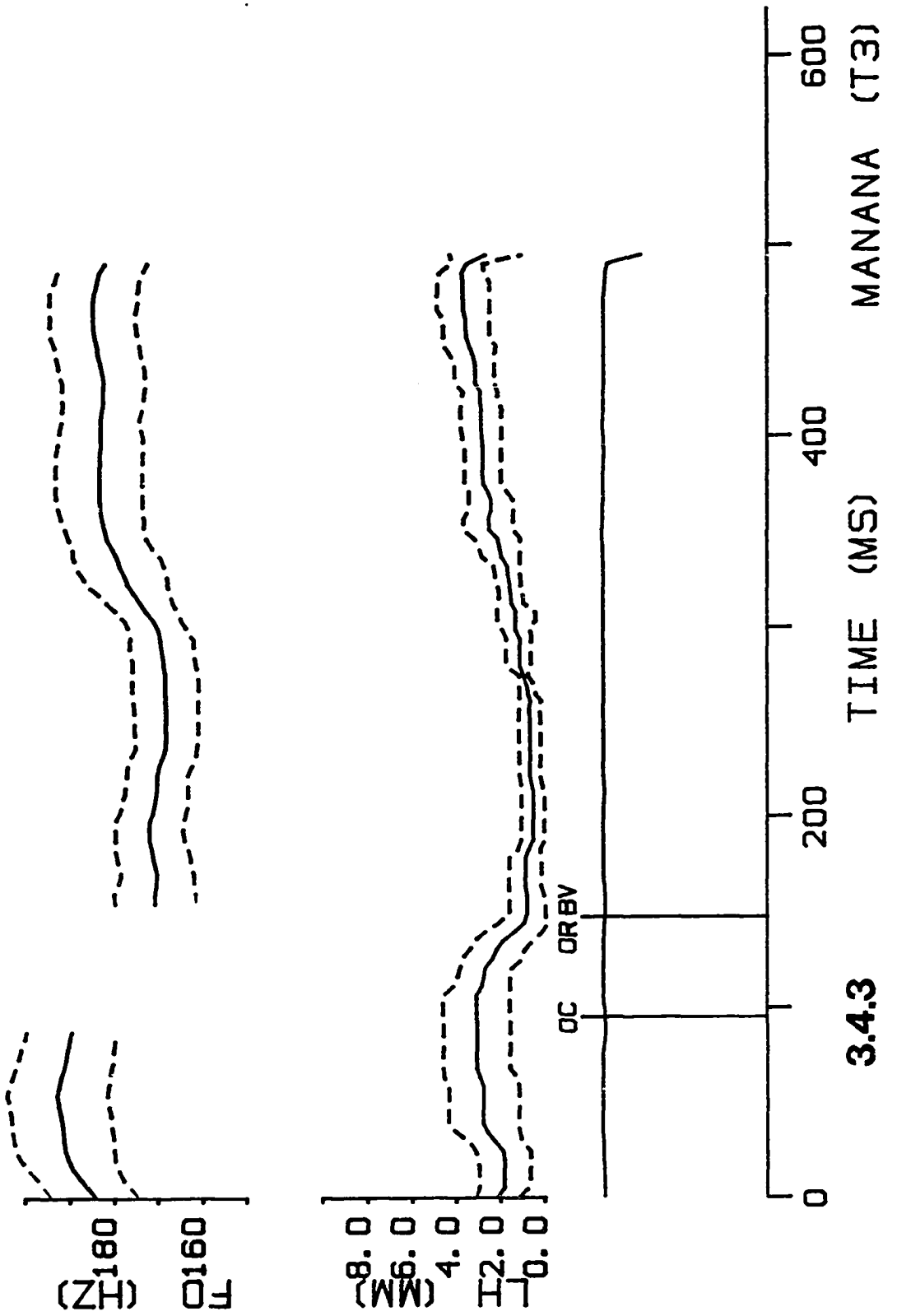

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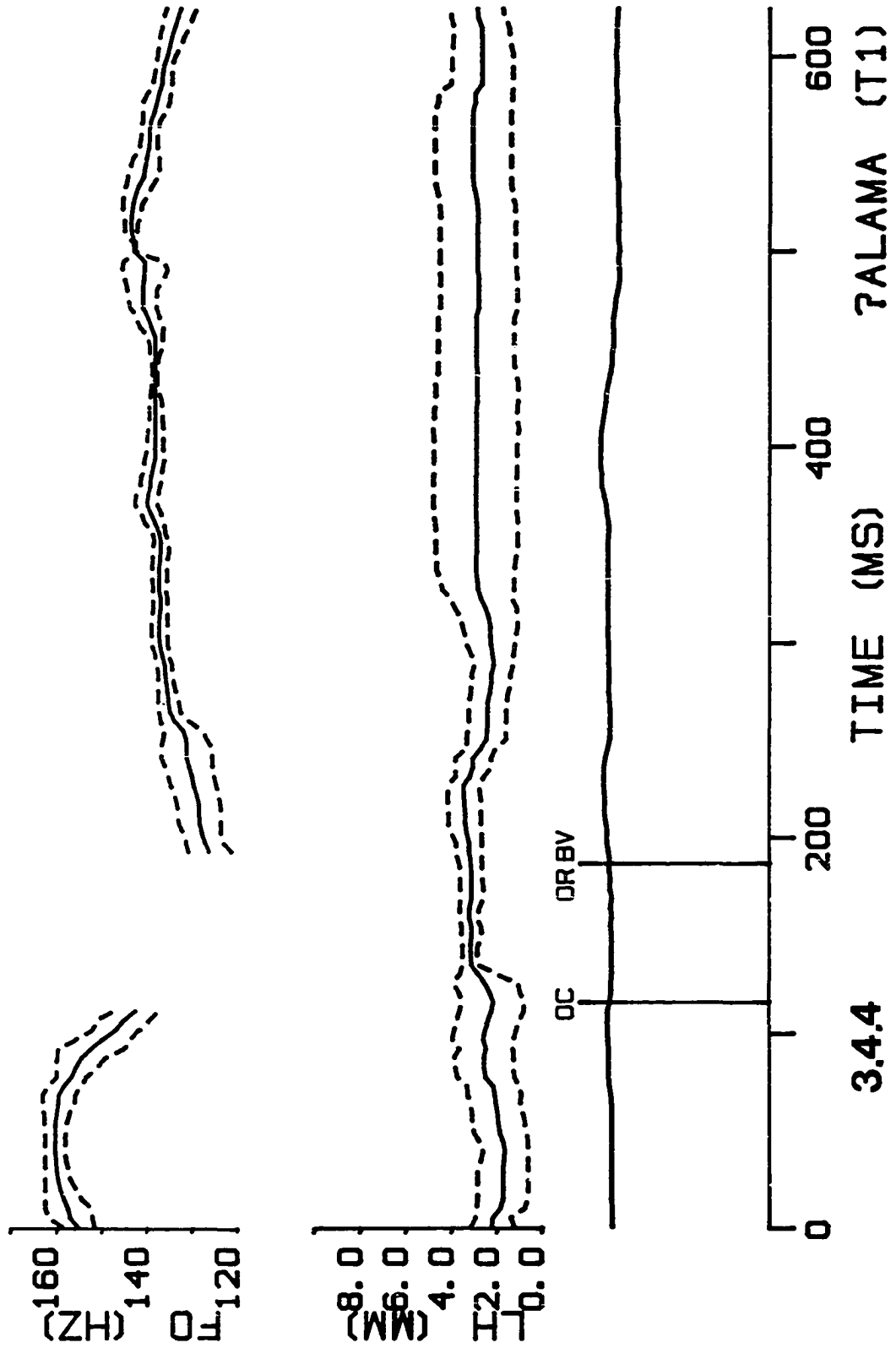

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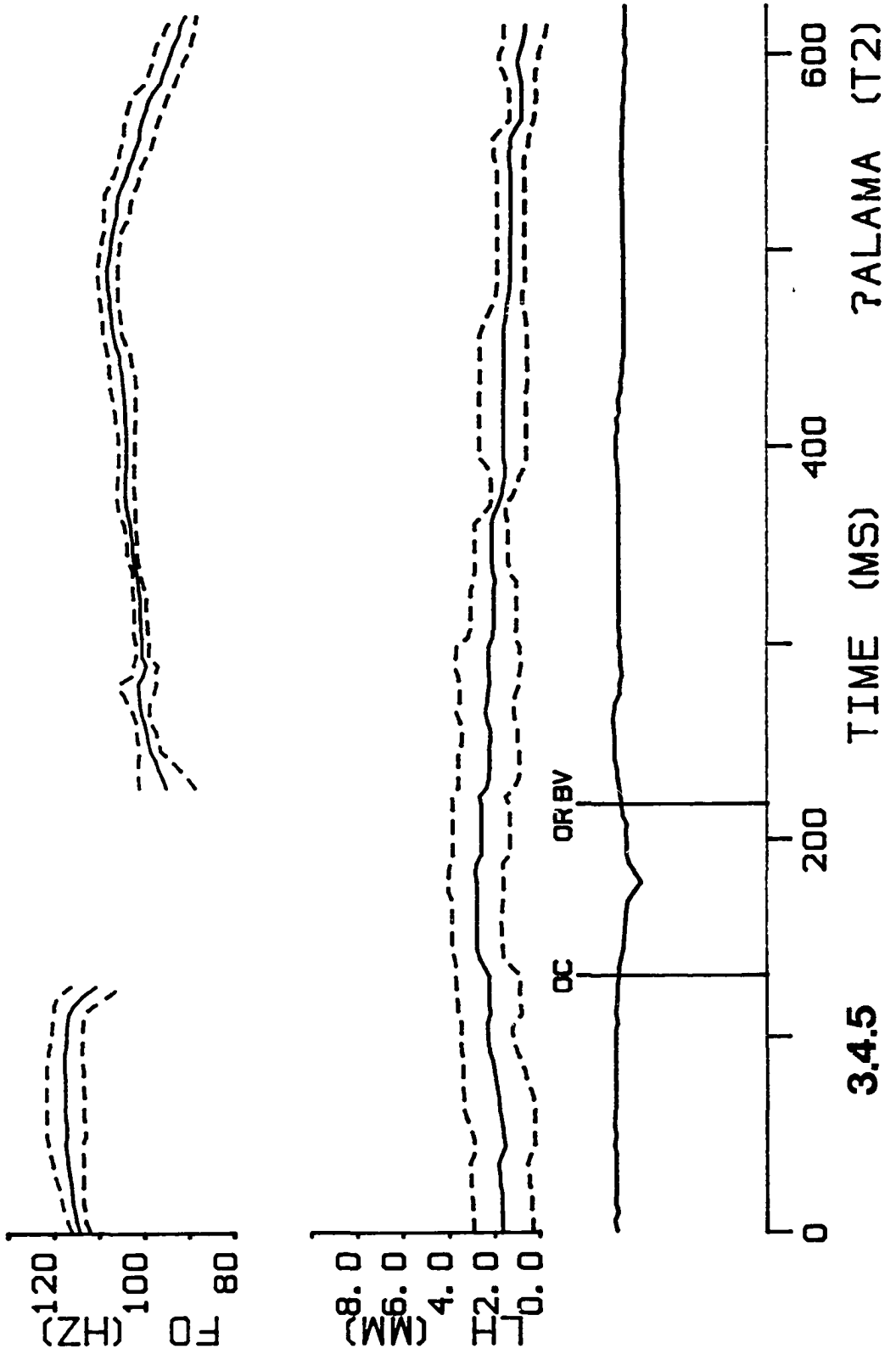

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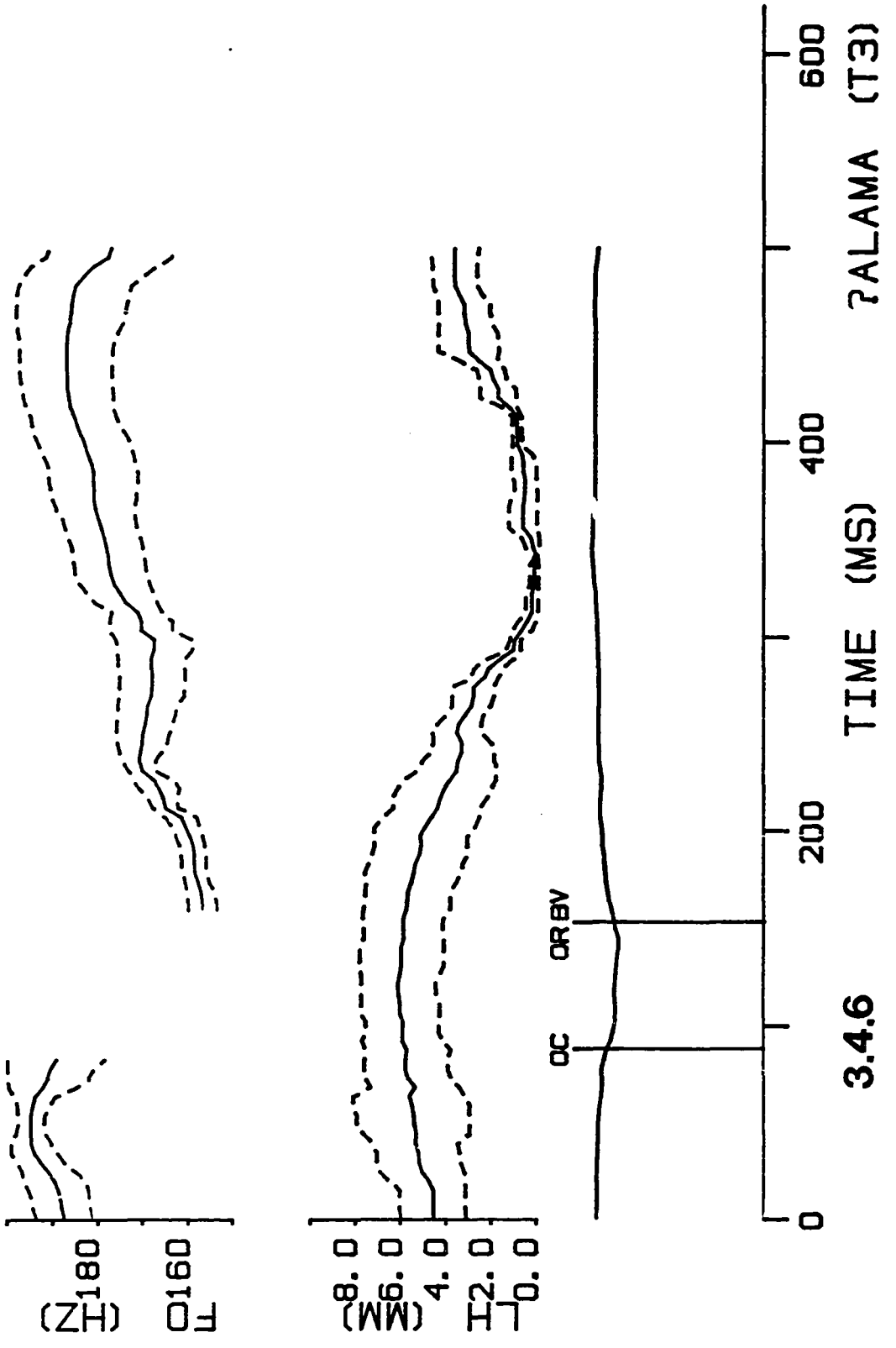

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The waveform for glottal stops (represented indirectly here in the amplitude trace) shows that there was actually no stop produced; /?/ is realized instead for all three speakers as creaky voice between the final vowel of the preceding frame word and the first vowel of the test token. It is therefore not surprising that there should be so little difference in larynx movement or for that matter Fo between the glottal stop and the nasal.

3.3.5 Comparison, summary, and discussion

In none of the data presented in the preceding three sections did Fo correspond to the height or movement of the larynx. This was true for all three kinds of stops examined. Though the failure of raising or lowering the larynx to raise and lower Fo is clearest for speaker T3, who exhibits the greatest amount of larynx movement, it is also apparent in the performance of T1, especially for ejectives, where the two curves move in opposite directions. As with the pressure data reported in the previous chapter, relatively little can be said about T2 since his larynx hardly seems to move at all and certainly does not assume different heights for voiced, voiceless, or ejective stops, unlike T1 and T3.

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A curious feature of the data presented here is the negligible differences in Fo at the onset of the vowel following the three kinds of stops, with the exception of the depression of Fo after ejectives observed in the speech of T1. In an earlier study, based on the speech of another speaker of Tigrinya (Kingston 1982), I found that Fo was initially higher after voiceless stops than ejectives, which in turn elevated Fo more than either voiced stops or nasals did. That finding has clearly not been replicated here. In the only subject where ejectives perturb Fo differently than the other stops do, T1, Fo is markedly depressed rather than elevated. Other studies of Fo perturbations after oral stops (see Hombert, Chala, & Ewan 1979 for review) have shown that Fo is consistently lower at vowel onset after voiced stops than voiceless ones. Only a slight difference in Fo at the onset of the following vowel, though in the same direction, was found between voiced and voiceless stops in this study.

I suggested above that the reason only small difference in Fo were found after the various kinds of stops in this study was because a nontraditional lineup point, the stop release, was used, rather than the onset of the vowel. Since the initially low Fo contour after a voiced stop rises

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steadily, it will eventually reach the same level as the contour following a voiceless one. Because the vowel begins at the same time as or very soon after the release of a voiced stop, the Fo contour during the beginning of the vowel directly reflects the transition in glottal state from a consonantal to vocalic condition. Because of the significant delay in the onset of a vowel following a voiceless stop, however, by the time the vowel finally begins, much of this transition is presumably complete. As a consequence, if one compares Fo at vowel onset for the two kinds of stops, then one is comparing different points with respect to the consonant-vowel transition. On the other hand, if the Fo contours are aligned with the stop release as they are in this study, the points so aligned are comparable with respect to the beginning of this transition.

Nothing in this realignment implies that Fo contours should turn out to be as similar as do. That they are similar indicates that the changes in glottal state which take place between a stop and a following vowel are, with respect to Fo, substantially the same. This result is somewhat surprising since for voiceless stops and perhaps ejectives[9], this change is presumably a relaxation of the folds from the relatively stiff and, in the case of ejectives, compressed

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state they assume to inhibit voicing during the stop, while some increase in fold tension occurs following voiced stops, as indicated by the fact that Fo is lower during the closure of a phonetically voiced stop than it is during the following vowel. This all implies that the Fo contours after the various kinds of stops should be quite different.

This difference, however, should only be found in the interval immediately after the release of the stop and since no voicing occurs during this interval after a voiceless stop (or ejective), much of the relaxation of the folds takes place before voicing actually begins. After voiced stops, on the other hand, because of the immediate onset of the vowel, the increase in fold tension which follows the release occurs in plain view. Since the cricothyroid, whose activity is suppressed during the closure of both voiced and voiceless stops, begins to contract once the stop is released, stretching the folds, Fo should then rise uniformly after all three kinds of stops, as this muscle contracts. The similarity in these Fo contours should be most evident if they are aligned with respect to the stop release when the activity of the cricothyroid begins to supplant that of the laryngeal muscles which affect vocal fold tension during the stop itself.

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In the next section, another approach is taken to evaluating the relationship between larynx height and Fo. Moment-by-moment correlations were calculated between these two parameters after the three kinds of stops.

3.4 Correlations between larynx height and Fo

It was noted above that if raising and lowering the larynx also raised and lowered Fo, then there should be a positive correlation between the height of the larynx and Fo. In the tables below, mean correlations between larynx height and Fo at 4.8 ms intervals are presented for each of the three varieties of stops. There are two tables for each subject: a long term mean correlation between larynx height and Fo for the entire word and a short term mean correlation over the first 100 ms of the vowel following the initial stop. Correlations were calculated separately for each type of stop. In the tables below, means and standard deviations are given for each kind of stop within each correlation condition. The numbers in parentheses after the labels for each stop type represent the number of tokens. A table is presented for each speaker individually and then a final table is given where the data from all three speakers is

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pooled. The results of a one-way analysis of variance comparing correlations among stops are also given in each subsection of the tables.

Table 3.4.1

Correlations between Fo and larynx height -- Subject T1

a. Long term

Stop type	Mean	Standard deviation	
Voiceless (8)	-Ø.133	Ø.228	
Voiced (9)	-Ø.Ø27	Ø.245	F(2,23) = 4.652 p < .Ø5
Ejective (9)	-Ø.429	Ø.327	

b. Short term -- unaligned

Stop type	Mean	Standard deviation	
Voiceless (8)	-Ø.29Ø	Ø.394	
Voiced (8)	-Ø.117	Ø.523	F(2,22) = Ø.85Ø p < .5 n.s.
Ejective (9)	-Ø.4Ø4	Ø.351	

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Table 3.4.2

Correlations between Fo and larynx height -- Subject T2

a. Long term

Stop type	Mean	Standard deviation	
Voiceless (1Ø)	Ø.Ø42	Ø.364	
Voiced (1Ø)	Ø.Ø83	Ø.393	F(2,27) = 3.322 p < .Ø5
Ejective (1Ø)	-Ø.353	Ø.428	

b. Short term

Stop type	Mean	Standard deviation	
Voiceless (1Ø)	Ø.Ø11	Ø.433	
Voiced (1Ø)	Ø.Ø37	Ø.385	F(2,27) = 3.142 p < .1 n.s.
Ejective (1Ø)	-Ø.391	Ø.397	

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Table 3.4.3

Correlations between Fo and larynx height -- Subject T3

a. Long term

Stop type	Mean	Standard deviation	
Voiceless (9)	-0.274	0.211	
Voiced (10)	0.519	0.320	F(2,26) = 43.736 p < .00000005
Ejective (10)	-0.47	0.15	

b. Short term

Stop type	Mean	Standard deviation	
Voiceless (9)	0.426	0.486	
Voiced (10)	-0.017	0.408	F(2,26) = 1.736 p < .2 n.s.
Ejective (10)	0.187	0.564	

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Table 3.4.4

Correlations between Fo and larynx height -- All subjects pooled

a. Long term

Stop type	Mean	Standard deviation	
Voiceless (27)	-Ø.115	Ø.311	
Voiced (29)	Ø.199	Ø.404	F(2,82) = 21.706 p < .00000005
Ejective (29)	-Ø.417	Ø.325	

b. Short term -- unaligned

Stop type	Mean	Standard deviation	
Voiceless (27)	Ø.060	Ø.525	
Voiced (29)	-Ø.039	Ø.440	F(2,82) = 1.804 p < .2 n.s.
Ejective (29)	-Ø.196	Ø.528	

The large standard deviations make evaluation of this data somewhat difficult; apparently, the correlations were highly variable from token to token. Nonetheless, it is clear that the height of the larynx is only positively correlated with Fo after voiced stops, but not after either voiceless stops or ejectives. For ejectives, the correlations tend to be negative instead, while they are neither consistently positive nor negative after voiceless stops.

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This confirms quantitatively the conclusion reached in the last section that the Fo contour following a stop is not determined by the positon or movement of the larynx during that stop.

Differences between the correlations for the three kinds of stops were only significant for the long term condition for any speaker. This result is somewhat puzzling since one would expect that if the interaction between the height of the larynx and Fo is different in the three kinds of stops, that this difference would be greatest in the immediate vicinity of the stop. Instead, it appears to be a global property of the word. The extremely slow movement of the larynx observed in the last chapter is also apparent in the data under discussion here, so it may simply be the case that the larynx moves so slowly from the position it assumes during the stop to that of the following vowel that no interaction between its position or direction and the more swiftly changing Fo contour can be observed until the correlation is extended to the entire word. If this is the correct interpretation of the absence of a significant difference between the larynx height-Fo correlations for the different stop types in the short term condition, then it can be taken as further evidence that larynx height during

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stops is no more responsible for local perturbations of Fo following a stop than it is for changes in Po during the stop itself.

In order to get a better sense of the distribution of individual correlations, the values for individual tokens pooled across all the subjects are displayed in interval histograms below. In these histograms, the X's represent ejectives, the V's voiced stops, and the Ø's voiceless ones. Each of the histograms represents one of the two conditions under which correlations were calculated: 1) long term and 2) short term.

The histograms for both conditions show that Fo is more often than not negatively correlated with larynx height after ejectives, while it tends to be positively correlated after voiced stops and uncorrelated after voiceless ones.

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Table 3.5.1

Long term correlations between larynyx height and Fo

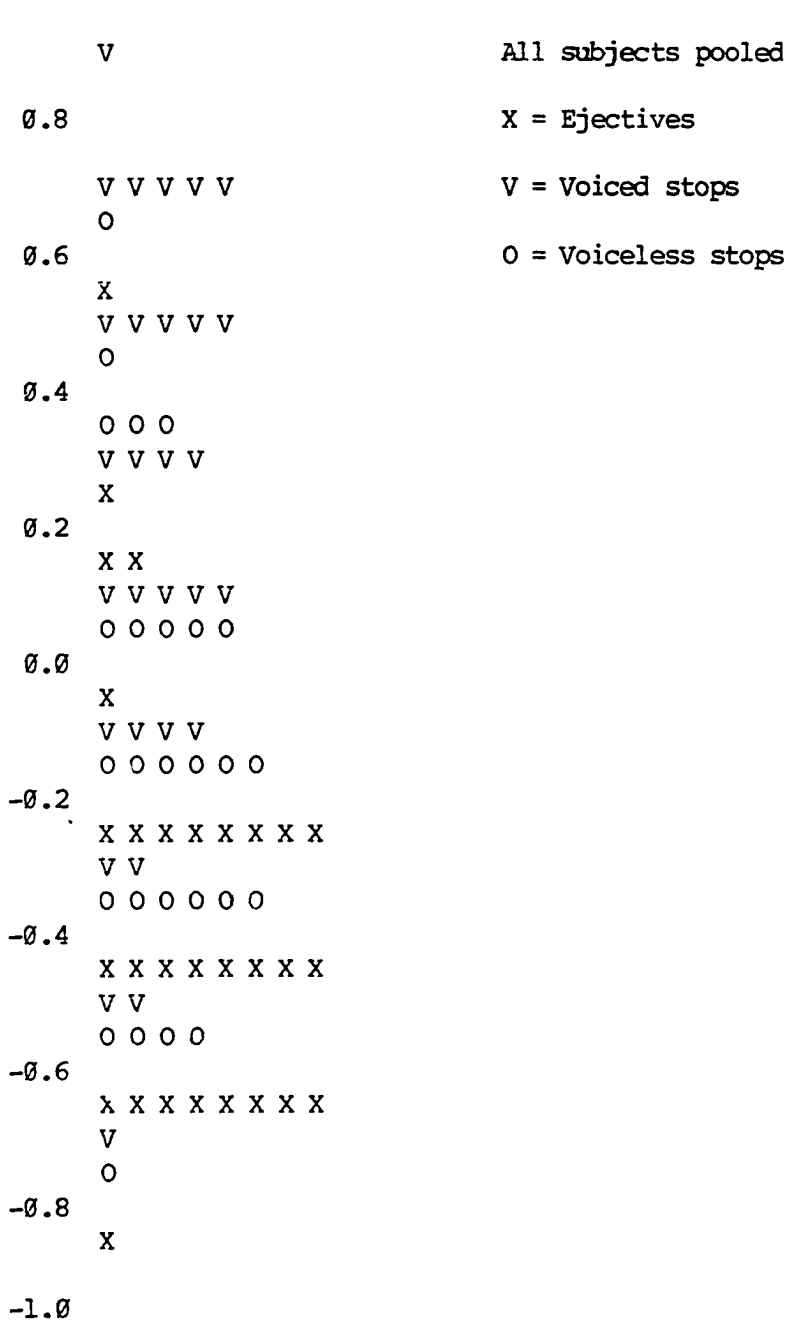

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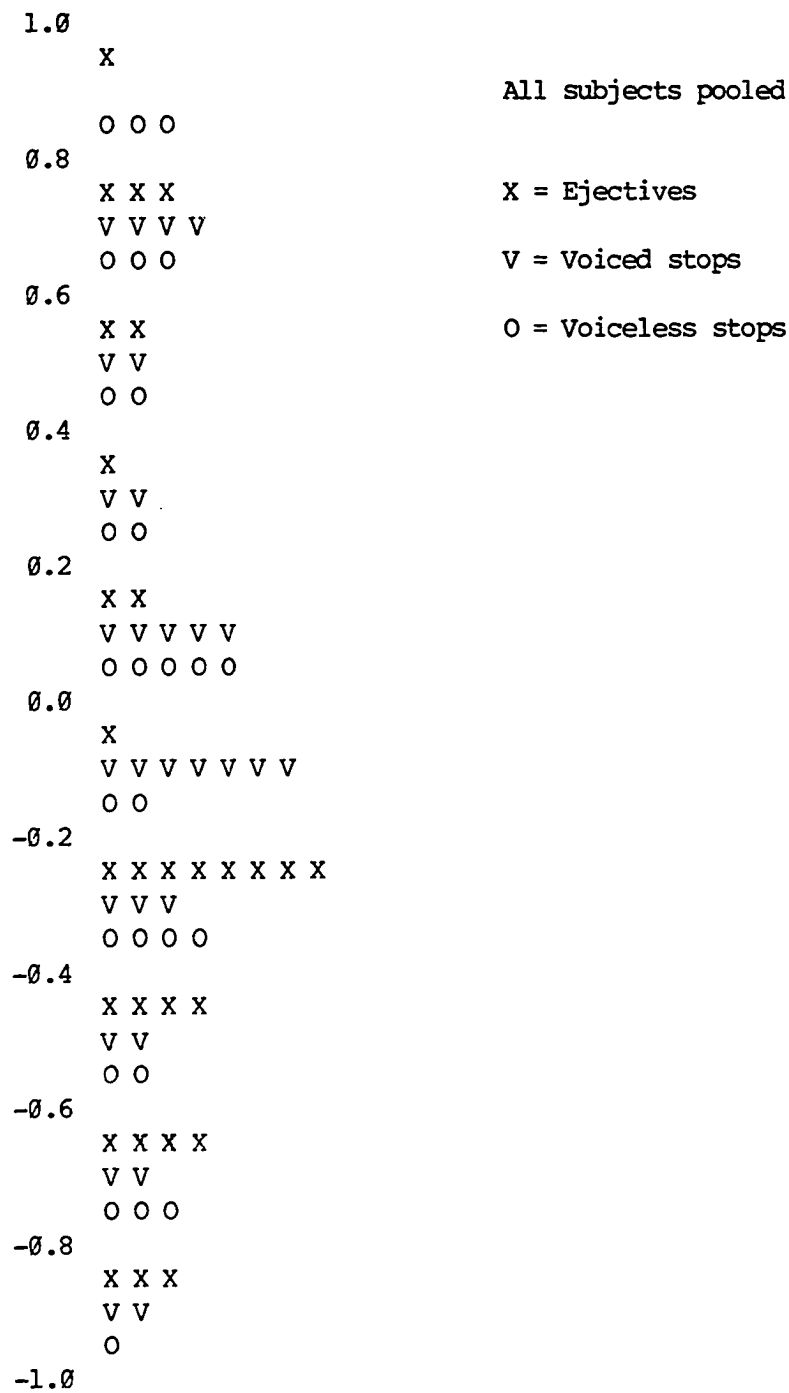
Table 3.5.2

Short term correlations between larynx height and Fo



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The positive correlation of Fo with larynx height after voiced stops is compatible with the vertical tension hypothesis of Hombert, Ohala, and Ewan (1979), but the negative correlations observed after ejectives, and the absence of any correlation following voiceless stops makes it unlikely that raising or lowering the larynx is the mechanism which perturbs Fo after stops (if Fo is, in fact, perturbed).

As the larynx falls from the high position it assumes during an ejective, Fo is rising rather than falling in tandem. The larynx rises instead with Fo after voiced stops. A rising contour is also observed after voiceless stops in Tigrinya, a similarity which points to the possibility that the same sequence of events occurs in the transition from stop to vowel after all three kinds of stops. The fact that a rising contour is observed after all classes of stops supports the hypothesis advanced in the preceding section that the Fo contours after stops are the product of a shift in control over vocal fold tension to the cricothyroid, whose gradually rising level of activity would produce a rising contour. The fact that the distribution of correlations is similar for both the shorter and longer intervals over which they were calculated provides further support for this

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hypothesis, since the cricothyroid is known to be used primarily in producing the Fo contours of longer strings such as words and phrases.

As I noted above, differences in Fo at vowel onset after different kinds of stops in the data presented here are primarily artifacts of looking at the Fo contour at different points with respect to its beginning point, the stop release, relatively earlier for voiced stops than voiceless ones or ejectives. In this view, the Fo contour of the vowel following a stop is not so much perturbed as revealed at different points along its trajectory. This is not to deny that changes in vocal fold tension during a stop can perturb Fo at the beginning of a following vowel; the low frequency creaky phonation observed after ejectives in the speech of T1 is an example of such perturbation. Instead, all I would claim is that once Fo contours are aligned at the stop release, certain smaller differences in Fo can be shown to be the result of sampling different points in a uniformly rising Fo contour. Genuine perturbations are the result of a significant delay in shifting control over vocal fold tension to the cricothyroid after the stop is released.

Before concluding this discussion, I should note that

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the evidence presented above may not be generalizable to other languages. Data presented in Hombert (1978) for English and French, in particular, shows that Fo starts at a relatively high level and then falls after voiceless stops, while starting at a relatively low level and rising after voiced stops. Given these facts, all we can conclude for the present is that such perturbations are not universal concomitants of the voicing contrast since they are absent in Tigrinya.

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Notes.

1. Reduced to the bare essentials, the larynx has one degree of freedom and the vocal folds have at least four, each controlled through the activity of a specific set of muscles. The larynx is moved up and down through the contraction of the muscles by which it is suspended in the neck, the stylohyoid and the posterior belly of the digastric above, whose contraction will raise the hyoid bone and with it the larynx, and the sternohyoid and sternothyroid below, the strap muscles whose contraction pulls the larynx down (Broad 1973).

The first degree of freedom of the vocal folds is the distance between them or, in other terms, the size of the glottis. The vocal folds may either be brought together, closing the glottis, by contracting the interarytenoid or held apart, opening the glottis, by contracting the posterior cricoarytenoid (Sawashima, Hirose, & Yoshioka 1978, Sawashima & Hirose 1980, Hirose, Lisker, & Abramson 1980).

The second degree of freedom of the vocal folds is

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their length. The length of the folds is increased by contracting the cricothyroid, which tilts forward the thyroid cartilage to which the vocal folds are attached anteriorly. Stretching the folds in this way will increase their length and thereby their rate of vibration.

Third, tension may be increased by stiffening the folds, a change accomplished by the contraction of the vocalis and/or lateral cricoarytenoid. Stretching and stiffening the folds have different effects on their rate and manner of vibration. This possibility is gone into thoroughly below.

Finally, the folds may be compressed medially, sealing the glottis. The way in which the folds are compressed is somewhat obscure, but available evidence suggests that it accomplished by contracting the interarytenoid, which brings the folds together, the lateral cricoarytenoid, which shortens them, and perhaps also by adducting the laryngeal ventricles and pressing them down onto the vocal folds (Catford 1977, Hollein, Moore, Wendahl, & Michel 1966).

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If the vocal folds are held together while the lungs are contracting, the air flowing up out of the lungs will first force them apart and then, if the folds are sufficiently tense, they are drawn back together by a combination of the Bernoulli force and elastic recoil. Once the folds are back together, air pressure beneath them will quickly build up again and force them apart, repeating the cycle -- this is the essence of the aerodynamic-myoelastic theory of vocal fold vibration (van den Berg 1958). This kind of pulsed air flow and hence vocal fold vibration will continue so long as subglottal pressure is sufficiently higher than intraoral air pressure. On the other hand, if the vocal folds are drawn apart and their tension is not reduced, at some degree of separation for a given degree of fold tension, vocal fold vibration will stop, even though air continues to flow between the folds. Besides providing a periodic sound source to excite the resonances of the air in the oral cavity, holding the vocal folds together slows the flow of air into the oral cavity. Since reducing air flow into the oral cavity will slow the buildup of Po, the bursts or frication noise of voiced obstruents will be less intense

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than those of their voiceless counterparts.

2. Successful articulation of speech sounds requires that the activity of the various sets of muscles and the articulations that they effect be coordinated with one another. Coordination is not equivalent to synchronization, i.e. one set of muscles may be governed by an entirely different neurological schedule than another. As was noted for contrasts in voice onset time, systematic variation in the timing of the closing of the glottis is the means by which contrasts between voiced, voiceless unaspirated, and voiceless aspirated stops are accomplished; the closing of the glottis is only synchronized (simultaneous) with the oral release in voiceless unaspirated stops. Secondly, even if changes in the activity level of the muscles which control different articulators are synchronized, the movement of the articulators themselves will not be synchronized if there are significant differences in inertia between them. For example, the longer voice onset times observed for velar stops compared to alveolars or bilabials have been attributed to the greater mass of the tongue dorsum relative to the tongue tip or lips. The greater inertia of the dorsum results in a slower

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opening gesture for velars and hence a slower venting of the air trapped behind the closure. Slower venting appreciably delays the moment when intraoral air pressure is reduced enough for air to start to flow through the glottis and voicing to begin (Keating, Westbury, & Stevens 1980). In this example, the physical properties of the oral articulator, the mass of the dorsum of the tongue, interfere with the initiation of vocal fold vibration by slowing the venting of air from the oral cavity.

3. Chao's numerical scheme for representing tones is used here. In this scheme, tones are numbered from 1, low, to 5, high. Usually a pair of numbers is given. If both numbers are the same, as in the examples above, a level tone is indicated, while if they are different, a contour tone is meant; e.g. 35 represents a mid-rising tone.

4. There are a number of cases of nontonal languages which have become tonal as a result of the collapse of the voicing distinction in the stops, with compensatory phonologization of the Fo perturbations. Haudricourt (1972a) suggests that Cham, an Austronesian language

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spoken in Vietnam and Cambodia, acquired a contrast between high and low tone from an original contrast between voiceless and voiced stops; and in Punjabi (Gill & Gleason 1969, 1972, Haudricourt 1972b), breathy-voiced stops have left behind a low tone on the following vowel in the course of becoming voiceless unaspirated. Tonogenesis in these languages is plausibly a result of areal influence, since they are both in contact with tonal languages which have undergone tone splits of the sort described for Lungchow.

5. It is also possible that the sound change move gradually through the lexicon, just as it moves gradually from speaker to speaker. The transfer of the distinction from the stop to the vowel would be complete in lexical items or morphological contexts where the voicing contrast is neutralized, while in other items or contexts the stops may still contrast for voicing. English offers an interesting parallel. In that language, vowels are redundantly longer before voiced than voiceless stops. Between a stressed and an unstressed vowel in American English, however, the contrast in voicing between /t/ and /d/ collapses as a result of both stops becoming the tap [D]. In some dialects, the vowel

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lengthening and tapping rules are in counterbleeding order and such pairs as writer and rider remain distinct despite the neutralization of voicing in the stops, i.e. [rajDɚ] and [ra:jDɚ]. If one were to suppose that this represents the beginning of a general collapse of the voicing contrast in postvocalic stops with the now redundant difference in duration gradually replacing stop voicing, then it is possible to see how a sound change can be essentially complete in part of the language, while continuing to work its way though the rest. I am indebted to Gregory Guy for this example.

6. Any clarity that the following discussion might have comes directly from a lengthy conversation with Victor Golla and Kenneth Whistler. I am indebted to them particularly for the insight that tone reversal, though not the reversal of other features, is perhaps not a excessively rare type of sound change. I am also grateful to Michael Krauss for sending me a copy of his paper on Athabaskan tone and extensive comments on a much more primitive version of the hypothesis regarding the phonetics of constriction presented below. None of these people is responsible, of course, for any errors

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or wild claims I might make.

7. In this section, I will depart from the terminological conventions outlined in the first chapter and refer to the class containing glottal stop and ejectives as "glottals"; also any stem ending in a glottal stop or ejective will be said to have "final glottalization".

8. I do not wish to claim here that the Korean tense stops are ejectives. Rather there are certain striking similarities between the tense and lax stops of Korean and the tense and lax ejectives found in Tigrinya and Quiché, respectively. As suggested below, the Korean tense stops probably lack the medial compression of the vocal folds which seals the glottis during ejectives. This is shown by the fact that Po is not elevated above Ps in these stops, as it would be if the glottis were sealed tightly enough to aerodynamically isolate the supraglottal cavity from the subglottal one (Kim 1967).

9. The difficulty, of course, with assuming that the folds are stiff during the closure of an ejective and then relax gradually following its release, is that for speakers like T1 (or the Quiché speaker examined in Kingston 1982), the vowel after an ejective begins with

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an extremely low frequency, creaky phonation. As the voice quality becomes modal, Fo slowly rises, which suggests that the tension applied to the folds is gradually increasing rather than decreasing. What follows is rather speculative, but it seems to me the most plausible scenario given our current understanding of how the state of the folds is changed in the transition between stop consonants and following vowels.

As suggested in the introduction to this chapter, the stiffening and medial compression which occurs during ejectives to seal the glottis is probably a result of contraction of the vocalis and lateral cricoarytenoid muscles. As these muscles relax following the release of the stop, control over vocal fold tension should gradually shift to the cricothyroid, whose activity level increases once the stop is released. Though there is little electromyographic data on ejectives (see Dent 1981), since the level of activity of the cricothyroid has been shown to increase markedly after all other types of stops examined, transferring control from the vocalis and lateral cricoarytenoid to this muscle seems plausible for ejectives as well. The contraction of the cricothyroid stretches rather than

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stiffening the folds. During the interval when the state of the folds is still primarily determined by the contraction of the vocalis and lateral cricoarytenoid, the folds will still be stiff enough to offer sufficient resistance to air flow through the glottis that they will vibrate slowly and irregularly. As the cricothyroid takes over and applies progressively more stretch to the folds, they will begin to vibrate more quickly and regularly. This is precisely the pattern observed after ejectives in the speech of T1 (and in the speaker of Quiché). The notion that the transition from consonant to vowel is primarily a matter of shifting control to the cricothyroid is developed further immediately below.

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Chapter 4

Articulatory Binding

4.1 Introduction

In this chapter, I will lay out a theory of the coordination of oral and glottal articulations that I will refer to as "articulatory binding". The essential claim of this theory is that a glottal articulation will be most tightly bound temporally to an oral articulation which completely obstructs the channel through which air escapes from the oral cavity. To be more precise, any glottal articulation which accompanies the articulation of a stop, i.e. a noncontinuant, will occur close to the release of that stop. Furthermore, this timing relationship between glottal and oral articulations in stops will be relatively stable. The result of anchoring the glottal articulation to the release of the stop is that the acoustic effects of the glottal articulation will be packed into the brief interval between the stop and a following vowel. Conversely, in any consonant where air flow out of the oral cavity is not obstructed, as in sonorants and to a lesser extent, fricatives, i.e. continuants, the glottal articulation will be

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more variable in its timing relative to the oral articulation. As a result, the acoustic effects of the glottal articulation in continuants will not be confined to any single part of the consonant.

The physiological basis for this difference between continuants and noncontinuants in the binding of glottal to oral articulations is the fact that the complete obstruction of the oral cavity in noncontinuants brings about a marked increase in intraoral air pressure, which, when the obstruction is removed, results in a brief burst of noise as the air pent-up in the oral cavity rushes out. The burst of noise which occurs at the release of the stop is an acoustically salient event to which glottal articulations which in one way or another contribute to changes in intraoral air pressure during the stop closure may be anchored. If any such glottal articulation is to effectively change intraoral air pressure, then careful coordination with the stop closure and more importantly the release is essential. The evidence presented in chapter 2 regarding the ineffectiveness of larynx movement as a mechanism for manipulating intraoral air pressure suggests that this articulation is not likely to be bound to any oral articulation. This would also follow from the relative slowness of larynx movement

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vis-a-vis any oral articulation. During sonorant articulations, glottal articulations are much less likely to have as even a proximate goal a change in intraoral air pressure. Instead, they must be designed to modify the segment or neighboring segments in other ways. For example, in association with sonorant articulations, glottalization modifies the voice quality and fundamental frequency of the sonorant and neighboring vowels. The size of the glottal aperture does effect the amount of pressure buildup which takes place behind a fricative constriction, but since the obstruction of the oral cavity is not complete, in fricatives like sonorants there is no acoustic event comparable to the stop burst to which the glottal articulation could be anchored.

Certain kinds of evidence for the binding of glottal to oral articulations in noncontinuants, where the stop release anchors the glottal articulations are well-known. The most familiar, perhaps, is voice onset time, where differences in when voicing begins relative to the stop release in prevocalic stops distinguish among:

(4.1)

a. prevoiced stops, where voicing begins significantly before the release of the stop,

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b. voiceless unaspirated stops, where voicing begins nearly at the same time as the release, and

c. voiceless aspirated stops, where voicing does not begin until significantly after the release (Lisker & Abramson 1964).

Even more direct physiological evidence for the binding of glottal articulations to oral ones has been demonstrated for a number of Germanic languages. In single voiceless obstruents and in clusters of voiceless obstruents in English, Swedish, and Icelandic (Löfqvist & Yoshioka 1980, Yoshioka, Löfqvist, & Hirose 1981, and Löfqvist & Yoshioka 1981), a single opening of the glottis -- the devoicing gesture -- occurs. Furthermore, in all but one case, the peak glottal opening in clusters of voiceless obstruents in these languages occurs at or before the release of the last stop.[1] The exception is clusters of a stop preceded by an /s/, where the widest glottal opening occurs late in the /s/ and the vocal folds are nearly completely adducted by the time the stop is released, resulting in a very short voice onset time for the stop. This difference may follow from a requirement for greater transglottal air flow during the fricative in order to maintain a high enough air pressure

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behind the oral constriction to produce turbulent, noisy air flow through it (John Ohala, p.c.).

In these languages, normally only the last stop in stop clusters is audibly released; accordingly, there is only a single anchor point for the glottal articulation.[2] Languages of this kind seem to be in the majority and based on them, the following corollary of the binding hypothesis can be offered:

(4.2)

First corollary: in obstruent clusters, the distinctive glottal articulation is bound preferentially to the last obstruent in the cluster.

As we will see, the statement in (4.2) needs to be extended to mention the nature of the segment following the cluster. Specifically, what is important about the last obstruent in an obstruent cluster is that it can immediately precede a more sonorant segment, ideally a vowel.

Though the motivation for the binding hypothesis does rest in part on simple considerations of when a glottal articulation will have the greatest effect on the pressure of the air inside the oral cavity, this is not the whole

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story. I indicated above that anchoring glottal articulations in stops to the release results in the acoustic effects of the glottal articulations occurring in large part after the release, during the transition from the stop to a following vowel. This is the interval during which a rapid modulation of the spectrum occurs as a result of rapid movement of the oral articulators (Stevens & Blumstein 1975,1978, Ohala & Kawasaki 1984). This rapid modulation contains the essential cues to the place of articulation of the consonant, though Stevens and Blumstein's claim that the nature of the modulation is invariant for a particular place of articulation is controversial (Ladefoged & Bhaskararao 1983). The state of the glottis also changes rapidly during this interval as the position and tension of the folds and the height of the larynx shift from the configuration required by the consonant to that of the following vowel. In terms of Fant's (1960) acoustic model of speech production the source as well as the filter function of the vocal tract is changing rapidly in this transition interval. The acoustic results of changes in the state of the glottis include modulation of signal energy, periodicity, and spectrum, all laid over the primarily spectral modulation brought about by the movement of the oral articulators. In short, the essential cues to

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both the place and the glottal type of a stop are contained in this interval. An acoustic corollary of the binding hypothesis may therefore be proposed:

(4.3)

Second corollary: as a result of binding glottal articulations to the stop release, the consonant-vowel transition contains the essential cues to the glottal, as well as oral, type of the stop.

This corollary will be recast in terms of syllable structure in the next section, where it will be argued that there is a functional difference between syllable onsets and syllable rimes. Briefly, syllable onsets are where the bulk of the paradigmatic constrasts in a language will be expressed, while the syntagmatic properties of an utterance, among them its pitch contour and rhythm, will be carried by the rime. The requirement that glottal articulations be bound to stops which precede vowels (or more generally sonorants) together with the requirement that adjacent segments in onsets differ in sonority (Steriade 1982) is what allows onsets to express the large range of paradigmatic contrasts that they typically do. What matters in onsets is what kind of segment follows another. In rimes, on the other hand, it is often

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less important what segments occur as how many segments there are in the rime. This is not to claim, of course, that stops cannot contrast for glottal features in rimes. Rather I claim that such contrasts are likely to more various in onsets that rimes as well as more stable.

The hypothesis that glottal articulations are bound to stop releases predicts that the onset position in the syllable is the place where the greatest number of distinctions among glottal features should be found, while coda position should exhibit the fewest. In Kingston (1982), I showed that of the 34 languages in the Stanford Phonological Archive which have ejectives, 22 (68%) do not allow them to occur in syllable codas,[3] though it should be noted that if the 8 languages in this sample which allow no stops of any sort in codas are excluded, then of the remaining 24 languages, 14 (54%) disallow ejectives in codas, while ejectives occur in codas in 12 (46%) languages. A difference of just two languages is too small, unfortunately, to rest any hopes on, so the prediction that more distinctions in glottal features will be found in onset than coda position will have to be left unconfirmed for the time being.

The remainder of this chapter is divided as follows.

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In section 4.2, the constraints on the occurrence and combination of consonants in Klamath and Cambodian are presented with an eye toward demonstrating that in phonological as well as phonetic terms, it is the last consonant in a cluster of obstruents preceding a sonorant which will bear a distinctive glottal feature. In sections 4.3 and 4.4, the different nature of the association of glottal articulations with continuants is considered. The discussion of glottalized sonorants in Wakashan languages and Yokuts shows that although glottal articulations are most likely to be realized at the end of a stop, they are most likely to be realized at the beginning of a sonorant. It is also shown that glottal articulations are less stablely associated with sonorants than stops. The last section of the chapter, 4.4, is a reanalysis of Athabaskan tonogenesis, which focuses on the importance of the spirantization of syllable-final stops in freeing glottalization to move into the preceding syllable nucleus and give rise there to marked tone.

4.2 The distribution of distinctive glottal features

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4.2.1 Klamath

4.2.1.1 Constraints on the distribution of consonants in Klamath

Klamath, a California Penutian language spoken in the very northern part of California, has four series of stops and three series of sonorants (the sources for Klamath are a dictionary (1963) and grammar (1964), by M.A.R. Barker):

Stop symbolization

T = any stop	R = any sonorant
T^{o} = voiceless unaspirated stops	R^{v} = voiced sonorants
T^{h} = voiceless aspirated stops	R^{h} = voiceless sonorants
D = voiced stops	R' = glottalized sonorants
T' = ejective (glottalized) stops	

In examples, these sounds will be symbolized as follows (/c/ and /j/ represent palatoalveolar affricates not palatal stops):

T^{o}: p,t,c,k,q	R^{v}: m,n,w,y,l
T^{h}: p^{h},t^{h},c^{h},k^{h},q^{h}	R^{h}: M,N,W,Y,L
D: b,d,j,g,G	R': m',n',w',y',l'
T': p',t',c',k',q'	

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The stop phones are distributed as follows:

(4.4)

a. only voiceless unaspirated stops (T^{O}) are found before obstruents:

$$\begin{bmatrix} -\text{continuant} \\ -\text{sonorant} \end{bmatrix} \rightarrow \begin{bmatrix} -\text{spread} \\ -\text{constricted} \end{bmatrix} / \_\_ \begin{bmatrix} -\text{syllabic} \\ -\text{sonorant} \end{bmatrix}$$

b. only voiceless aspirated stops (T^{h}) are found before word boundary:

$$\begin{bmatrix} -\text{continuant} \\ -\text{sonorant} \end{bmatrix} \rightarrow \begin{bmatrix} +\text{spread} \\ -\text{constricted} \end{bmatrix} / \_\_ \#$$

c. medially and in absolute word-initial position before a vowel or sonorant, voiceless unaspirated (T^{O}), voiced (D), and ejective (T') stops are found (the statements below are positive morpheme structure conditions rather than phonological rules):

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$$\begin{bmatrix} -\text{spread} \\ -\text{constricted} \\ -\text{voice} \end{bmatrix}$$ ***

$$\begin{bmatrix} -\text{spread} \\ -\text{constricted} \\ +\text{voice} \end{bmatrix} \quad / \quad \_\_\_ \quad [\ +\text{sonorant}\ ]$$

$$\begin{bmatrix} -\text{spread} \\ +\text{constricted} \\ -\text{voice} \end{bmatrix}$$

*** This series is slightly aspirated intervocalically and word-initially before a sonorant consonant.

d. After a word-initial consonant and before a vowel, voiceless aspirated (T^h), voiceless unaspirated (T^o), and ejective (T') stops occur:

$$\begin{bmatrix} +\text{spread} \\ -\text{constricted} \\ -\text{voice} \end{bmatrix}$$

$$\begin{bmatrix} -\text{spread} \\ -\text{constricted} \\ -\text{voice} \end{bmatrix} \quad / \quad \#\ (\ [\ -\text{syllabic}\ ])\ \_\_\_\ [\ +\text{syllabic}\ ]$$

$$\begin{bmatrix} -\text{spread} \\ +\text{constricted} \\ -\text{voice} \end{bmatrix}$$

If we ignore the slight aspiration of T^o in (c), then it is clear that the voiceless unaspirated stops are in complementary distribution with both the voiceless aspirated stops and with the voiced stops:

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(4.5)

a. $\begin{bmatrix} -\text{spread} \\ -\text{constr} \\ +\text{voice} \end{bmatrix}$ ---> [-voice] / # ([-syl]) ___ [+syl]

b. $\begin{bmatrix} +\text{spread} \\ -\text{constr} \\ -\text{voice} \end{bmatrix}$ ---> [-spread] elsewhere

With these allophonic rules, it is clear that Klamath contrasts at most three stop series in any single environment, though before another obstruent or word-boundary all glottal contrasts among the stops collapse. Klamath will be considered to have three phonemic classes of stops: voiceless aspirated /T^h/ (= /p^h,t^h,c^h,k^h,q^h/), voiced /D/ (= /b,d,j,g,G/), and ejective /T'/ (= /p',t',c',k',q'/). The phonemic overlapping represented by the rules in (4.5) does not represent a violation of biuniqueness, because it does not result in any confusion between voiced and voiceless aspirated stops since the environments are distinct.

The three classes of sonorants are also subject to neutralization, but it is not as thorough-going as for the stops and the environments are somewhat different:

(4.6)

a. word-initially before a consonant and between consonants, only syllabic voiced sonorants (R^V) are found:

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$$\begin{bmatrix}\text{+sonorant}\end{bmatrix} \text{ ---> } \begin{bmatrix}\text{+syllabic}\\ \text{-spread}\\ \text{-constricted}\\ \text{+voice}\end{bmatrix} \Big/ \left\{\begin{matrix}\#\\ [\text{ -syl }]\end{matrix}\right\} \_\_ [\text{ -syl }]$$

b. word-finally after vowel, a contrast between voiced (R^V) and glottalized (R') sonorants is maintained for the laterals and the glides, but not the nasals; only voiced nasals are found in this environment. No voiceless sonorants of any type occur word-finally after a vowel.

$$\begin{bmatrix}\text{+sonorant}\\ \left\{\begin{matrix}\text{+nasal}\\ \text{+lateral}\\ \text{+high}\end{matrix}\right\}\\ \text{-spread}\\ \text{-constricted}\\ \text{+voice}\end{bmatrix} \Big/ [\text{ +syllabic }] \_\_ \#$$

$$\begin{bmatrix}\text{+sonorant}\\ \left\{\begin{matrix}\text{+lateral}\\ \text{+high}\end{matrix}\right\}\\ \text{-spread}\\ \text{+constricted}\\ \text{+voice}\end{bmatrix}$$

Both voiced and glottalized sonorants have voiceless offglides in this environment.

c. so long as a vowel occurs before or after a sonorant which is not word-final, all three varieties of nasals (N^V, N^h, N'), all three varieties of laterals (L^V, L^h,

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L'), but only voiced (W^{v}) and voiceless (W^{h}) glides are found:

$$\begin{bmatrix} +\text{sonorant} \\ \begin{Bmatrix} +\text{nasal} \\ +\text{lateral} \\ +\text{high} \end{Bmatrix} \\ -\text{spread} \\ -\text{constricted} \\ +\text{voice} \end{bmatrix}$$

$$\begin{bmatrix} +\text{sonorant} \\ \begin{Bmatrix} +\text{nasal} \\ +\text{lateral} \\ +\text{high} \end{Bmatrix} \\ +\text{spread} \\ -\text{constricted} \\ -\text{voice} \end{bmatrix} \qquad \begin{matrix} / \ \# \ ([\ -\text{syl}\ ])\ \underline{\quad}\ [\ +\text{syl}\ ]\ *** \\ /\quad [\ +\text{syl}\ ]\ \underline{\quad}\ [\ -\text{syl}\ ] \\ /\quad [\ +\text{syl}\ ]\ \underline{\quad}\ [\ +\text{syl}\ ]\ *** \end{matrix}$$

$$\begin{bmatrix} +\text{sonorant} \\ \begin{Bmatrix} +\text{nasal} \\ +\text{lateral} \end{Bmatrix} \\ -\text{spread} \\ +\text{constricted} \\ +\text{voice} \end{bmatrix}$$

*** Glottalized glides (W') are found between and before vowels, but not after vowels before consonants.

The term 'glottalized' will be used in the immediately following discussion to represent [-spread, + constricted] segments and the term 'aspirated' will refer to [+spread, -constricted] segments, whether stops or sonorants. Note that unlike the stops, where glottalization and aspiration are modifications of how the consonant is released, the corresponding glottalized and aspirated (= voiceless)

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sonorants are either preglottalized and preaspirated or glottalization and aspiration are realized coterminously with the oral articulation. Preglottalization and preaspiration are typical when the sonorants occur before vowel or word-boundary, or following either vowel, consonant, or word-boundary:

(4.7)

a. $/R^h/ \text{ ---> } [^hR]$

$/R'/ \text{ ---> } [?R]$

$$/ \begin{Bmatrix} V \\ C \\ \# \end{Bmatrix} \_\_ V$$

$$/ \quad V \_\_ \#$$

Between a vowel and word-boundary, the voiced portion of glottalized sonorants is syllabic, i.e. [V?R̩#]. After a vowel and before a consonant, glottalization and aspiration are realized more nearly simultaneously with the oral articulations.

The essential fact revealed by these distributions, which are amplified by the discussion of consonant clustering in Klamath below, is that for stops, a three-way glottal contrast is only found before more sonorant segments. The environments where the three classes of sonorants may contrast are more diverse; most importantly, they include the position between a vowel and a following obstruent, where glottal contrasts are invariably neutralized for stops. As

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noted above, what is essential in these environments (listed in 4.6c) is that there be a syllabic segment on at least one side of the sonorant. The greater freedom of occurrence of voiceless and glottalized sonorants prevents one from simply grouping them with the stops as obstruents, though like stops, they cause a neutralization of glottal contrasts in stops which precede them.

4.2.1.2 Consonant clusters and syllabification in Klamath

In the preceding section, the constraints on the distribution of the various kinds of stops and sonorants in Klamath were stated strictly in terms of the classes of sounds which immediately preceded or followed the sound in question. In recent work on Klamath, Clements and Keyser (1983) have argued persuasively that syllable affiliation is a condition on the operation of a number of phonological rules in the language. By examining consonant clusters in this and following sections, I will try to show that the difference between the environments where glottal contrasts in stops and sonorants are neutralized vs. those where the contrasts are maintained is in part a difference in how the consonants are affiliated with syllables. This attempt will

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prove an interesting sort of failure, since if Klamath clusters are syllabified in a way that would allow us to state neutralization in terms of where the neutralized consonant is in a syllable, other, entirely regular, rules which appear to be sensitive to syllable structure could not be formulated in any general way. It will be suggested that if both these other rules and neutralization are to be written so as to refer to syllable structure, then Klamath words will have to be syllabified twice, once quite early in a derivation and then resyllabified quite superficially.

Consonant clusters appear in three positions: at the beginnings of words, medially, and at the ends.

4.2.1.2.1 Word-initial clusters

At most two consonants can combine word-initially in Klamath. Four types of word-initial clusters are found (cf. Clements & Keyser 1983: 118 ff.):

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(4.9)

a. obstruent-sonorant: $T\text{-}R^V$, s-R'

b. obstruent-obstruent: $T^O\text{-}T$, s-T, T^O-s

c. sonorant-obstruent: $\underset{|}{R^V}\text{-}T$, $\underset{|}{R^V}$-s

d. sonorant-sonorant: $\underset{|}{R^V}\text{-}R$

Note that /s/ may be either the first or second obstruent in clusters containing an obstruent. The four types of clusters are exemplified below (all neutralized stops are written as unaspirated, i.e. T^O):

(4.10)

a. $T^h\text{-}R^V$: p^hni?a:k 'little wild onion'

D-R^V: Glaws 'sand'

T'-R^V: k'lockc^ha 'goes to get a fire, torch'

s-R^V: swalqs 'sweat'

s-R': sl'aps 'bloom'

b. $T^O\text{-}T^h$: kt^hodi:la 'hits with the fist underneath'

T^O-D: qdo:c^has 'rain'

T^O-T': qp'al'atk 'curled up'

T^O-s: ksawalt 'can lie upon'

s-T^h: sk^{h}odas 'blanket'

s-D: sdaglank 'having picked up a live object'

s-T': sk'a:Was 'cold'

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c. R^V-T^h: wq^{h}a 'fishpole'

R^V-D: lboga 'round object lies (durative)'

R^V-T': nt'eLq'a 'squashes with a round object'

R^V-s: wso 'chest'

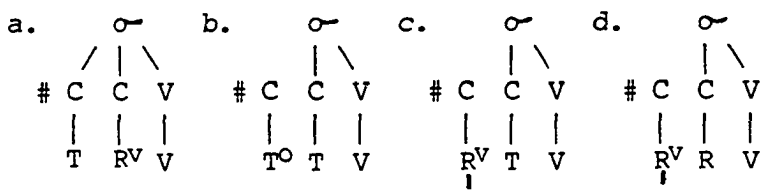
d. R^V-R^V: wlep'als 'lightning'

R^V-R^h: wLic'a 'shakes out'

R^V-R': lm'ac 'metate'

According to Clements and Keyser, the voiceless unaspirated stops and the (syllabic) voiced sonorants in first position in (b,c,d) are extrasyllabic. They imply that neutralization of glottal contrasts is a result of these consonants' lack of syllable affiliation. Conversely, both members of any sequence of a stop followed by a voiced sonorant (a) can be syllabified. The different treatment of the clusters in (a) compared to those in (b,c,d) is sketched below:

(4.11)



Note that a stop may be preceded in word-initial clusters either by a segment of equal obstruency (b) or by one of lesser obstruency (c), while a sonorant which is either

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voiceless or glottalized can only be preceded by another, voiced, sonorant. Voiced sonorants can be preceded by one of their own kind (d) or by a stop of any sort (a). The asymmetry in word-initial clusters can be stated quite simply: in any word-initial sequence of a stop followed by a sonorant, only the stop can bear a distinctive glottal feature. The statement of neutralization is equally straightforward: a stop will not bear a distinctive glottal feature if it is followed by a [-sonorant] segment and sonorants may only contrast for glottal features in word-initial clusters if a [+syllabic] element immediately follows. In other words, it is an unnecessary complication to refer to the lack of syllable affiliation in the statement of the neutralization process; reference to the feature matrix following the segment in question in the segmental melody is sufficient to predict where neutralization will occur.

4.2.1.2.2 Word-final clusters

Turning now to word-final clusters of consonants, we find three possibilities not four. Sequences of an obstruent followed by a sonorant do not occur because there

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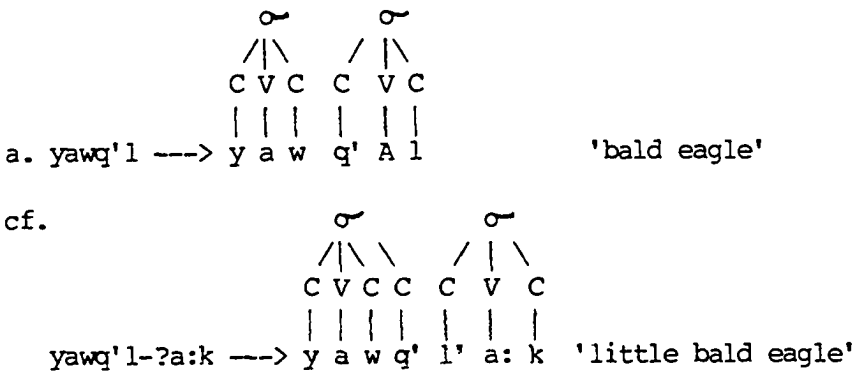
is a rule of presonorant epenthesis in the language which inserts a schwa, represented here as A, in front of a morpheme-final sonorant which is preceded by a consonant and followed by a word-boundary (or another consonant). Clements and Keyser suggest that this rule is triggered by the failure of the sonorant in such an environment to affiliate to any syllable.

(4.12) Presonorant epenthesis

$$C \overset{\wedge}{\underset{|}{}} R + \{\#, C\}$$
$$A$$

In the following examples, syllabification is shown following epenthesis:

(4.13)



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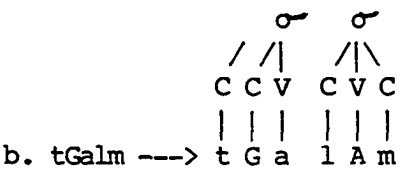
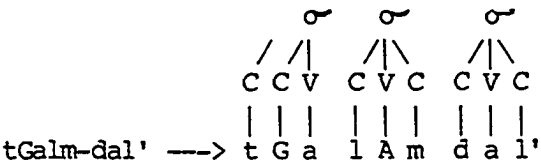


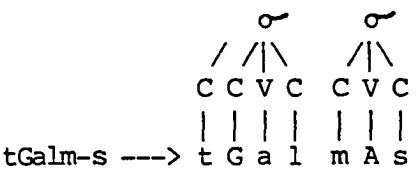
b. tGalm ---> t G a l A m 'west'

and



tGalm-dal' ---> t G a l A m d a l' 'toward the west'

cf.



tGalm-s ---> t G a l m A s 'west wind'

In the last case, presonorant epenthesis is bled by another epenthesis rule, which inserts a schwa in front of the nominalizing suffix /-s/.

Despite the fact that presonorant epenthesis applies even when the preceding consonant is a sonorant, as in (b), VCC# clusters where both consonants are sonorants do occur.

(4.14) Word-final clusters of two consonants

a. obstruent-sonorant: no cases because of presonorant epenthesis

b. obstruent-obstruent: T^O-T^O ***, T^O-s, s-T^O ***

c. sonorant-obstruent: R-T^O ***, R-s, except not R^h-s

d. sonorant-sonorant: R^V-R^V

*** Strictly speaking, these stops should be represented as

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T^h, but in order to avoid confusion with the use of the superscript h for aspirated stops in environments where glottal contrasts are maintained, the unaspirated stop symbols, T^o, will be used hereafter.

(4.15)

a. none

b. T^o-T^o:	p'awapk	'will eat'	T^o-s:	c'asGi:ps	'nighthawk'
	Glegatk	'dead'		Lo:ts	'bird embryo'
	ksiwl'aqt	'can dance'		c'e:ks	'sp. bird'
s-T^o:	gist	'being'		boqs	'camas root'
c. R^v-T^o:	kank	'that much, so much'	R^v-s:	?iLo:ls	'year'
R^h-T^o:	qoLt	'otter'			
R'-T^o:	sqel'am'c	'Old Marten'	R'-s:	?o:l's	'dove'

As indicated, presonorant epenthesis should prevent clusters of type (d) as well as type (a) from occurring word-finally, but one sequence of voiced sonorants was found, yn, in

d. R^v-R^v: t'eyn 'new'

Barker lists /yl/ as a possible word-final sonorant sequence, though not /yn/, but I was unable to find any examples. Syllable-finally, this sequence occurs, for example, in

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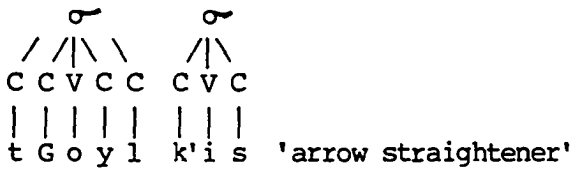
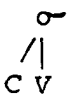
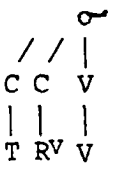


The most significant feature of these word-final clusters is the complete absence of any glottal contrasts for stops in either first or second position in the cluster. As shown by the examples in (4.15c), however, glottal contrasts are not neutralized for sonorants in the first position in a cluster. Taking these facts together with those obtained from the earlier examination of word-initial clusters, we can tentatively propose the following possibilities for syllable onsets and codas in Klamath:

(4.16)

a. syllable onsets

i. any single C: 

ii. any stop followed by a voiced sonorant: 

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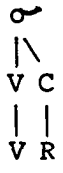
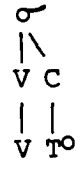
b. syllable codas

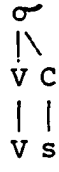
i. any sonorant:



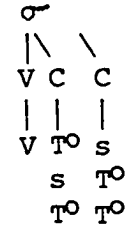
ii. any voiceless stop:



or /s/:



iii. voiceless stops and /s/ in either order:



iv. a sonorant followed by a voiceless stop or /s/:

Inspection of longer word-final clusters, illustrated in (4.17), shows that these patterns generalize:

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(4.17)

a. $S\text{-}T^{O}\text{-}T^{O}$: no example found; /s/ occurs freely in noninitial positions in final clusters, but is quite rare as C_1.

b. $T^{O}\text{-}S\text{-}T^{O}$:	nqotst	'scorching'
c. $T^{O}\text{-}T^{O}\text{-}S$:	steLapks	'right side'
d. $S\text{-}T^{O}\text{-}S$:	goWy'asqs	'venereal disease'
e. $T^{O}\text{-}T^{O}\text{-}S\text{-}T^{O}$:	latbambalyi:wapkst	'that one would be arriving with a round object for someone again'
f. $R^{V}\text{-}T^{O}\text{-}T^{O}$:	toqy'altk	'horned'
g. $R^{V}\text{-}S\text{-}T^{O}$:	lwelst	'slaying'
h. $R^{V}\text{-}T^{O}\text{-}S$:	celks	'skin'
i. $R^{V}\text{-}T^{O}\text{-}T^{O}\text{-}S$:	lwelpks	'slaying (durative)'

with a maximum of four consonants being possible. Clearly, there is no constraint on the position or order of stops, but if a sonorant of any type occurs in a final cluster, it is invariably first, right after the preceding vowel. The possibilities in word-final codas might be represented most generally as:

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(4.18)

where T may be any voiceless unaspirated stop or /s/ in any order.

4.2.1.2.3 Medial clusters

Medial clusters of two or three consonants are common in Klamath and under relatively restricted conditions even four or five consonants may occur side-by-side medially. The discussion will not treat these longer clusters explicitly, but they do not present any problems for the analysis proposed. The following possibilities for VCCV clusters are found:

(4.19)

a. obstruent-sonorant: $T\text{-}R^{V}$, $T^{O}\text{-}R$, s-R

b. obstruent-obstruent: $T^{O}\text{-}T$, s-T

c. sonorant-obstruent: $R^{V}\text{-}T$, $R^{h}\text{-}T$

d. sonorant-sonorant: $R^{V}\text{-}R$, $R^{h}\text{-}R$

For example:

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(4.20)

a. i.	T^h-R^V:	yoc^{h}laqcn'a	'foot slips'
	D-R^V:	jeGle	'blood'
	T'-R^V:	sik'nampga	'endures pain'
ii.	T^o-R^V = T^h-R^V		
	T^o-R^h:	q'atYa:w'as	'sp. of seagull'
	T^o-R':	mboty'a	'wrinkle from water'
iii.	s-R^V:	hiswaqs	'man'
	s-R^h:	sem'asLa	'moves, changes one's dwelling'
	s-R':	sw'esw'anga	'destroy, tear down (dist.)'

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b.	T^o-T^h:	?ikc^{h}i:ya	'goes to get plural objects for someone'
	T^o-D:	?itgalt	'can pick up plural objects'
	T^o-T':	k^{h}opk'as	'torch'
c. i.	R^v-T^h:	gank^{h}akc^{h}at	'can go hunting'
	R^v-D:	himbaks	'log'
	R^v-T':	loyk'atga	'been picking berries'
ii.	R^h-T^h:	?eMk^{h}anga	'go around in a line'
	R^h-D:	sat'wa:Ydaksc^{h}i	'worth helping'
	R^h-T':	sm'oq'aLt'alGa	'wets something down'
d. i.	R^v-R^v:	qbiwtgalwapk	'will suck out disease'
	R^v-R^h:	nt^{h}ewLi	'breaks into'
	R^v-R':	newl'aqs	'rule, law'
ii.	R^h-R^v:	?iWlapt^{h}a	'is away from against'
	R^h-R^h:	?iLWa	'pulls plural objects down flat onto'
	R^h-R':	?iWm'a:c'a	'is on the end, point'

If these medial clusters are syllabified according to the principles suggested for word-initial and word-final clusters, then in all cases but the stop-sonorant sequences in (a.i), the syllable boundary will fall between the two consonants:

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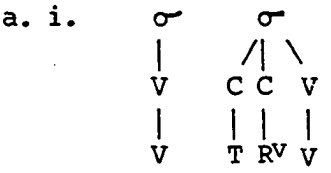
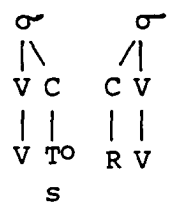
(4.21)

a. i.

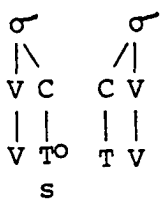


vs.

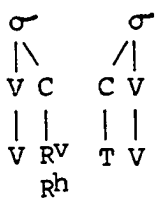
a. ii, iii.



b.



c.



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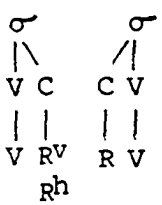

The consonants in first position in these clusters, which ended up being extrasyllabic in word-initial clusters: T^O, R^V, and /s/, and which were coda segments in word-final clusters, are also coda segments in medial clusters. The

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only class of segments which is not found in medial codas are the glottalized sonorants, R'. The glottalized sonorants can occur in codas in word final clusters, for example /psik'am'c/ 'big old nose' and in Barker's chart of medial clusters, /m'c/ is listed, but I have been unable to find any examples. Furthermore, glottalized sonorants which end up in medial codas as opposed to final ones as a result of morphological processes lose their glottalization, becoming simple voiced sonorants, R^V. Voiceless sonorants remain voiceless, however:

(4.22)

a. c'iya:l's	'salmon'
b. c'ic'ya:lk'a	'little salmon (dist.)'
cf.	
c. wic'o:Las	'fishnet'
d. wiwc'o:Lk'a	'little fishnets (dist.)'

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(4.23)

a. wt'am's 'lid, top'

b. wt'ambli 'puts a lid back on'

cf.

c. haYk^{h}anga 'tracks around'

d. haYGoga 'tracks into'

e. haYwallGa 'tracks up'

f. haYLi 'tracks inside'

(4.24)

a. m'ol'a 'suppurates'

b. m'ol's 'pus'

c. m'olye:ga 'starts to suppurate'

cf.

d. coLyo:ga 'takes off a shirt'

(4.25)

a. l'ocq'a:l'a 'bends the knee'

b. spaq'allGa 'folds a cloth'

cf.

c. q'aLgalbli 'is hurt again'

d. sq'aLtgi 'is, becomes hurt'

In each of these examples, a glottalized sonorant remains glottalized in word-final codas, as well as generally before vowels, but loses its glottalization in medial codas. Voiceless sonorants remain voiceless in all environments

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illustrated.

Glottalization is lost from coda position when glottalized sonorants vocalize, but when voiceless sonorants vocalize, the glottal feature survives as an /h/ offglide of the vowel created by vocalization. Glides vocalize between consonants (or between a consonant and a following word boundary), for example:

(4.26)

a. c'iWp'a 'sits on and bends'

b. pic'o:hp'a 'pulls and bends'

(4.26b) is derived in (c):

c. [pV [c'iWp'-a]]

c'iWp'a	1st cycle = 4.26a
	2nd cycle
pic'iWp'a	vowel copy
pic'AWp'a	vowel reduction
pic'o:hp'a	glide vocalization & dissociation of /h/.

The survival of the voiceless component of the sonorant as an /h/ suggests that the voiceless component remains associated to the consonant slot to which the voiceless glide was originally linked.

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where V C
\ / = o:
w

No trace of the glottalization of /w'/ or /y'/ survives the vocalization of the glide; for example, when /y'/ vocalizes in (4.26b) below, its glottalization disappears entirely:

(4.26)

a. ?iwy'aq 'put in plural objects!'

b. ksiwi:Ga 'puts a living object into a container'

A derivation of (4.26b) is given in (c):

c. [ksV [iwy'G-a]]

iwy'Ga	1st cycle
	2nd cycle
ksi-iwy'Ga	vowel copy
ksiwy'Ga	initial vowel deletion
ksiwAy'Ga	preglide epenthesis
ksiwi:Ga	vocalization and loss of glottalization

Clearly, unlike the voiceless component, /h/, of a voiceless sonorant, the glottalization, /?/, of a glottalized sonorant does not maintain any association to its original slot.

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Furthermore, if the /w/ in the stem /iwy'G/ rather than the /y'/ vocalizes and the /y'/ ends up in a syllable coda, as in (e) below, it predictably loses its glottalization:

d. ?iwi:Ga 'put plural objects into a container'

e. ?i?o:yGa 'put plural objects into a container (dist.)'

The second example is derived in (f):

f. [CV [?V [iwy'G-a]]]

iwy'Ga	1st cycle
	2nd cycle
?i-iwy'Ga	vowel copy
?iwy'Ga	initial vowel deletion ***
	3rd cycle
?i?iwy'Ga	reduplication
?i?Awy'Ga	vowel reduction
?i?o:y'Ga	glide vocalization
?i?o:yGa	deglottalization

*** This representation leads to (d) by the same derivational route as was illustrated in (c).

The loss of glottalization in medial syllable codas reflects a general loss of /?/ in this environment. As illustrated below, /V?/ is replaced by /V:/, i.e.

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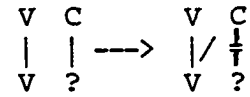

when the /?/ is followed by a consonant. As in the derivation in (f), deglottalization occurs in the derivation of (4.27b) in (4.27c), where an original glottal stop ends up in a syllable coda (necessarily before a consonant):

(4.27)

a. ?odi:la 'puts a long object underneath'

b. so:di:la 'puts a long object underneath one's arm'

(b) is derived in (c):

c. [sV [?V [odi:l-a]]]

odi:la	1st cycle
	2nd cycle
?o-odi:la	vowel copy
?odi:la	initial vowel deletion = 4.27a
	3rd cycle
so?odi:la	vowel copy
so?Adi:la	vowel reduction
so?di:la	vowel deletion
so:di:la	deglottalization and compensatory lengthening

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Glottalization is much more stable when /?/ is attached to a consonant slot which is in onset position. Neither /?/ nor /h/ is lost in syllable onsets when the oral features of a sonorant are detached from its original consonant slot. For example, in some homorganic sequences of sonorants, where the second is voiceless or glottalized, i.e. $R^{V}R^{h}$ or $R^{V}R'$, the sequence is replaced by Rh and R?, respectively.

(4.28)

a.	holLi ---> holhi	'runs inside'
b.	holl'a:l'a ---> hol?a:l'a	'jumps into the fire'
c.	hoyy'a:ya ---> hoy?a:ya	'runs in front of'
d.	momm'o:c'ak ---> mom?o:c'ak	'little ears'
e.	?iww'a:l'a ---> ?iw?a:l'a	'is on the end'
cf.		
f.	hollac'wi	'runs right up to'
g.	howwa	'runs, jumps into the water, flat place'
h.	hoWWasga	'runs off, away'

Further evidence of the stability of /?/ in onsets is provided by "floating glottalization". There are a fairly large number of morphemes in Klamath which have a final /?/ which appears as glottalization of the last consonant of the morpheme when it is followed by a vowel. This /?/ is not,

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however, inherent to the final consonant of the morpheme (In underlying forms, this contrast is represented as C? for morphemes with floating glottalization and C' for inherent glottalization). Floating glottalization can also be induced on the last consonant of a morpheme by certain suffixes, e.g. the diminuitive /-?a:k/. This /?/ behaves in exactly the same way as a morpheme-final /?/.

(4.29)

a.	wk'al'a	'cuts, severs with a long instrument'
b.	yakl'a	'cuts the foot'
c.	yak'al	'cut the foot!'

(4.30)

a.	le:mlem'a	'is dizzy'
b.	lemtgi	'gets dizzy'

(4.31)

a.	lamlam'a	'makes a thundering noise'
b.	lamlamcn'a	'goes along making a thundering noise'

(4.32)

a.	GoMGam'a	'is hollow on top'
b.	GoMGaml'i	'hollow on top (place name)'

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(4.33)

a. l̥ti:gl̥tik'a 'lopes, paces, tiptoes'

b. l̥tigl̥tiks 'Pacer (dog's proper name)'

c. l̥tigye:ga 'rises on one's toes'

The final consonants in these morphemes: (4.29) /k'al?/, (4.30) /lem?/, (4.31) /lom?/, (4.32) /GoM?/, and (4.33) /ltig?/, cannot be considered inherently glottalized. The copy of the stem-final consonant in the first syllable of the reduplicated forms in (4.32b) and (4.33a,b) shows that the stem-final consonant is voiceless /M/ and voiced /g/, respectively, rather than glottalized. If this consonant were inherently glottalized, we would expect */GomGom'a/ in (4.32a) with voiced /m/ rather than voiceless /M/ as a result of coda deglottalization and */l̥tik'l̥tik'a/ in (4.33a) and */l̥tik'l̥tiks/ in (4.33b). Compare /l̥?e:k'l̥?ek'a/ 'prickles', which has a inherently glottalized final consonant, with /k'/ in the reduplicated syllable. Because R' deglottalizes before a consonant, no contrast can be demonstrated between reduplicated forms of a morpheme which ends in R? and a morpheme which ends in R'; both will be realized as R^V in the reduplicated syllable.

In these examples, the place of origin of the floating glottal stop is to the right of the consonant that it is

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realized on. Clearly both stops and sonorants can be glottalized by floating glottalization to their right. There is another glottalization process which applies to sonorants alone, where glottalization arises before rather than after the sonorant. In the majority of cases where a morpheme beginning with a sonorant is reduplicated, the original sonorant, but not the one in the reduplicated syllable shows up glottalized; for example:

(4.34)

a. we:c'a 'slobbers'

b. wew'e:c'a 'slobbers (dist).'

(4.35)

a. yaNWa: 'weakly'

b. yay'aNWa:ni 'weak ones (dist.)'

(4.36)

a. le:w'a 'plays'

b. lel'e:w'a 'plays (dist.)'

(4.37)

a. no:ga 'is cooked, ripe, ready'

b. non'o:ga 'are cooked, ripe, ready (dist.)'

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(4.38)

a. manq 'housefly'

b. mam'anq'a:k 'little flies (dist.)'

Compare these cases with those below where the morpheme-initial sonorant was originally glottalized and a glottalized sonorant appears in the reduplicated syllable as well:

(4.39)

a. w'alq'acga 'fisher'

b. w'aw'alq'acga?a:k 'little fishers (dist.)'

(4.40)

a. y'aMtgi 'forgets'

b. y'ay'aMtgi 'forget (dist.)'

(4.41)

a. l'ocpga 'is kneeling'

b. l'ol'ocpga 'kneel (dist.)'

(4.42)

a. n'a:q'a 'brown bear'

b. n'an'a:q'a?a:k 'little brown bears (dist.)'

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(4.43)

a. m'a:k 'pubic, body hair'

b. m'am'a:ks 'body hair, fuzzy beard of young boy'

Reduplicative glottalization is not always found with morphemes beginning with sonorants; for example:

(4.44)

a. we:?as 'child'

b. wewe:?as 'children'

but it applies more often than not. The sonorant is predictably not glottalized when followed by a consonant rather than a vowel; for example:

(4.45)

a. wnak 'son'

b. wnawnak 'sons'

(4.46)

a. yeba 'digs, scrapes a hole'

b. yeyba 'dig (dist.)'

(4.47)

a. laGi 'misses someone, feels sad over an absence'

b. lalGi 'miss (dist.)'

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(4.48)

a. nt^{h}opt^{h}a 'chokes on a mouthful of food'

b. nt^{h}ont^{h}apt^{h}a 'choke, strangle (dist.)'

(4.49)

a. may 'tule'

b. mamy'a:k *** 'little tules (dist.)'

*** The glottalization of the /y/ here comes from the diminuitive suffix, /-ʔa:k/, not the reduplication.

Glottalization is absent here because the morpheme-initial sonorants occur in syllable codas rather than onsets.[4]

There is a clear asymmetry between the two glottalization processes discussed above. Both sonorants and stops can be glottalized by a following floating glottal stop, but only sonorants are glottalized by a preceding one. No morpheme-initial stop which is not glottalized in nonreduplicated forms acquires glottalization in reduplicated ones. This asymmetry is, I believe, a subtle confirmation of the binding hypothesis, which predicts that glottal features will be bound to the release of a stop, but not anchored to any particular point in the articulation of sonorants. Floating glottalization can be linked to a stop so long as it originates after the stop, on the same "side" as the release. Sonorants can accept glottalization freely from

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both preceding and following floating glottal stops because they lack any salient acoustic event comparable to the stop release to which glottalization must be anchored. It remains unclear, therefore, whether glottalized sonorants in Klamath should be analyzed as preglottalized -- the mirror image of stops -- or as postglottalized.[5] The voiceless sonorants are similarly ambiguous.

To sum up, only voiced and voiceless sonorants are found in medial as well as final codas. Deglottalization in codas is a process delinking a glottal stop from its consonant slot. The neutralization of contrasts is much more thorough-going for stops than it is for sonorants: only voiceless unaspirated stops (T^{O}) are found in syllable codas.

Medial clusters of three or more consonants present a novel twist on the distributions already seen. The following patterns are found:

(4.50)

a. when the first consonant is a voiceless unaspirated stop (T^{O}), /s/, or a voiced sonorant (R^{V}), i.e. a coda segment, then any of the patterns illustrated in (4.20)

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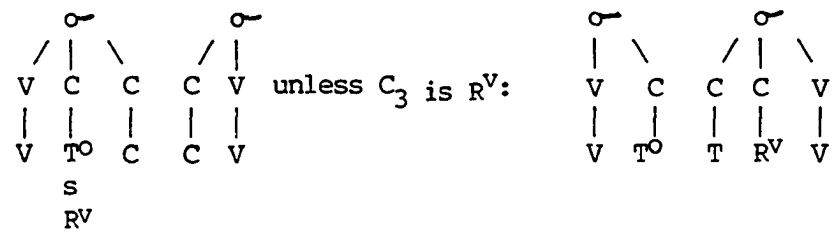
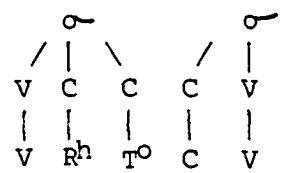
can found in the second and third positions; as the contrast between the two patterns below shows, unless C_3 is a voiced sonorant, there will only be a single consonant in the onset of the following syllable.



b. when the first consonant is a voiceless sonorant (R^h), however, the second consonant may only be a voiceless unaspirated stop (T^O), but the third consonant may be a voiced stop (D), an ejective (T'), or a glottalized sonorant (R'). The gaps in the third position in such clusters are probably accidental since they would be syllabified:



c. when the second consonant is a voiced sonorant (R^V), the first consonant may be any stop (T^h, D, T') or a voiced or voiceless sonorant (R^V, R^h). In these clusters, any consonant can occur in third position. Since the

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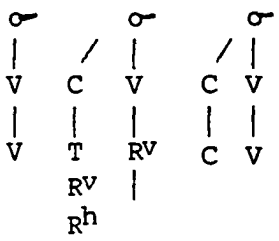
second consonant is syllabic in such clusters they can be syllabified:



The strongest evidence for the syllabification in (c) is that glottal contrasts in stops are not neutralized in first position in these clusters. Note, however, that the only sonorants that occur in first position in such clusters are those which can occur in syllable codas; no glottalized sonorants are found. Though the distributional evidence is therefore ambiguous, the maintenance of glottal contrasts for stops, otherwise entirely neutralized in codas, suggests that C_1 could be considered an onset position in these clusters. The reason for assuming this is that the neutralization of glottal contrasts for stops seems to more sensitive to position in syllable than neutralization of glottal constrasts in sonorants. Examples are given below of this third type of cluster:

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(4.51)

a. $C_1 = T^h$: mak^{h}l̥q^{h}a 'camps at'

b. $C_1 = D$: wt^{h}ogl̥k^{h}i 'comes to beat someone'

c. $C_1 = t'$: Ga:yak'l̥gi 'comes to search for'

d. $C_1 = R^v$: pecq^{h}all̥Ga 'puts the foot down through'

e. $C_1 = R^h$: ?iWl̥alli:na 'is all along the edge, bank'

4.2.1.2.4 Summary of the discussion of consonant clusters

In the preceding discussion, an attempt has been made to show that the distribution of the various kinds of stops and sonorants in Klamath is sensitive to the position in the syllable the consonant occupies. Onsets have been identified as the site where the maximum number of glottal distinctions for both stops and sonorants are maintained. In codas, on the other hand, neutralization of glottal contrasts occurs -- complete for stops, but only partial for sonorants. Furthermore, one type of complex onset, a stop folowed by a voiced sonorant, has been suggested. The distribution of stops in initial and medial clusters revealed that, with one exception, glottal contrasts are only found on

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the last stop in the cluster, the one which immediately preceded a more sonorant segment and the one which is invariably in a syllable onset. The exceptional cases are those three consonant medial clusters where the second consonant is a voiced sonorant, before which any of the three contrasting stop types in Klamath may occur. It was suggested that glottal contrasts could be maintained in the first position of such clusters because sonorants become syllabic when they occur in between consonants. This allowed the preceding consonant to be, in effect, an onset segment.

It is shown in the next section that allowing complex onsets of the form TR and establishing internal syllables in V.CR.CV clusters creates considerable difficulties for the operation of a rule deleting vowels which are in open syllables. If they are allowed, both complex onsets and cluster-internal syllables would have the effect of making the preceding syllable open. If these syllables are open, vowel deletion should apply to their vowels, but it does not. I will show in the next section that the way to avoid these difficulties is to first syllabify words so that at most one consonant occurs in an onset at the stage in the

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derivation when vowel deletion applies. Furthermore, at this stage in the derivation medial VCR.CV clusters will have no internal syllable -- the sonorant in second position will in fact be left unsyllabified until quite late in the derivation. Following the application of vowel deletion, at a relatively late stage in the derivation, Klamath words will be resyllabified in the way outlined in the preceding sections. The maintenance or neutralization of glottal contrasts for stops and sonorants refers to this second, more superficial syllabification rather than the first, more abstract one.

4.2.1.3 Vowel deletion and uniform syllabification

When a prefix of the shape C(C)V is attached to a stem in Klamath, the stem vowel is reduced to schwa. This schwa is subsequently deleted if the stem syllable is open, but retained if the syllable coda contains at least one consonant (cf. Clements & Keyser 1983). In the forms on the left below, only reduction applies, while those on the right are also subject to deletion of the reduced vowel -- two forms are given for each

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example, the first without a prefix to show the original stem vowel and a second prefixed form showing vowel reduction or deletion:

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(4.52)		(4.53)	
	Vowel reduction	Vowel deletion	
a. 'pays attention'	Geqc'a	wik'a:	a. 'near'
b. 'pay attention to each other'	seGAqc'a	wiwk'a:	b. 'near (dist.)'
c. 'cheats'	sditGa	sq'am'a	c. 'beats someone in a fight'
d. 'cheat (dist.)'	sdisdAtGa	hosqm'a	d. 'beat each other'
e. 'is ashamed, shy'	ndecgi	ndoc'a	e. 'freezes'
f. 'are ashamed, shy (dist.)'	ndendAcgi	ndontc'a	f. 'freeze (dist.)'
g. 'is lying flat on the back'	wLetpga	wLic'a	g. 'shakes out'
h. 'are lying flat on the back'	wLewLAtpga	wLiwlc'a	h. 'shake out dist.'
i. 'tangles up something'	sw'elwa	sl'aba	i. 'blooms'
j. 'tangle up something dist.)'	sw'esw'Alwa	sl'aslba	j. 'bloom (dist.)'

Derivations of (4.52i) and (4.53i) are given below to illustrate the vowel reduction and deletion processes:

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(4.54) [CCV [wLet' [obg-a]]]

	1st cycle
wLet'bga	initial vowel = 4.52h deletion
	2nd cycle
wLewLet'bga	reduplication
wLewLAt'bga	vowel reduction
n.a.	vowel deletion
wLewLAtpga	neutralization

(4.55) [CCV [wLic'-a]]

wLic'a	1st cycle = 4.53h
	2nd cycle
wLiwLic'a	reduplication
wLiwLAc'a	vowel reduction
wLiwLc'a	vowel deletion
wLiwlc'a	sonorant syllabification

Note that as a result of vowel deletion, the sonorants in (4.53i,j) are trapped between consonants and both become syllabic voiced sonorants.

The essential difference between all the forms on the left in (4.52) where only vowel reduction applies and those on the right in (4.53) where vowel deletion

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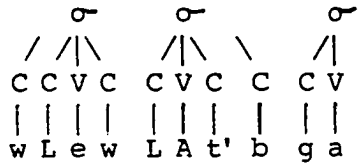
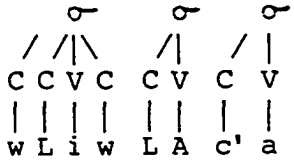
applies, too, is that the reduced vowel is in a closed syllable in (4.52) but in an open one in (4.53). Syllabifications for the forms derived in (4.54) and (4.55) at the stage when vowel deletion applies are given below:

(4.56)



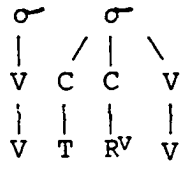
(4.57)



Now, if, as these forms show, vowel deletion is sensitive to whether the reduced vowel is in an open syllable or not and if medial sequences of a stop followed by a voiced sonorant are tautosyllabic; i.e.

(4.58)

a.



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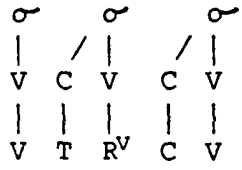

then vowel deletion should apply before such sequences. The following forms show that it does not:

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(4.59)

a. selq'ibli 'drives something back on the road'

b. selAq'yo:la 'drives off the road'

c. toq'ɬGa 'stops an action'

d. totAq'ɬGa 'stops (dist.)'

These forms are derived below:

(4.60)

a. [sV [lV [eq'y-ebli]]]

	1st cycle
eq'ybli	initial vowel deletion
	2nd cycle
le-eq'ybli	vowel copy
leq'ybli	initial vowel deletion
leq'Aybli	preglide epenthesis
leq'i:bli	glide vocalization
	3rd cycle
seleq'i:bli	vowel copy
selAq'i:bli	vowel reduction
selq'i:bli	vowel deletion

In this case, vowel deletion applies because the syllable containing the schwa is open as a result of glide

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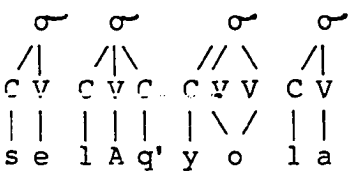
vocalization on the previous cycle; compare:

b. [sV [lV [eq'y-o:la]]]

eq'yo:la	1st cycle
	2nd cycle
le-eq'yo:la	vowel copy
leq'yo:la	initial vowel deletion
	3rd cycle
seleq'yo:la	vowel copy
selAq'yo:la	vowel reduction
n.a.	vowel deletion[6]

In this case, even though the sequence /q'y/ following the reduced vowel consists of a stop followed by a voiced sonorant, which if it were a complex onset would leave the preceding syllable open, the schwa still does not delete. At the stage when vowel deletion applies, this form must, therefore, be syllabified:

(4.61)



The derivation of the other two forms in (4.59) is given below:

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(4.60)

c. [toq' [el'G-a]]

el'Ga	1st cycle
	2nd cycle
toq'l'Ga	initial vowel deletion
toq'$_{\text{i}}$lGa	sonorant syllabification

d. [CV [toq' [el'G-a]]]

el'Ga	1st cycle
	2nd cycle
toq'l'Ga	initial vowel deletion
	3rd cycle
totoq'l'Ga	reduplication
totAq'l'Ga	vowel reduction
n.a.	vowel deletion
totAq'$_{\text{i}}$lGa	sonorant syllabification

The failure of vowel deletion to apply in (d) requires that it be syllabified:

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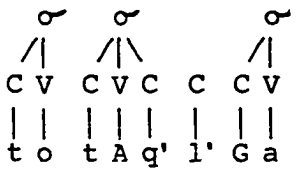
(4.62)



with the sonorant /l'/ not affiliated with any syllable. In both (4.59b) and (4.59d), then, where the maintenance of glottal contrasts in the stops would lead us to syllabify them with the following voiced sonorant, that syllabification will give the wrong results when vowel deletion applies.

If both vowel deletion and the distribution of stops are to depend on syllabification, we must assume that Klamath words are initially syllabified so that syllables begin with at most a single consonant. Relatively late in a derivation, after the application of vowel deletion, any stop which is followed by a sonorant is resyllabified, so that it ends up in the onset of the following syllable. The forms in (4.61) and (4.62) are resyllabified below:

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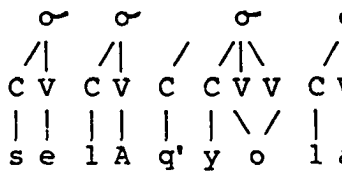
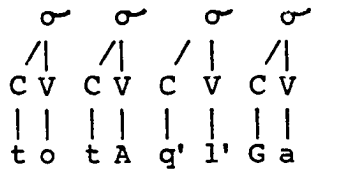
(4.63)

a.



b.



This resyllabification is presumably what triggers the syllabification of the sonorant in (b); this could be formulated as substituting a V for the C that dominates it. Following resyllabification, neutralization of glottal contrasts occurs for all stops which still languish in syllable codas.

Such an approach has a certain intuitive appeal if one considers that syllable structure is being put to two quite different uses in Klamath. On the one hand, vowel deletion, which is sensitive to whether there is a tautosyllabic consonant following the reduced vowel, is insensitive to what kind of consonant that is. All that matters is that if there is at least one, the rule fails to apply. In structural terms, all that matters is whether the syllable rime branches or not.[7] The rule is essentially quantity-sensitive, applying only in light syllables, and its effect is to eliminate such a syllable.

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On the other hand, all the evidence presented regarding the distribution of stops and sonorants in Klamath shows that it is precisely the nature, i.e. the feature content, of neighboring segments which determines where glottal contrasts are maintained or neutralized. Specifically, the various kinds of stops are distinguished only before more sonorant segments, ideally vowels, but in a pinch, sonorants as well.[8] That the condition on the distribution of stops is strictly local and quite superficial is entirely in keeping with the perceptual motivation of the binding hypothesis. If only stops which precede more sonorant segments can bear distinctive glottal features, then these features can be packed into the interval of rapid acoustic modulation which carries the bulk of the cues to the paradigmatic contrasts in the language.

If resyllabification is a possibility, then the distribution of stops can, like vowel deletion be stated in terms of syllable structure. An analysis which allows resyllabification after vowel deletion expresses an essential functional difference between syllable onsets and rimes. Onsets are the sites where paradigmatic contrasts are maximized, while in rimes,

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often at the expense of a loss of paradigmatic contrasts to neutralization, it is simply the number of segments -- in more abstract terms, the weight of the syllable -- which is important. I am not claiming here that paradigmatic contrasts will be entirely absent in syllable codas, just that neutralization is more likely there. Furthermore, evidence from stress rules shows that the number of segments in a syllable rime is often important for determining whether a syllable will be stressed or not, but there apparently are no examples of stress rules which are sensitive to the number of segments in syllable onsets.

In Klamath, for vowel deletion to apply properly the structure of particular rimes must be established early in the derivation, while one may be equally economical in stating the distribution of stops by waiting to establish the ultimate content of onsets until nearly the very end of the derivation.

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4.2.3 Variations on the theme

4.2.3.1 The structure of Cambodian onsets

Some languages do not restrict the appearance of glottal contrasts to the last stop in a cluster. In Cambodian (Huffman 1972, see also Halle & Clements 1983), glottal contrasts are instead a feature of the entire cluster rather just its last member. The following two-consonant clusters occur in this language:

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(4.64)

	C_1	C_2		C_1	C_2		C_1	C_2 ***
1a.	p	h	1b.	s	p m w	1c.	p^h	p m w
	t	s			t n l r		t^h	t n l
	c	r			ɲ		c^h	c ɲ y
	k				k ŋ		k^h	k ŋ

*** C_1 may not have the same place of articulation as C_2.

	C_1 ə	C_2		C_1 ə	C_2
2.	p	ɓ	3.	m	p b m w
	t s	ɗ		l	t d s n l r
	c				c ɲ
	k				k ŋ
		ʔ			ʔ h

Clusters of type (3), where the first consonant is a sonorant, will not be discussed further, except to note that the epenthetic schwa occurring between the two consonants appears regardless of the type of the following consonant (only /y/ seems to be missing from second position in these clusters).

The patterns illustrated by clusters of types (1) and (2) become clear once the consonants are classified in terms of their glottal features -- the features [spread] and

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[constricted] refer to the degree of abduction/adduction of the glottis (Halle & Stevens 1971):

(4.65)

[+spr, -constr, -voice]	[-spr, -constr, -voice]	[-spr, -constr, +voice]	[-spr, +constr, +voice]	[-spr, +constr, +voice]
	p^h	p	m w	ɓ
s	t^h	t	n l r	ɗ
	c^h	c	ɲ y	
	k^h	k	ŋ	
h			?	

The feature [voice] is actually irrelevant to the patterning of clusters in Cambodian but is included in the chart above so that its relationship to the other glottal features can be seen. The possibilty of a three-valued feature for glottal aperture, e.g. [adducted], where [1 adducted] = [+constricted], [Ø adducted] = [-constricted,-spread], and [-1 adducted] = [+spread] (cf. Ladefoged 1971) should be entertained and some evidence in support of it is presented below.

The classification above makes the patterns in clusters of types (1) and (2) obvious: 1) either the first or second consonant is [+spread] and the other is [-spread], or more

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generally, when the first consonant is [a spread], the second consonant is [-a spread], and 2) when the second consonant is [+constricted], a schwa is inserted between it and a preceding [-spread] segment.

If the aspiration of voiceless stops before [-spread] segments, i.e. their transformation from [-spread] to [+spread] is seen as an insertion of a [+spread] segment, then in clusters where the first and second consonants are both stops, i.e. [-continuant,-sonorant], types (1c) and (2), then the inserted segment is one degree less adducted than the second consonant. Aspiration could be considered a voiceless vowel of neutral quality. The schwa inserted between the [-spread] consonants /p t c k/ and the [+constricted] consonants /ɓ ɗ ʔ/ is, on the other hand, [-spread,-constricted]. Clusters of these two types can be represented as follows:

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(4.66)

1c.
$$\begin{matrix} & & & & V & & \\ & & & & | & & \\ \begin{bmatrix}-\text{cont}\\-\text{spr}\\-\text{constr}\end{bmatrix} & *** & \begin{bmatrix}+\text{spr}\\-\text{constr}\end{bmatrix} & & & \begin{bmatrix}-\text{cont}\\-\text{spr}\\-\text{constr}\end{bmatrix} \end{matrix}$$

2.
$$\begin{matrix} & & & & V & & \\ & & & & | & & \\ \begin{bmatrix}-\text{cont}\\-\text{spr}\\-\text{constr}\end{bmatrix} & *** & \begin{bmatrix}-\text{spr}\\-\text{constr}\end{bmatrix} & & & \begin{bmatrix}-\text{cont}\\-\text{spr}\\+\text{constr}\end{bmatrix} \end{matrix}$$

*** This feature matrix includes the stops /p t c k/ but not the fricative /s/, see below.

where the inserted element in both cases is one degree less adducted than the following one.

The fact that the inserted segment is one degree less adducted than the segment to its right is the strongest piece of evidence in the language for a nonbinary glottal feature. An epenthetic element is inserted either when the adjacent segments have the same glottal aperture underlyingly (1c), when they differ by one degree (2), or when they differ by two degrees as in the clusters of type 2 where the first consonant is the inherently [+spread] /s/. Clusters of this last type have the following structure:

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(4.67)

$$\begin{bmatrix}+\text{cont}\\+\text{spr}\\-\text{constr}\end{bmatrix}\ \overset{V}{\begin{bmatrix}-\text{spr}\\-\text{constr}\end{bmatrix}}\ \begin{bmatrix}-\text{cont}\\-\text{spr}\\+\text{constr}\end{bmatrix}$$

Apparently, a [-spread,-constricted] segment is invariably inserted before [-spread,+constricted] segments, regardless of the degree of glottal adduction of the preceding segment. This possibility can only be squared with the patterns illustrated by the other consonant clusters in Cambodian if we admit that it is the degree of adduction of the last consonant in the cluster -- the prevocalic one -- which determines the glottal events that can occur within the cluster.[9]

The statements in (4.66) and (4.67) can be collapsed, i.e. the patterns of consonant clusters in Cambodian can be represented in such a way that /s/ forms a natural class with the voiceless unaspirated stops /p,t,c,k/, as in (4.68):

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(4.68)

a.
$$\begin{array}{ccc} & V & \\ & | & \\ \left[\begin{array}{l}\text{a cont}\\ \text{a spr}\\ \text{-constr}\end{array}\right] & \left[\begin{array}{l}\text{+spr}\\ \text{-constr}\end{array}\right] & \left[\begin{array}{l}\text{-cont}\\ \text{-spr}\\ \text{-constr}\end{array}\right] \end{array}$$

b.
$$\begin{array}{ccc} & V & \\ & | & \\ \left[\begin{array}{l}\text{a cont}\\ \text{a spr}\\ \text{-constr}\end{array}\right] & \left[\begin{array}{l}\text{-spr}\\ \text{-constr}\end{array}\right] & \left[\begin{array}{l}\text{-cont}\\ \text{-spr}\\ \text{+constr}\end{array}\right] \end{array}$$

which can in turn be collapsed into:

c.
$$\begin{array}{ccc} & V & \\ & | & \\ \left[\begin{array}{l}\text{a cont}\\ \text{a spr}\\ \text{-constr}\end{array}\right] & \left[\begin{array}{l}\text{b spr}\\ \text{-constr}\end{array}\right] & \left[\begin{array}{l}\text{-cont}\\ \text{-spr}\\ \text{-b constr}\end{array}\right] \end{array}$$

This requires a rule reducing a sequence of [+spread] segments, specifically, /s^{h}/, to just a single [+spread] segment, /s/. This rule is motivated by the dissimilation of the feature [spread] already described.

It should be noted that /r/ does not fit neatly into the scheme proposed here since it appears to be both [+spread], as in /pr/, /tr/, etc. and [-spread], as in /sr/. The structure of these clusters can probably better be described in terms of the sonority sequencing condition (Donca Steriade p.c.), rather than in terms of the glottal features of their members. Note that clusters of type 3 are not covered by the dissimilation of glottal features seen in

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the other types either, so it would be necessary in any case to assume that the cluster possibilities in Cambodian were determined by more than a single criterion.

4.2.3.2 An apparent difficulty -- Attic Greek

In Attic Greek, when a word ending in a vowel is procliticized to one beginning with a vowel bearing the 'rough breathing', symbolized here as a superscript /^{h}/, the vowels contract into a single nucleus and the rough breathing is realized as aspiration of the preceding voiceless stop, if there is one (Steriade 1982: 154 ff.), e.g.

(4.69)

a. 'and the other'	kai ^{h}ateros ---> k^{h}ateros
b. 'the garment'	to ^{h}imation ---> t^{h}oimation
c. 'entrance'	pro ^{h}odos ---> p^{h}roudos
d. 'driving four horses'	tetra ^{h}ippos ---> tet^{h}rippos
e. 'of seven days'	^{h}epta ^{h}emeros ---> ^{h}ep^{h}t^{h}emeros
f. 'night whole (acc. sg.)'	nukta ^{h}olen ---> nuk^{h}t^{h}olen

In the first four examples above (a-d), the aspiration of the stop can be understood as a straightforward dissociation of /^{h}/ from the following vowel as a result of the contrac-

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tion of that vowel with the preceding one, followed by its reassociation with the final segment of the preceding onset (when it is a stop; sonorants are not aspirated in Greek). The same reassociation links the /^{h}/ to the last stop in the stop clusters in the last pair of examples (e,f). The /^{h}/ set adrift by contraction is realized in all cases as a release feature of the preceding stop, or, in the terms proposed here, is bound to the release of the tautosyllabic stop. Contraction makes /^{h}/ tautosyllabic with the stop it binds to.

This binding is similar to a process discussed by Ohala (1979) in his explanation of dissimilation. He argues that when a vowel is flanked on both sides by consonants which perturb it in similar ways, e.g. both aspirated, glottalized, or nasalized, the vowel will be so strongly perturbed that listeners may not be able to tell which of the flanking obstruents is the source of the perturbation. Dissimilation will result when the listeners take their turns as speakers and arbitrarily resolve their earlier perceptual quandary by designating either the pre- or post-vocalic consonant as the source of the perturbation. In the case of the 'rough breathing' under consideration here, the vowels which contract are both likely to be perturbed by the /^{h}/. Since

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this perturbation is produced by air rushing rapidly through the open glottis, it is perceptually similar to the effect an aspirated stop would have on an adjacent vowel; and, therefore, the realization of the /^{h}/ as aspiration of the preceding stop is not especially surprising.

The aspiration of the nonprevocalic stops in the clusters in the last pair of examples (e,f) is a result of assimilation to the now aspirated prevocalic stop which follows. The binding hypothesis predicts that the /^{h}/ would only be bound to the stop which is released into a vowel. Steriade (1982) suggests that these nonfinal stops are not aspirated directly by the reassociation of the /^{h}/ but instead by a later rule assimilating a nonfinal stop in a cluster to the glottal features of a stop following it (the rule actually only applies when the following stop is a coronal). This separation of the processes by which the two stops become aspirated removes the difficulty these examples present to the binding hypothesis, since the crucial claim of this hypothesis is that a distinctive glottal feature will preferentially associate with the last stop in a prevocalic cluster, bound temporally to its release. Assimilation is simply another means of neutralizing glottal contrasts in positions other than before vowel. The Attic data

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creates no difficulty for this claim since the /^{h}/ does associate with that stop in all the examples in (4.69). Nonfinal aspiration is not, however, distinctive in these clusters, since it arises as the result of a regular assimilation. Anticipatory spreading of aspiration (as well as voicing) eliminates clusters in Attic which are heterogeneous for glottal features (as noted above similar facts can be found in Kabardian). These facts, therefore, show that the binding hypothesis is essentially a statement about the well-formedness of surface strings, which is not terribly surprising given its likely perceptual motivation.

4.2.3.3 A second apparent difficulty — "preaspiration" in Icelandic and Southern Paiute

In Icelandic (Thrainsson 1978) and Southern Paiute (Sapir 1930), geminate stops are realized as preaspirated stops. This would appear to make it impossible to claim that languages completely avoid letting glottal features surface in the transition to as well as from a stop, especially since Icelandic, though not Southern Paiute, has distinctive postaspiration of stops as well. In other words, [+spread] can be realized on either side of a stop in that

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language.

A reanalysis of preaspirated stops is possible in Icelandic, which avoids allowing glottal features per se to surface before as well as after stops. Heterorganic stop clusters such as /pt/ and /kt/ are typically realized as a fricative followed by a stop, i.e. as [ft] and [xt], respectively (sonorants also devoice in this position). Preaspiration of geminates could be seen as a variation on the spirantization of the first stop in a cluster of stops, though one would expect the resulting fricative to have the same place of articulation as the stop it came from, rather than being laryngeal. Unfortunately, the development of preaspirated stops from geminates cannot be analyzed as a spirantization of the initial half of the geminate, because of the strong and rather ubiquitous restrictions against the two halves of geminates (at least tautomorphemic ones) being individually subject to phonological rules. In this context, it is particularly appropriate to note that postvocalic spirantization of stops in Hebrew and the Ethiopian Semitic languages (where only the velars /k/ and /k'/ are susceptible) does not apply to the first component of geminates (Sampson 1973, Barkai 1974, Schein 1981, Kenstowicz 1982).

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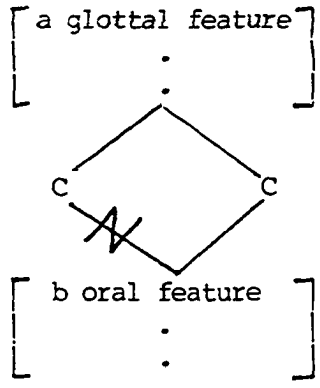
If this constraint is assumed to hold in Icelandic and Southern Paiute, then preaspiration of geminates cannot be the result of the spirantization of the first half of the geminate. It would therefore appear that glottal articulations are not universally bound to stop releases, but can in particular languages bind to other parts of the stop. Two considerations show, however, that the binding hypothesis is not falsified by the Icelandic and Southern Paiute facts. First, spirantization was an unlikely route to preaspiration anyway, since it should produce an oral rather than a laryngeal fricative. Preaspiration could instead be the result of dissociation of the oral features of the stop from the first half of the geminate, as Thrainsson has argued. A schematic representation of the dissociation of the oral features from the first consonant slot in the geminate is given in (4.70):

(4.70)



then the laryngeal fricative can be obtained directly. The

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restrictions against phonological rules applying to just half of a geminate do not as far as I know bar delinking, but instead prohibit the linking of some other feature, such as [+continuant] in Semitic spirantization, to only half of a geminate. Second, the preaspirated stops in both Icelandic and Southern Paiute continue to behave as two consonants. In Icelandic, only short vowels can precede consonant clusters and preaspirated stops, and in Southern Paiute unstressed vowels devoice before preaspirated stops, but not before simple voiceless ones. Both of these facts suggest that preaspirated stops (geminates) close the preceding syllable, which is only possible if they are in fact biconsonantal. In other words, although geminates are phonetically preaspirated stops in both languages, they continue to behave phonologically like a sequence of two consonants. Neither case, then, needs to analyzed as a binding of aspiration to a stop closure; they are instead clusters of an /h/ followed by a stop.

4.3 The nature of glottalized sonorants

In the examples discussed above, glottal features were shown to be preferentially bound to the stop immediately

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preceding a vowel. In all these examples, segments of equal and maximum obstruency competed for the glottal feature; the winner was the stop whose release would be most perceptually salient. A different outcome is observed when a glottal feature is introduced by a segment of lesser obstruency, such as a fricative or a sonorant, especially when that segment occurs after a vowel rather than before it. Though they are not especially common in the world's languages taken as a whole, glottalized sonorants and even glottalized fricatives are frequently encountered in the American Indian languages of the Pacific Northwest and California. The behavior of glottalized sonorants in the Wakashan languages and in Yokuts is discussed in the following sections.

4.3.1 Glottalized sonorants in Wakashan

In the Wakashan languages spoken on Vancouver Island, glottalization floats off sonorants under certain circumstances, while remaining stablely linked to stops under the same circumstances. (Glottalized fricatives do not occur overtly in either group.)

Within Wakashan, glottalized sonorants are only found

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immediately before vowels. In Nootka and Kwakw'ala (= Kwakiutl), they occur at the beginning of both words and syllables, after both consonants and vowels medially. Since there are extensive correspondences between the glottalized sonorants of the two languages, they clearly must be set up for the protolanguage (Sapir 1938); for example, N(ootka) /y'ak-/ 'in view, peering out, having one's neck stretched', K(wakw'ala) /y'əx^{w}-a/ 'land looms up'; N /m'ok^{w}-/ 'stone', K /m'ək^{w}-/ 'a round thing somewhere'; and N /n'op-/ 'one', K /n'əm-/ 'one'. Despite the fact that in many instances the glottalized sonorants can be reconstructed back to the protolanguage, Sapir was also able to show that many cases of medial glottalized sonorants in these two languages are secondary developments, the result of coalescence of /ʔ/ with an originally nonglottalized sonorant, either from *ʔVR > ʔR > R' or *Rʔ > R'.

Glottalized sonorants have decayed considerably, however, in Nootka's closest relatives, Nitinat and Makah (Jacobsen 1968, Gamble 1977). The glottalized sonorants have disappeared without a trace from the beginning of the word in these languages, e.g. (data from Jacobsen 1968; the following special symbols are used: H = voiceless pharyngeal fricative and 9 = pharyngealized glottal stop; L = voiceless

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lateral fricative):

(4.71)

		Nootka	Makah	
*w'	'cedar bark apron'	w'anus(.-)	wadis	'skirt, dress'
*y'	'younger sibling'	y'uk^{w}i:qsu	yuk^{w}i:qs(u)	id.
*m'	'raining'	m'itL-	bitL-	id.
*n'	'to sew'	n'iq-	diq-	id.
*l'	'Nimkish Indians'	n'imqi:$\underset{\vee}{s}$-?atH	limqi:$\underset{\vee}{s}$atX	id.

Note that ProtoWakashan nasals have become the corresponding voiced oral stops in Makah; this development is also found in Nitinat. These correspondences of Nootka R' to Makah R should be contrasted with the R:R correspondences illustrated by the following cognate sets:

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(4.72)

	Nootka	Makah	
*w 'to go home'	waL.-	waL-	id.
*y 'to step'	yac.-	yac-	'to step, kick'
*m 'sockeye salmon'	ma9a:t	biq'a:t	id.
*n 'strong, firm'	naš̆.-	daš̆-	id.
*l 'having'	napx-, napX^{w}	lupX-	id.

This contrast shows that Nootka has retained the *R':R contrast which has been lost at the beginning of words in Makah (and Nitinat).

Medially, in both Nitinat and Makah, a glottalized sonorant also loses its glottalization, but if the preceding segment is a short vowel, that vowel is compensatorily lengthened. This process is quite regular in Makah, but variable in Nitinat, where, as Gamble (1977) convincingly argues, the sound change is still working its way through the lexicon. For this reason, examples will again only be presented for Makah (Jacobsen 1968):

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(4.73)

		Nootka	Makah	
*w'	'steel-head salmon'	qiw'aH	qi:waX	id.
*y'	'picking berries'	cay'ax	ca:yax	id.
*m'	'wild rhubarb'	hum'a:q	hu:ba:q	id.
*n'	'smelt'	man'u:	ba:dawi	id.

(The status of /l'/ in the protolanguage is quite uncertain and no examples of medial correspondences for this phoneme are available in my sources.) If the medial sonorant was originally not glottalized, on the other hand, no lengthening of a preceding short vowel occurs, e.g.

(4.74)

		Nootka	Makah	
*w	'deer'	muwač	buwač-, bukʷač	id.
*y	'hat'	ciyapuxsim	ciyapuxʷs-, cikya:puxʷs	id.
*m	'horse clam'	ʔami:q	q'abi:q	id.
*n	'wedge'	tLanat	tLadit	id.

No trace of the original glottalization is found after long vowels, either, e.g.,

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(4.75)

		Nootka	Makah	
*w'	'to steal'	ku:w'iL	ku:wiL	id.
*y'	'interpreting'	9u:y'ap	q'u:ya:p	id.
*m'	'new canoe'	tLa:m'aq-ak	tLa:baq-ak	id.
*n'	'drift whale, food, thing found adrift'	hu:n'i:	hu:di(:)	id.

As Jacobsen argues, the loss of glottalization from sonorants in Makah and Nitinat results from their reanalysis into a ?R cluster. Since no clusters of any kind occur at the beginnings of words in any Wakashan language, the glottal stop would be lost from in front of the sonorant in this position following reanalysis. Glottalization is also lost without a trace from glottalized sonorants which immediately followed another consonant in medial cluster, showing that the constraint which brings about deglottalization is a one against consonant clusters in syllable onsets generally. Glottalized and laryngeal consonants: including ejectives, glottalized sonorants, /?/, and /h/, do not occur between a vowel and a consonant in these languages. Since at most two consonants can occur side-by-side in medial clusters and no

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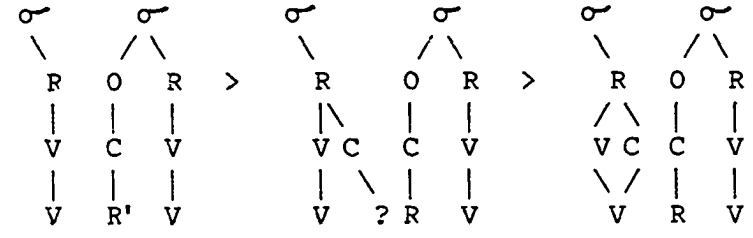
clusters are found in syllable onsets, medial clusters have a syllable boundary between the two consonants. This means that the failure of glottalized and laryngeal consonants to occur before another consonant is a restriction against these consonants occurring in coda position. Given this restriction, the /?/ resulting from reanalysis of R' to ?R in intervocalic position should be lost as well.

The compensatory lengthening of the preceding vowel would be accomplished as follows:

(4.76)



The intermediate or Pre-Makah stage is entirely hypothetical since /?/ cannot occur in coda position at any point; in short, the transition from V?R to VVR would instantaneously follow the reanalysis of R' as a cluster ?R. The glottal stop cannot attach to the preceding rime when both its branches are linked to a vocalic segment, so when the preceding vowel is long, the glottal stop is simply lost.[10]

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Finally, it should be noted that the developments outlined above occur when the medial sonorant has been glottalized by one of the 'hardening' suffixes. In all the Wakashan languages, there are suffixes which glottalize the final segment of stems to which they are attached. When attached to a stem ending in a stop, these suffixes transform it into an ejective, e.g. Makah 'to sit' /t'iq-/ + /-a:s/ 'up on', a nonhardening suffix, is realized simply as /t'iq^{w}a:s/ 'to sit up on', but when the hardening suffix /'-as/ 'on the ground' is added to this stem, /q^{w}/ becomes /q'^{w}/, /t'iq'^{w}as/ 'to sit on the ground'.

As the following examples illustrate, when a hardening suffix is added to a stem-final fricative in Nootka, a glottalized sonorant appears[11], while in corresponding forms in Makah, the preceding stem vowel, if short, is lengthened before fricatives which have been hardened. In the following examples, '- indicates a hardening suffix, "- a softening one (these consonants simply deobstruentize a stem-final fricative without glottalizing it), and no diacritic, a suffix which does not modify the stem-final consonant.

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(4.77)

	Nootka			Makah		
a.				t'iL- + -u:L to wet face s.t.	>	t'iLu:L wet face
b.	t'iL- + "-is to wet on the s.t. beach	>	t'iyis *** wet spot on the beach	t'iL- + "-is	>	tiLis id.
c.	t'iL- + '-as on the ground	>	t'iy'as wet spot on the ground	t'iL- + '-as	>	ti:Las id.
d.	c'os- + "-is dig	>	c'oyis hole dug in the beach	c'us- + "-is	>	c'uyis id.
e.	c'os- + '-as	>	c'oy'as hole in the ground	c'us- + '-as	>	c'u:yas id.
f.	tL'o$\overset{\vee}{s}$- + "-is dry	>	tL'oyis dry spot on the beach	tL'u$\overset{\vee}{s}$- + "-is	>	tL'uyis id.
g.	tL'o$\overset{\vee}{s}$- + '-as	>	tL'oy'as dry spot on the ground	tL'u$\overset{\vee}{s}$- + '-as	>	tL'u:yas id.

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h.	koH^{W}-	+ "-iL	> kowiL	kuX^{W}-	+ "-iL	> kuwiL
	open, hollow	in the the house, on the floor	hole the floor			id.
i.	koH^{W}-	+ '-a:	> kow'a	kuX^{W}-	+ '-a:	> ku:wa:
		on the rocks	hole in the rocks			id.

*** /L/ is realized as a palatal glide /y/ when softened.

Example (a), where the stem is not followed by a hardening or softening suffix, shows that in Makah these stems end in a fricative underlyingly. Examples (c,e,g,i) show that stem-final fricatives become glottalized sonorants in Nootka when one of the hardening suffixes is attached. In Makah, these glottalized sonorants are in turn replaced by a long vowel followed by a nonglottalized sonorant. In both languages, when a softening suffix is attached (b,d,f,h), the stem-final fricative simply becomes a sonorant. Crucially, in Makah, a preceding short vowel remains short when a softening suffix is attached. This shows that it is the glottalization of the sonorant by the hardening suffixes that is replaced by lengthening of a preceding short vowel. In Makah, the glottalized sonorants derived by hardening a stem-final fricative behave just like original glottalized sonorants; they lose their glottalization and a preceding short vowel is compensatorily lengthened. The dissociation

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of glottalization from a sonorant, either original or derived, contrasts sharply with the stable binding of glottalization to stops in Makah -- no loss of glottalization occurs and preceding short vowels remain short.

There seems to be a phonetic contrast between stops and continuants as well in that sonorants are preglottalized in the Wakashan generally, while stops are postglottalized. When the release of an oral closure produces an audible burst, then glottalization is bound to it, but when no such burst occurs, because of the failure of the oral articulation to obstruct the passage of air out of the mouth enough to raise Po, then glottalization is not tightly bound to any part of the oral articulation. It can, therefore, dissociate from the segment which originally bore it and attach itself elsewhere. I presently see no good reason why continuants should be preglottalized, but this would straightforwardly lead to the compensatory lengthening of the preceding vowel seen in Makah.

In section 4.4, an analysis of tonogenesis in Athabaskan is proposed which depends fundamentally on the stable binding of glottalization to stops, contrasting with its easy dissociation from continuants.

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4.3.2 Glottalized sonorants in Yokuts

Ejectives and glottalized sonorants are found in the various Yokuts dialects, all once spoken in the Central Valley of California and in the foothills of the Sierras (Newman 1944, see also Archangeli 1984 for some discussion of the facts presented here). Roots in Yokuts consist of two or three consonants, called 'biliteral' and 'triliteral', respectively, by Newman. In addition to the consonants, each root has a basic vocalism represented by two vowels, one after the first root consonant and the other after the second. In ways which are broadly parallel to the nonconcatenative word formation processes of the Semitic languages (McCarthy 1979), the quality and quantity of the root vocalism is modified depending on the morphological context the root occurs in. These root modification processes leave the consonants almost entirely alone.

Ejectives occur freely as the first, second, and third consonant in roots, as illustrated below (the names of the various Yokuts dialects are abbreviated as follows: Yaw. = Yawelmani; Chaw. = Chawchila; Chuk. = Chukchansi; Wik. = Wikchamni; Choy: = Choynimni; and Gash. = Gashowu. A dot underneath a symbol in Newman's transcription indicates the

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consonant is alveolar, while the absence of a dot indicates a dental segment.):

(4.78)

	C_1 = T'	C_2 = T'	C_3 = T'
a. Yaw.:	c'uluy	ʔɔṭ'ɔw	ṭinik'
	'hide, skin'	'head'	'nose'
b. Yaw.:	k'e:nic'	k'ut'os	ṭ'it'et'
	'red ant'	'tail'	'anus'

Glottal stop occurs as the first or second, but not the third consonant of roots; for example:

(4.79)

	C_1 = ?	C_2 = ?
Yaw.:	ʔɔṣit	ṣeʔel
	'fire'	'rain'

Glottalized sonorants, on the other hand, may only be the second or third consonant of a root and as third consonant they appear to be quite rare; for example:

(4.80)

	C_1 = R'	C_2 = R'
Yaw.:	da:m'ot	mɔkiy'
	'beard'	'wife'

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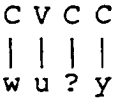
In order to properly understand the nature of the glottalized sonorants in Yokuts, two levels of representation for phonological strings must be recognized. The first is the CV-skeletion, originally introduced by McCarthy in his discussion of the nonconcatenative word formation common to Semitic. This is a string of consonant and vowel slots representing abstractly the number and arrangement of the timing units in a phonological phrase (this level of representation was used without comment in the preceding sections). Linked to the skeleton by association lines are traditional segments, which consist of full or partial feature matrices.

The various root alternants, called 'stems' by Newman, can each be represented formulaically in the CV skeleton as a particular arrangement of consonant and vowel slots (cf. Archangeli 1984); for example, the zero alternant of the base *wo:?uy 'go to sleep, fall asleep' (bases are indicated with a preceding asterisk; they represent the underlying consonant and vowel pattern of a form) has the form

(4.81)

a. zero stem:



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with the first vowel short and the second zeroed out. This stem contrasts formally with a variety of other stem shapes, including

b. the weak stem:

```
C V C V C
| | | | |
w o ? u y
```

c. the strong stem:

```
C V C V V C
| | | \ / |
w o ?  u  y
```

The particular advantage to partitioning the representation of Yokuts words into two tiers in this way is that it provides a means of resolving what appears to be a completely ambiguous, if not paradoxical, behavior of the glottalized sonorants. These consonants act in some respects like single segments and in other respects like a sequence of two segments. The particular feature of partitioned representations of the sort sketched above that makes resolution of the behavior of glottalized sonorants possible is the fact that many-to-one mappings can be set up between the segmental tier and the skeleton and vice versa. Such a mapping, from the skeleton to the segmental tier, has already been illustrated in the formula for the strong root alternant in (c) above, where the long second vowel is represented as

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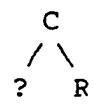
(4.82)

a.

A long vowel is a single segment linked to two vowel slots (an entirely analogous treatment of geminate consonants is currently in vogue, see McCarthy 1979, Schein 1981, Kenstowicz 1982 and many others). The representation of glottalized sonorants in Yokuts is a case of the reverse, a mapping of two segments onto a single consonant slot; i.e.

(4.82)

b.


This representation allows us to treat glottalized sonorants as 'monoconsonantal' for some purposes, but 'bisegmental' for others (the distinction is Steriade's (1982) -- see the immediately following discussion).

Before looking at how the representation in (4.82b) resolves the paradoxical behavior of glottalized sonorants in Yokuts, let us look at another example, the case of the Latin labiovelar consonants, qu /k^w/ and gu, /g^w/ where the same kind of representation resolves a quite similar paradox. Steriade (1982: 17 ff.) observes that the Latin

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labiovelars fail to close preceding syllables, yet do not occur before another consonant on the surface. The first property is that of a single segment, while the second is that of a sequence of two segments. Steriade suggests that the first property follows from the fact that the labiovelars are monoconsonantal, i.e. linked to a single consonant slot in the CV-skeleton, while the second follows from the fact they are bisegmental, i.e. a sequence of a velar stop followed by a glide in the segmental tier.

Though the labiovelars do not occur before consonants in surface forms, it is possible for them to do so in underlying representations. Such sequences cannot, however, be exhaustively syllabified because the sequence of segments between the edge of a syllable in Latin and its nucleus must increase in sonority in the direction of the nucleus. A string consisting of stop-w-consonant will under any syllabification violate this requirement (it should be emphasized that sonority sequencing conditions are highly language-specific (Steriade 1982) and there appear to be a number of languages where syllabification easily violates any such conditions the analyst might care to formulate, see Jaeger & Valin 1982).

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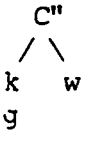
In Latin words where such sequences arise in underlying forms, the /w/ undergoes one of two processes which eliminate the violation of sonority sequencing: the /w/ can either be vocalized to /u/ as in lingula 'little tongue' or eliminated as in coctus 'cooked'. Steriade formulates the first process as the insertion of a vowel slot linked to the /w/ and the second as the delinking of /w/ from the consonant slot it shared with the velar stop, followed by erasure of stray segments which are not linked to any skeleton slot:

(4.83)

a. insertion of a V slot

b. delinking



C" is an unsyllabified consonant.

The delinking of the /w/ in (b) feeds the insertion of a vowel slot in (a), as illustrated in the derivation of lingula below:

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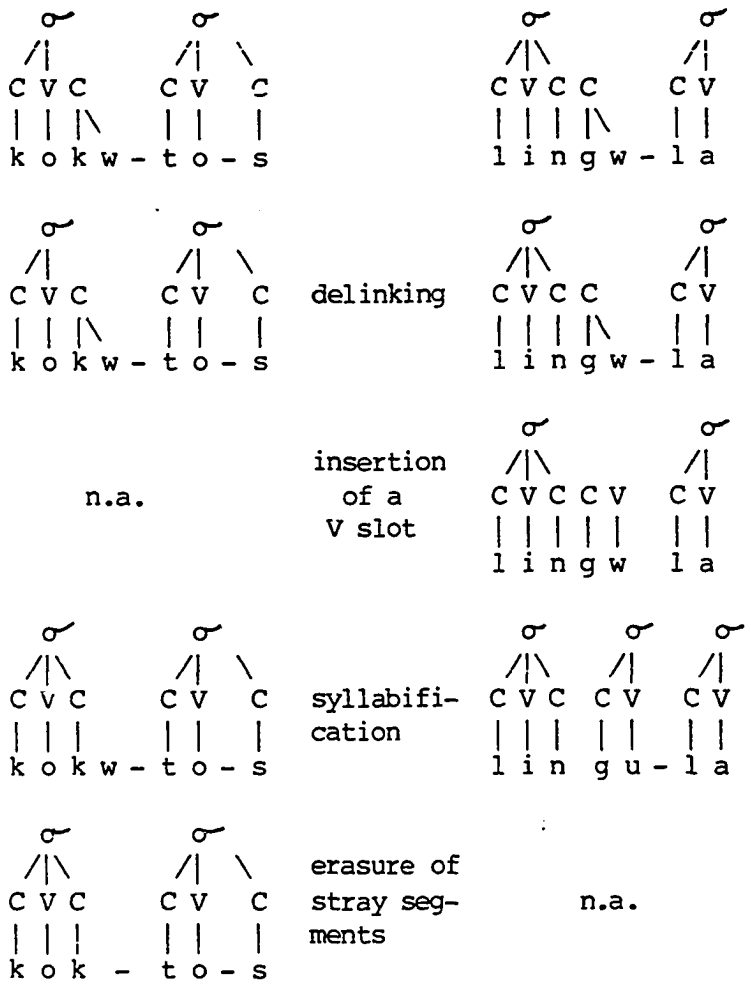
(4.84)

a.



As indicated in the underlying representations, the labiovelar is originally unsyllabified since attaching the complex consonant would result in a sonority violation.[12] The /w/ is accordingly delinked and a vowel slot inserted above it in lingula, but not coctus, which is an exception to that rule. Following syllabification, the /w/ in coctus is stray and therefore erased, but as a result of the

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insertion of a vowel slot in lingula, the now syllabic /w/ can form a syllable with the preceding velar and therefore surfaces.

The glottalized sonorants in Yokuts behave in a fashion quite parallel to the Latin labiovelars. First of all, though vowels are normally short before consonant clusters in Yokuts, which close the preceding syllable as a result of the syllable boundary falling between the two members of any medial cluster, vowels may be long or short before glottalized sonorants. A long vowel occurs, for example, before /m'/ in /da:m'ot/ 'beard'. This suggests that the glottalized sonorants are single segments. On the other hand, consonant clusters cannot occur at the beginnings or ends of words in Yokuts and at most two consonants can occur side-by-side between vowels. Glottalized sonorants are not found at the beginnings of words either,[13] and if a medial glottalized sonorant is brought into contact with a preceding consonant, it loses its glottalization;[14] for example, Chaw.: /mɔkiy'/ 'wife' has a glottalized sonorant in third position (cf. Yaw.: /mɔkɔy'mɔm/ 'deceased wife'), but in /mɔkyɔ/ the objective form, which takes the zero root alternant, the sonorant has lost its glottalization. The failure of glottalized sonorants to occur at the beginnings of words

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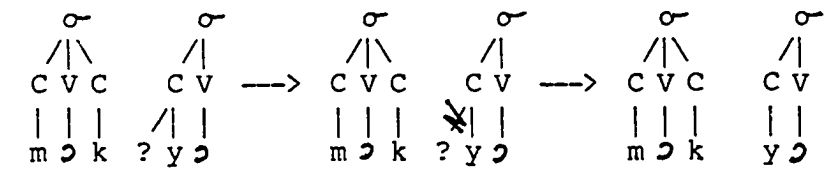
and after another consonant suggests that they are a sequence of two segments rather than single segments. The resolution of this ambiguity is entirely parallel to that offered by Steriade for the Latin labiovelars, except that there is only one process available to prevent sequences of more than two segments from occurring intervocalically: delinking of the glottal component. Discussion of how glottalized sonorants can occur word-finally, where no consonant clusters are allowed either, is deferred for the moment.

Delinking is illustrated for Chaw.: /mɔkyɔ ́/

(4.85)



Unlike the loss of /w/ in Latin coctus, which eliminates preconsonantal /k^w,g^w/ sequences, the loss of glottalization in postconsonantal glottalized sonorants in Yokuts is not a result of a failure to syllabify the glottal component of the sonorant. A prevocalic glottalized sonorant can be syllabified as indicated in the following example:

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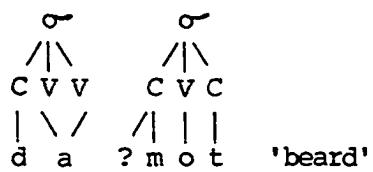
(4.86)



Delinking of the glottal component must instead be a context-sensitive rule:

(4.87)

delinking[15]

However, as was the case with underlying sequences of stop-w-consonant in Latin, the violation of permissible segment sequences in Yokuts which prompts deglottalization must be stated in terms of the segmental tier rather than the CV-skeleton. From the point of view of the CV-skeleton, the sequence in (4.86) is, of course, impeccable, since it consists of just two consonant slots, which are normally quite acceptable between vowels. Unlike Latin, however, the intervocalic sequence consonant-?-sonorant is not ill-formed because it violates any sonority sequencing condition, but simply because no more than two nonvocalic segments of any sort may occur between vocalic segments in Yokuts.

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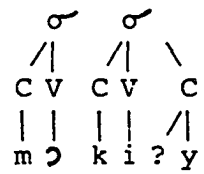
There is no problem with /da:m'ot/ because two segments can occur between vowels, but

(4.88)



should not be possible, since no consonant clusters can occur word-finally. As indicated above, the prohibition against glottalized sonorants at the beginnings of words and after consonants was motivated by general constraints in the language on the clustering of consonants in the language at the level of the segmental tier, where glottalized sonorants are represented as a sequence of two segments rather than as a single consonant. In the segmental tier, /mɔkiy'/ = /mɔ-ki?y/ should also be ill-formed since it ends in two segments; nonetheless, the sonorant does not lose its glottalization. It would appear to be necessary therefore to stipulate that the prohibition against word-final clusters refers to the CV-skeleton rather than the segmental tier.

On the face of it, such a stipulation is extremely unwelcome, since it leads unavoidably to a collapse of the skeleton and the segmental tier into a single level of

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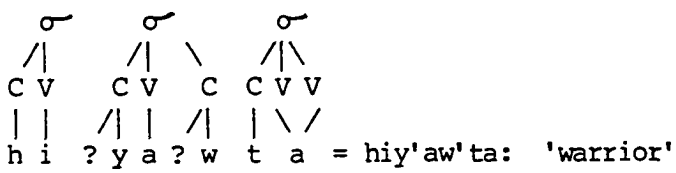
representation. However, if one recognizes that the constraint on word-final clusters is a statement about syllable codas in Yokuts, while the constraint on word-initial and post-consonantal segments is a statement about syllable onsets, then this stipulation becomes much less horrifying. Syllable codas may contain at most a single consonant slot, which may be either mono- or bisegmental. An example with a medial bisegmental coda is

(4.89)



The occurrence of bisegmental consonants in onsets, on the other hand, is sensitive to whether the preceding segment is dominated by a vowel slot or not (i.e. syllabic).

In broader terms, this is simply another instance of the essential difference in the kind of constraints which determine what can occur in syllable onsets and what can occur in rimes. The failure of glottalized sonorants to occur unless preceded by a syllabic segment shows that the sensitivity of onset segments to the feature content of neighboring segments extends to segments which are adjacent

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but in a different syllable. The structure of rimes is constrained rather more abstractly; in Yokuts, only a single nonsyllabic may follow the syllable nucleus.

Let us look now at a morphological process which glottalizes sonorants. Certain suffixes cause the second consonant in a root to become glottalized if it is a sonorant. If the root is biliteral and the second consonant is not a sonorant, then a glottal stop shows up after it when one of these glottalizing suffixes is attached. Examples with the consequent agentive suffix /-?...a?/ and contemporaneous gerundial suffix /-?...in'ay/ are given below — these both take the zero root alternant discussed previously, where the second vowel has been zeroed out and the first vowel is short:

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(4.90)

Biliteral roots -- CVC

a. CVR:	din'a?	'one who has (it) protected'
	pan'in'ay	'arriving'
b. CVT***:	wis?a?	'one who has (it) straightened'
	muh?a?	'one who has dived'
	dub?in'ay	'leading by the hand'

*** T represents any obstruent.

Triliteral root -- CVCC

c. CRT:	t'ɔy'xɔ?	'one who has given (it) medicine'
	hiw'tin'ay	'walking'
d. CRR:	lɔw'nɔ?	'attendant at a feast'
	no example with -?...in'ay	
e. CTR:	?ugna?	'one who has (it) drunk'
	waxlin'ay	'weeping'

The forms in (a), (c), and (d) show that if the second root consonant is a sonorant, it becomes glottalized if suffixes of this type are attached, while the forms in (e) make it clear that a sonorant which is the third consonant in the root cannot be glottalized, nor can the obstruent in second

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position. The sonorant in the examples in (e) could not bear glottalization anyway, since it follows a consonant -- this point is pursued further immediately below. Finally, the examples in (b) show that a glottal stop appears, essentially in third position,[16] when these suffixes are attached to biliteral roots whose second consonant is an obstruent, which cannot accept glottalization.

In a fairly subtle way, the realization of glottalization in the examples in (4.90) is reminiscent of the allomorphic variation in such suffixes as the desiderative /-atin/-hatin/. If we contrast the examples in (b) with those in (e), the parallelism is, in fact, quite striking: a glottal stop appears after biliteral roots, which take the consonant-initial allomorph of the desiderative suffix, while no glottal stop is found after triliterals, which take the vowel-initial allomorph. The difference is that under a fairly special set of circumstances, i.e. when the second root consonant is a sonorant, glottalization shows up "inside" the root, regardless of its number of consonants.

Its appearance on the second consonant when that is a sonorant, regardless of whether the third consonant is a sonorant or not, shows that this is not a simple case of

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'contact glottalizaton' of the sort seen in the Wakashan languages. The Yokuts suffixes do not simply glottalize the nearest consonant. Since glottalization clearly originates after the root (see b), it is instead likely that it moved into the root via metathesis; i.e. VR(C)+?V —> V?R(C)+V. In biliteral roots, where the second consonant is a sonorant (see a), metathesis only has to apply once to get glottalization into postvocalic position, but in triliteral roots (see b or d), it must apply twice.

Besides the fact that it ends up on the second root consonant when it is root-internal (a,c,d), it is also invariably postvocalic, which is the only position where glottalized sonorants can occur in Yokuts. The most striking point about the entire class of glottalizing suffixes in Yokuts is that they only occur with the simple zero stem illustrated here and the strong-zero stem, which is structurally identical to the weak-zero stem except that the first vowel is morphologically long rather than short, i.e. with stems of the shape CV(:)C(C)-. If the insertion of glottalization into the root takes place after the derivation of the stem, then glottalization is a process which only applies to postvocalic sonorants. Glottalization cannot be realized on the third consonant of such a stem for

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the simple reason that it is invariably postconsonantal as a result of the zeroing out of the second root vowel.

There are a number of root alternants of fairly restricted distribution across the various Yokuts dialects which have an internal glottal stop:

(4.91)

glottal-weak stem

a. Gash:	hut?uk'	< *huto:k'	'weed pulling'
b. Gash:	xay?an	< *xaya:	'placing'
c. Choy:	ʔɔpɔ?tɔ	< *ʔɔpɔ:t	'getting up from bed'

(4.92)

weak-glottal stem

a. Chaw:	ʔa:ma?y-a-n	< *ʔamay	'be coming'
b. Chaw:	he:wi?t-a:-x ʔ	< *hiwe:t	'keep walking'

(4.93)

ʔA-induced stem

a. Gash:	k'ih?ay	< *k'e:hiy	'will feel sorry'
b. Gash:	?ad?an	< *ʔa:dan	'will get lost'
c. Choy:	sɔn?ɔl	< *sɔ:nɔl	'will pack on the back'
d. Choy:	buh?at'	< *bo:hut'	'will grow up'

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(4.94)

causative stems

strong

a. Wik: ʔugoʔn-u < *ʔugun 'make drink'

weak

b. Yaw: mɔʔɔʔn-e:-nit < *mɔ:yɔn 'be made tired'

c. Chaw: biyiʔt'-e:k' < *niye:t 'make twist'

d. Gash: hɔt'ɔʔn-i-ntin < *hɔt'ɔn 'causing to burn'

e. Choy: salaʔk'-i < *sa:lak' 'wake someone up'

In all but the causative stems in (4.94), Newman indicates that the glottal stop is inserted immediately after the second root consonant, where it shows up, for example, in (4.91a,b). This glottal stop undergoes metathesis with the following vowel if the third root consonant is followed itself by a vowel,

(4.95)

Newman's metathesis rule

$$? \; V \; C_3 + V \longrightarrow V \; ? \; C_3 + V$$

In the causative stems, which are invariably followed by a vowel-initial suffix, the glottal stop is inserted immediately before the third root consonant rather than after the second. It seems possible to insert the glottal stop before the third root consonant in all cases, not just the

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causative stems. In order to obtain forms such as (4.91a,b), a metathesis rule is still needed, but one which does exactly the opposite of Newman's rule:

(4.96)

$$V\ ?\ C_3\ ]_{\sigma} \text{---->}\ ?\ V\ C_3\ ]_{\sigma}$$

Besides unifying glottal stop insertion into a single process, this inversion has the advantage of a built-in motivation for its metathesis rule. Newman's rule transposes the /?/ with the following vowel in a form such as that in (4.91c), i.e. /?ɔp?ɔt-ɔ/ becomes /ʔɔpɔ?t-ɔ/, but as (4.91a,b) show, there is in principle nothing wrong with medial C? clusters. Both consonants can be syllabified, since the syllable boundary falls between them. Newman's rule is therefore just an arbitrary reordering requiring a complex environment statement. On the other hand, if we start out with /hutu?k'/ and /xaya?n/ in (4.91a) and (4.91b), respectively, then metathesis is simply one means of avoiding a violation of the constraint in the language against final consonant clusters. The final appeal of this inversion of Newman's analysis is that now all processes which insert glottal stops into stems put them into syllable codas.

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There are, however, three marked differences between the glottal insertion process just described and that induced by suffixes. First, with the exception of the glottal-weak stem in Gashowu and Choynimni, glottal insertion only applies to triliteral roots, while suffix-induced glottalization applies to biliteral roots as well. Second, insertion of a glottal stop is completely indifferent to whether the second consonant of the root is a sonorant or not. Finally, glottal insertion does not apply to stems whose second vowel has been zeroed out; in all cases the stem has the form CVCV(C). These last two differences follow from the fact that the glottal stop is inserted directly into the root before the third consonant, rather than shifting into it by metathesis. The metathesis rule which brings about stem-internal glottalization was motivated by the fact that glottalized sonorants could not occur after a consonant. Since the third root consonant is preceded by a vowel in the cases where glottal insertion applies, no violation of distributional constraints arises from inserting the glottal stop right before it (unless that consonant is itself word-final, in which case the independent constraint against clusters in syllable codas applies).

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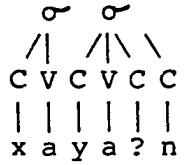
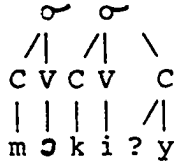
Finally, it should be noted that examples such as /xaya?n/ which undergo metathesis to produce /xay?an/ must be structurally different from forms such as /mɔkiy'/, i.e.

(4.97)

a.


b.


since the former but not the latter undergoes metathesis (in other words, the rule applies to the skeleton slots rather than segments).

The general conclusion that can be drawn from the Yokuts data presented here is that glottalization shows a strong preference for syllable codas. With respect to the distribution of glottal stop as an independent segment, this is only a preference. Many glottal stops occur at the beginnings of words and after consonants. However, when the glottal stop is linked to the same consonant slot as a sonorant, it must be postvocalic. Furthermore, all processes inserting glottal stops into stems put them into codas rather than onsets, though they may be shifted to onset position subsequently by metathesis.

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4.4 Athabaskan tonogenesis revisited

4.4.1 The underlying representation of constriction

In the preceding chapter, the phonetic realization of constriction in Athabaskan as a creaky or tense voice quality was described. In this section, I consider its most likely underlying representation together with a set of rules which account for its development from final glottalization. The following facts need to be accounted for in this section:

i) in stems ending in an ejective, glottalization has been lost from the stop and marked tone appears on the stem vowel in the Athabaskan languages which have developed tone,

ii) unless the stem vowel was full, in which case, glottalization is simply lost without leaving marked tone behind (the full vowels in Proto-Athabaskan are represented here as /i:, e:, a:, u:/. They contrast with the reduced vowels /e, a, u/; these symbols correspond to full /i, e, a, u/ and reduced /ə, ɑ, ʊ/ in Leer (1979)).

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iii) however, if the ejective is spirantized, then marked tone will appear on full vowels as well.

These contrasts are illustrated by the following verb paradigms (taken from Leer 1979). Four forms of each verb stem are given: 1) the perfective stem, which is followed by a syllabic, nasalized suffix, represented as /Ỹ/ by Leer; 2) the basic stem, which is identical to the perfective stem but without the suffix; 3) the lengthened stem, which invariably shows a full vowel -- the perfective and basic stems may have either a full or reduced vowel, depending on the lexical item; both underlyingly full and reduced vowel stems have a full vowel in the lengthened stem --; and 4) a stem followed by an obstruent suffix, which always has a reduced vowel. At the bottom of each column of forms, the full or reduced quality of the stem vowel, whether the stop has spirantized or not, and whether marked or unmarked tone appears is indicated. Abbreviations: PPA (**) = Pre-Proto-Athabaskan, PA (*) = Proto-Athabaskan. Recall that Navajo and Kutchin are low-marked languages; Chipewayan is high-marked; and Koyukon, Ahtna, and Hupa are nontonal.

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(4.98)

a. t'aq 'fly'

	Perfective	Basic	Lengthened	Obstruent-suffixed
PPA	** t'aq-Ỹ	** t'aq	** t'a:q	** taq-L
PA	* t'aq	* t'aq	* t'a:X	* t'aXL
Navajo	t'à?	t'à?	t'á:h	t'àh
Kutchin	t'ák	t'ák	t'í:	t'á:
Chipewayan			t'à	t'àh
Koyukon	t'aq	t'aq	t'ox	t'aXtL
Ahtna	t'aq	t'aq	t'a:X	t'aX
Hupa	t'aw		t'aw	t'awaL
Vowel quality:	reduced	reduced	full	reduced
Final stop:	not spirantized	not spirantized	spirantized	spirantized
Tone:	unmarked*	unmarked	unmarked	unmarked

* Navajo shows marked tone in all stems with reduced vowels, regardless of the presence or absence of glottalization of the stem-final consonant. Kutchin better represents the developments of low-marked languages in this paradigm since it shows high, i.e. unmarked, tone throughout.

Of the languages represented in this paradigm, only Kutchin

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and Koyukon preserve the original contrast between reduced vowels in the perfective, basic, and obstruent-suffixed stems and full vowels in the lengthened stem: full */a:/ > /i/ in Kutchin and > /o/ in Koyukon, while reduced */a/ becomes /a/ in Kutchin and /ɑ/ in Koyukon. In the next paradigm, the stem ends in a glottalized rather than an oral consonant:

b. neq' 'swallow'

	Perfective	Basic	Lengthened	Obstruent-suffixed
PPA	** neq'-Ỹ	** neq'	** ne:q'	** neq'-L/-k
PA	* ne?q'	* ne?q'	* ne:?X	* ne?XL/k
Navajo	nà?		nè:h	nàh
Kutchin	ndàk		ndzì:	ndà:
Chipewayan	náɣ		nÉ	náih
Koyukon	nəq	nəq	naX	nəXtL
Ahtna	na?		ne:X	naX
Hupa	nəq'		nəw	nəwəL
Vowel quality:	reduced	reduced	full	reduced
Final stop:	not spirantized	not spirantized	spirantized	spirantized
Tone:	marked	marked	marked	marked

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These two paradigms show the typical tone developments in reduced vowel stems ending in an unglottalized stop (a) and in a glottalized one (b): unmarked tone (except Navajo) in (a) and marked tone throughout in (b). Even though the vowel is full in the lengthened stems in (b), marked tone develops as a result of spirantization of the final stop. Clearly spirantization frees glottalization to shift into the preceding rime, and, as a consequence of this shift (constriction), marked tone develops. The stem-final stop also spirantizes before an obstruent suffix in the last column, but it fails to spirantize in the perfective stem before the syllabic suffix and in the basic stem. Nonetheless, marked tone develops in these stem alternants because the preceding vowel is reduced. The constriction process which led to the development of marked tone in (b) might tentatively be formulated as follows (in this rule, K in the segmental tier indicates a stop, X the corresponding continuant, and T any obstruent):

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(4.99)

```
a.      V   C       V   C
        |   |  -->  / \  |      In reduced vowel stems, i.e.
        V   K'      V ?  K      in the perfective.

b.      V V C       V V C
        \ / |  -->  |/| |      In the lengthened alternant.
         V  X'      V ? X

        V C  C       V   C C
        | |  | -->  / \  | ↓   In obstruent-suffixed forms.
        V X' T      V ?  X T
```

This rule is fed by spirantization:

(4.100)

```
      C   ---> [+cont] /   VV ___ #
   [+obst]                 V ___   C
                                [+obst]
```

where VV represents a full vowel and V a reduced vowel.

The connection between spirantization and constriction is strictly speaking not the standard sort of feeding relationship between two phonological rules. Instead, a side effect of spirantization is the delinking of glottalization from the final consonant in stems.

(4.101)

```
        V   C     V   C     V   C
        |   | -->  |   | -->  |\  |
        V   X'    V ? X      V ? X
```

After it delinks from the consonant, glottalization relinks to a preceding vowel slot. This is the constriction

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process. As indicated, spirantization is only a necessary precursor to constriction when the stem vowel is originally full, though it also occurs in the obstruent-suffixed stems, where constriction would take place anyway because the stem vowel is reduced (compare (4.99a) and (4.99c)).

Now consider the following paradigms, where the stem vowel is underlyingly full rather than reduced (R represents a voiced uvular fricative):

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(4.102)

a. Xa:t 'shake (out)'

	Perfective	Basic	Lengthened	Obstruent-suffixed
PPA	** Xa:t-$\tilde{Y}$		** Xa:t	** Xat-L/-k
PA	* Ra:t		* Ra:t	* RaL/Rɑtx
Navajo	ɣáːd		ɣáːt	ɣàL/ɣà?
Kutchin	ɣát		ɣát	/ɣák
Chipewayan	ɣàːr		ɣàːr	/ɣày
Koyukon	ɣot		ɣot	ɣaL/ɣak
Ahtna	ɣaːt		ɣaːt	ɣaL/ɣat
Hupa	wad		wad	wadəL
Vowel quality:	full		full	reduced
Final stop:*	not spirantized		not spirantized	not spirantized
Tone:	unmarked		unmarked	unmarked

* Final t does not have a spirantized alternant.

The basic stem has the same form as the lengthened stem for this verb.

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b. ?a:tš' 'few go'

	Perfective	Basic	Lengthened	Obstruent-suffixed
PPA	** ?a:tš'-Ỹ	** ?a:tš'	** ?a:tš'	** ?atš'-L/-k
PA	* ?a:tš'	* ?a:?š	* ?a:?š	* ?ašL/?ašk
Navajo	?á:ž	?à:š	?à:š	?àš/?àš
Kutchin	?ó:		?ò:	?àL/?ò:
Chipewayan	?àz	?ás	?ás	?ás/?ais
Koyukon	?ots	?os	?os	?astL/?as
Ahtna	?a:ts'	?a:s	?a:s	?as/?as
Hupa	?atš'		?aW	?ɑW@L
Vowel quality:	full	full	full	reduced
Final stop:	not spirantized	spirantized	spirantized	spirantized
Tone:	unmarked	marked	marked	marked

The appearance of unmarked tone in the perfective stem in (4.102b) in the tonal languages contrasts with the appearance of marked tone in the same stem alternant in (4.98b) above. On the other hand, marked tone appears in both the basic and lengthened stems, which are in all respects identical in (4.102b), as well as (4.102a). This constrast demonstrates the complex conditioning outlined at the beginning of this section for the constriction of the vowel that

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leads to the evolution of marked tone: a full vowel does not become constricted before a stem-final ejective unless the ejective has spirantized.

The approach to the constriction of stem vowels developed above acquires support from stems where the vowel was constricted in Pre-Proto-Athabaskan. Representative paradigms are given below:

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(4.103)

a. ne?k- 'move hand'

	Perfective	Basic	Lengthened	Obstruent-suffixed
PPA	** ne?k-Ỹ	** ne?k	** ni:k	** nek-L
PA	* ni?k	* ni?x̂	* ni:x̂	nexL̂
Navajo	nì:	nì:h	ní:h	nìh
Kutchin	ndzǐ̂k		ndzǐ́:	ndá́l
Chipewayan	ní(y)	níy	nì(h)	nìL
Koyukon	nik	nix̂	nix̂	nəxtL̂
Ahtna	ni:k	ni:s	ni:s	nes
Hupa	nəG		nəG	nəGəL
Vowel quality:	full	full	full	reduced
Final stop:	not spirantized	spirantized	spirantized	spirantized
Tone:	marked	marked	unmarked	marked

In the paradigm below l̲ represents a voiced lateral sonorant, while L̲ as usual represents a voiceless lateral fricative. The latter is the spirantized reflex of Pre-Proto-Athabaskan **/tL/ in Proto-Athabaskan. The lateral sonorant, on the other hand, derives directly from the original stop in those languages which have lost final glottalization (except Koyukon), when that stop was intervocalic.

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b. ?a?tL' 'chew'

	Perfective	Basic	Lengthened	Obstruent-suffixed
PPA	** ?a?tL'-Y		** ?a:tL'	** ?atL'-L
PA	* ?a?tL'		* ?a?L	* ?a?L
Navajo	?à:l		?à:L	?àL
Kutchin	?àl		?à:	?à:
Chipewayan	?á̀l		?á̀:L	?á̀L
Koyukon	?otL			?aLtL
Ahtna	?a:tL'		?a:L	?a̲L̲
Hupa	?atL'		?aL	?aleL
Vowel quality:	full		full	reduced
Final stop:	not spirantized		spirantized	spirantized
Tone:	marked		marked	marked

The basic stem is identical to the lengthened stem in this example. The necessity for setting up constricted stems in the protolanguage is the appearance of marked tones in (4.103a) above where cognates in the nontonal languages do not exhibit final glottalization. (4.103b) shows that both constriction and final glottalization may occur in the same stem in the protolanguage. More subtle evidence of original constriction is provided by the appearance of reflexes of

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original full vowels in Ahtna in the perfective and basic stems in (4.103a), where /i/ from full */i:/ rather than /e/ from reduced */e/ appears (compare the obstruent-suffixed stem for this language which shows the reflex of the reduced vowel). The /a/ in the Ahtna perfective and basic stems in (4.101a) could be a reflex of full */a:/ or reduced */a/, since this pair of vowels has merged in Ahtna. Apparently, when the original constriction was lost in this language, the preceding vowel lengthened compensatorily,

(4.102)

and consequently, a full rather than reduced vowel reflex appears. It is important to note that this is evidence that constriction originally had the status of a segment in underlying representations, represented here as /?/, rather than simply being a modification of the preceding vowel, like the tone that has developed from it. Otherwise, it would not be expected to be linked independently to the rime and no compensatory lengthening should occur when it dropped in Ahtna (this representation is also crucial to the understanding of the failure of full vowels to accept

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constriction in the perfective stems in (4.103b) above).

Proto constriction is lost throughout Athabaskan in the lengthened stems in (4.103), as indicated by the unmarked tones which have developed there in (4.103a). The marked tones in the lengthened alternant in (4.103b) arise from the glottalization of the final stop rather than the original constriction. The loss of constriction from lengthened stems is undoubtedly an analogical leveling based on the lengthening of reduced stem vowels exhibited in (4.98) above.

4.3.4 Conclusion

The reason I have considered the Athabaskan example at such length is that the dissociation of glottalization from stops which have spirantized is compelling proof that the association of glottal features to continuants is highly unstable. Glottalization also dissociates from stem-final sonorants in Athabaskan, giving rise ultimately to marked tone, but this constriction is not constrained in such stems by the occurrence of a preceding full vowel. All sonorant-final stems with final glottalization develop marked tone.

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The failure of glottalization to remain stably linked to a sonorant is predicted by the binding hypothesis, as is its dissociation from a spirantized stop, since neither class of segments has a salient release.

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Notes.

1. This was true so long as the clusters contained no word boundary. In clusters interrupted by a word boundary, a separate opening and closing of the glottis occurred in the string of obstruents preceding the boundary and in the one following it.

2. In some languages, stops other than the one which immediately precedes a vowel in clusters of stops are each separately released, but there is still no contrast between stops of different glottal type in this position. This suggests that it is release into a vowel, with the transformation of vocal tract aerodynamics and acoustics that that implies which binds glottal articulations, not a stop release per se.

3. Syllable coda position was defined for the purposes of this survey as:

$$V \_\_\_ \begin{matrix} C \\ [+obst] \end{matrix} \quad Co\ V$$

Insisting that the stop in question be able to occur medially before an obstruent was considered the best

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way to insure that it was in fact in a syllable coda, since considerations of sonority would lead one to expect the syllable boundary to fall between the stop and the following obstruent. Note that it does not matter whether the stop is the last consonant in the syllable, just that it is postvocalic and in the syllable coda. Though word-final position might also be considered a coda position, in particular languages there are stricter constraints or more rarely greater freedom on the occurrence of stops of different types in word-final position than when the stop is in the coda of a medial syllable. For this reason, the fact that a stop of a particular type could occur in word-final position was not considered to mean that it could generally be a coda segment; it must in addition be able to occur in the coda of a medial syllable.

4. One could, of course, assume that these sonorants undergo reduplicative glottalization just as those which end up in syllable onsets do. They would later be deglottalized when they come into coda position. In examples (4.45,48) the sonorant is followed immediately by another consonant in the nonreduplicated form so it would be in the coda in any case, but in (4.46,47,49)

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it ends up there as a result of deletion of the stem vowel. For example, the form /lalGi/ in (4.47b), the original stem-initial sonorant is an onset consonant until the stem vowel is deleted, so in principle the initial sonorant could be glottalized by reduplication. In this example, deletion of the stem vowel brings the stem-initial sonorant into contact with a following stop. The question arises as to whether it is the nature of the following segment which triggers deglottalization or if it is simply the fact that the sonorant is left in coda position by vowel deletion. The second of the following pair of examples shows that deglottalization also occurs if the following consonant is a sonorant:

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i. wele:qs 'old lady'

ii. wewle:qs 'old ladies (dist.)'

(ii) is derived in (iii):

iii. [CV? [wele:q'-s]]

weleq's	1st cycle
	2nd cycle
we?wele:q's	reduplication
wew'ele:q's	sonorant glottalization
wew'Ale:q's	vowel reduction
wew'le:q's	vowel deletion
wewle:qs	deglottalization ***

*** The /q'/ is also deglottalized because it is in coda position.

It would appear, therefore, to be necessary to state the deglottalization rule for sonorants in structural terms, i.e. as applying in syllable codas, rather than with reference to the kind of segment which follows.

5. The difficulty is compounded by the fact that glottalization, when delinked from a consonant slot as a result of the vocalization of a glottalized glide, does not relink to a sonorant to its right; for example:

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i. sw'ewa 'shakes something in the water; fishes with hook and line'

ii. sw'eso:wa 'fish (dist.)'

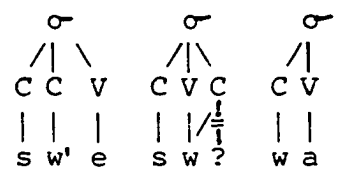
(ii) is derived in (iii):

iii. [CCV [sw' [ew-a]]]

ewa	1st cycle
sw'ewa	2nd cycle = i
	3rd cycle
sw'esw'ewa	reduplication
sw'esw'Awa	vowel reduction
sw'esw'wa	vowel deletion
sw'esAw'wa	preglide epenthesis
sw'eso:wa	vocalization and deglottalization

i.e. */sw'eso:w'a/, with the following glide glottalized, does not occur. This is true despite the fact that following vocalization and delinking, this form might be represented as in (iv):

iv.



which is nearly identical to the structure which leads to glottalization in the reduplication of morphemes

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which begin with a sonorant. Linking the floating glottal stop to the following sonorant cannot be blocked by some version of the strict cycle condition (Kiparsky 1982) because it was delinked by the application of a cyclic rule, glide vocalization. Its failure to relink also cannot be attributed to the fact that it was not introduced by reduplication since other prefixes, such as reflexive/reciprocal /sV-/, can glottalize a morpheme-initial sonorant:

v. ye:ywi 'is proud of, values highly'
vi. yey'e:ywi 'are proud of (dist.)'
vii. sey'e:ywi 'is proud of oneself, each other'

The only alternative seems to be to insist that glottalization can only affect morpheme-initial sonorants (which are followed by a vowel).

6. I have been able to find only a single example where vowel deletion applies before a sequence of a stop followed by a voiced sonorant:

i. pek'ye:wa 'pulls the vagina open'
ii. sepk'ye:wa 'stretches one's own vagina open'

The form in in (ii) is derived below:

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iii. [sV [pV [k'ye:w-a]]]

k'ye:wa	1st cycle
	2nd cycle
pek'ye:wa	vowel copy = i
	3rd cycle
sepek'ye:wa	vowel copy
sepAk'ye:wa	vowel reduction
sepk'ye:wa	vowel deletion

7. No internal structure has been proposed for Klamath syllables in the preceding discussion, so strictly speaking the notion rime is undefined. Nothing in this analysis would change if the syllable node were considered to immediately dominate onset and rime nodes which themselves dominated consonant and vowel slots.

8. Examples such as /totAq'lGa/ whose immediate predecessor in a derivation is /totAq'l'Ga/ (see 4.63b) suggest that the following sonorant need not be a voiced sonorant, but may be glottalized or voiceless as well. Exchanging a vowel slot for the consonant slot which originally dominated the sonorant, i.e. making it syllabic, results in deglottalization or voicing of the sonorant, however.

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9. The more common manifestation of control over glottal articulations within clusters of obstruents is assimilatory, as in Kabardian (Kuipers 1960) where all nonprevocalic consonants agree with the glottal features of the prevocalic obstruent.

10. The loss of glottal stop from coda position with compensatory lengthening of the preceding vowel is a quite common development, occurring, for example, in Tiberian Hebrew, where /h, H, 9, r/, the so-called 'gutterals' (/H/ is a voiceless pharyngeal fricative and /9/ is its voiced counterpart), also drop from coda position with compensatory lengthening (Rappaport 1984, Kaye & Lowenstamm n.d.), and in Hopi, where /h/ in addition to /?/ lengthens the preceding vowel as it drops (Jeanne 1982). Closer to Wakashan is Chemakuan where essentially similar processes are found (Powell 1975). In Quileute, a member of this family, medial ejectives following a stressed vowel are pre- as well as post-glottalized in casual speech, while the preceding vowel is lengthened instead in careful, monitored speech, e.g.

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		Casual	Careful
i)	'flea'	wí?k'is	wí:k'is
ii)	'fart'	pí?tl'a	pí:tl'a

Other consonants show an alternation between a lengthened medial consonant in the casual style and a lengthened vowel in the careful one, e.g.

		Casual	Careful
iii.	'break'	lás:al	lá:sal
iv.	'mark'	cíx:il	cí:xil
v.	'shark'	káy:ad	ká:yad
vi.	'raccoon'	qaqáw:it	qaqá:wit
vii.	'camas'	k^{w}ál:a	k^{w}á:la
viii.	'bear'	?íb:a	?í:ba
ix.	'father'	híd:a	hí:da

/b/ and /d/ in this language derive from Proto-Chemakuan /m/ and /n/, respectively; as in Makah and Nitinat.

There are a number of words where the consonant is pre-glottalized rather than lengthened in the casual style, although it does not appear otherwise to be a glottalized segment:

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		Casual	Careful	
x.	'meadow'	lóʔwot	lóːwot	* w'
xi.	'frog'	hagáʔy	hagáːy	* y'
xii.	'tight'	cíʔba	cíːba	* m'
xiii.	'almost'	cáʔdas	cáːdas	* n'
xiv.	'uncle'	cíʔla	cíːla	* l'

As indicated, the examples where the consonant is preglottalized rather than lengthened derive from original glottalized sonorants in Proto-Chemakuan. The synchronic variation in Quileute between V?RV and V:RV provides support for the analysis of the Makah developments given above. Note also that in the casual style, glottalization remains a release feature of stops, while shifting entirely to preconsonantal position when introduced by a sonorant, an indication that in Quileute there is a tighter bond between oral and glottal features in stops than in sonorants.

11. The weakening of fricatives to sonorants represents a coalescence of hardening and softening processes. Besides the hardening suffixes which glottalize stem-final consonants, these languages also have a set of softening suffixes which transform a fricative into a corresponding sonorant. This transformation has

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apparently been extended analogically to hardening of stem-final fricatives, which are as a result both hardened (glottalized) and softened (deobstruentized). Kwakw'ala (Boas 1947) points to the original separation of the two processes since its fricatives are not uniformly softened at the same time as they are hardened, i.e.

Original fricative	Hardened	Softened
s	ts' or y'	dz or y
xy	n'	n
x^w	w'	w
x	x'	x
x^w	w'	w
l	l'	l

Both /x/ and /s/ retain their original obstruency, at least in some cases.

12. Steriade (p. 23) suggests instead that consonants that are final on any cycle, as /k^w/ and /g^w/ are on the stem cycle in these forms, are ignored by the syllabification rules because they are extrametrical. In either view, the labiovelars will not be syllabified.

13. Since Yokuts has no prefixes, this means that

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glottalized sonorants may not be the first consonant in roots.

14. There is a contrast in Newman's transcription between ?R, R?, and R'. For example, in the zero stem alternant of the base *wo:?uy 'go to sleep, fall asleep', where the second vowel has been zeroed out, Newman writes /?y/ in Yaw.: /wu?y-atin-xo:-nit/ 'is being desired to go to sleep'. The first vowel in this form is short as expected, since zeroing the second stem vowel created a consonant cluster out of the second and third root consonants. It is of some interest that most of the suffixes which take this root alternant, where the second vowel is zero, have two allomorphs: a vowel-initial one which is attached to triliteral roots and a consonant-initial one attached to biliteral ones. For example, the desiderative suffix above has the form /-atin/ after triliteral roots, but shows up as /-hatin/ after biliteral ones; compare /dos-hotin-xo:-hin/ 'was trying to tell' < *do:so 'tell, report' with the example above. The result of this alternation in suffix shape is that after zeroing out the second root vowel, the first vowel is always followed by two consonants, in biliteral as well as triliteral roots.

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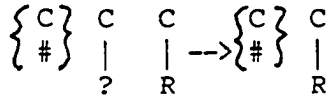
Therefore, the fact that the vowel is invariably short in this root alternant is predictable from the fact that it always occurs in a closed syllable. Unfortunately, there are a number of suffixes which select the zero root alternant for biliteral but not triliteral roots and which themselves always begin with a vowel. The first root vowel is invariably short in these cases, too, despite the fact that it occurs in an open syllable; for example, /c'um-a:la-k'/ 'make destroy (it)' < *c'o:mu 'destroy, devour'. The length of the vowel in these cases must be determined morphologically rather than phonologically.

15. Recall that after glottalized sonorants were reanalyzed in ?R clusters in the Wakashan languages, they were deglottalized word-initially and after consonants because consonant clusters are not permitted in syllable onsets. In these languages, each component of a glottalized sonorant was linked to its own consonant slot after reanalysis:

(i)



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and, as indicated, deglottalization is the loss of the slot as well as the /?/ that it dominated. Preconsonantal deglottalization is motivated in the same way by the prohibition against coda clusters:

(ii)

```
V  C  C  C     V  C  C
|  |  |  | --> |  |  |
V  ?  R  C     V  R  C
```

Note that no compensatory lengthening occurs in this case because the consonant slot as well as the /?/ is deleted. In this context ejectives are also absent, as are the laryngeal consonants /?/ and /h/, so this rule should probably be formulated as applying to any consonantal slot in coda position dominating a glottal segment (T indicates any stop), i.e.

(iii)

```
V  C  C  C     V  C  C
|  |  |  | --> |  |  |
V  T  ?  C     V  T  C
```

(iv)

```
V  C  C     V  C
|  |  | --> |  |
V  ?  C     V  C
   h
```

Analyzing ejectives as biconsonantal raises the obvious problem of explaining how they can occur at the

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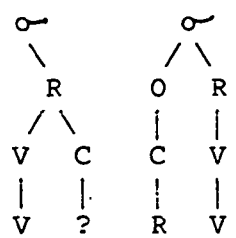
beginnings of words and after consonants. Perhaps they underwent a reanalysis analogous to that which applied to glottalized sonorants, but only postvocalically.

After vowels glottalized sonorants would be syllabified as follows after reanalysis:

(v)

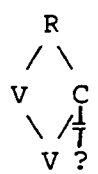


A rime of the form

(vi)

is transformed into a long vowel in Nitinat and Makah:

(vii)



but retained as such in Nootka.

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In summary, glottalized sonorants are synchronically biconsonantal as well as bisegmental in the Wakashan languages, unlike Yokuts where they remain monoconsonantal.

16. Recall that /?/ cannot normally be the third consonant in a triliteral root. Its appearance in this position when one of this class of suffixes is attached to a biliteral root whose second consonant cannot be glottalized effectively fills the gap. Apparently, the contrast between triliteral roots of the form CVTV? and biliteral roots of the form CVT has been neutralized in favor of the latter. In this vein, we might consider the contrast between CVR' and CVR to reflect an underlying contrast between CVRV? and CVR.

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Chapter 5

Summary and Conclusion

In each of the three preceding chapters, a single aspect of the coordination of laryngeal or glottal articulations with oral ones has been examined.

In chapter 2, the efficiency of vertical movement of the larynx as a means of manipulating Po was assessed. Of particular interest was whether raising the larynx was the primary means by which Po was elevated in ejectives. This kind of stop is articulated by sealing the glottis tightly and raising the larynx. Larynx raising is supposed to compress the air in the oral cavity, which has been isolated aerodynamically from the subglottal cavity by the sealed glottis. Larynx lowering is supposed to rarefy the air in the oral cavity during implosives. This is Catford's (1939) and Ladefoged's (1971) "glottalic airstream" mechanism. Though larynx lowering during implosives was not investigated, larynx raising during the articulation of ejectives by speakers of Tigrinya was found to be too slow and too poorly coordinated with the closure and release of the stop to have any dramatic effect on Po. This suggests that larynx raising is not the principal mechanism behind the extreme elevation of Po observed for ejectives.

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This hypothesis is supported by modelling ejective articulations where the contraction of the oral cavity that could be obtained by larynx raising alone was found to not elevate Po sufficiently. Other maneuvers which would contract the cavity, such as retracting the tongue root, together with an increase in the stiffness of the walls of the vocal tract to reduce passive expansion in response to increasing Po, must also be employed if Po is to be elevated as high as it typically is in the articulation of an ejective.

Data presented in chapter 3 shows that vertical movement of the larynx is also an unlikely mechanism for perturbing Fo of following vowels. A correlation has been observed between the height of the larynx during the stop and Fo at the onset of the following vowel for voiced and voiceless stops in a number of languages: both the larynx and Fo are relatively lower during voiced than voiceless stops. This correlation led Hombert, Ohala, and Ewan (1979) to suggest that raising or lowering the larynx increases or reduces the amount of vertical tension applied to the vocal folds, thus elevating Fo after voiceless stops and depressing it after voiced ones. In its simplest form, this hypothesis predicts that larynx raising will always elevate Fo, while larynx lowering will depress it; therefore, Fo should be elevated after ejectives and depressed after implosives. Phonological evidence suggests that implosives pro-

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bably elevate Fo rather than depress it, but little phonetic data is available. The data on ejective's effects on Fo is ambiguous, even within a single language. Though Fo was elevated after ejectives in the speech of one speaker of Tigrinya (Kingston 1982), in the data from the three speakers whose speech is described in chapter 3, Fo is either unperturbed or depressed instead, despite the fact that all three speakers raise their larynges, though in different amounts, in producing ejectives. The fact that larynx raising does not elevate Fo after ejectives for these speakers could be attributed to the stiffening and medial compression of the vocal folds which is required to effect a tight glottal seal and which could swamp the increase in vertical tension brought about by raising the larynx. The effect of vertical movement of the larynx on Fo may therefore only be noticeable in oral stops, where no especial stiffening or slackening of the folds occurs (but see Halle & Stevens (1971)). This attempt to salvage the larynx movement as the mechanism behind the perturbation of Fo for oral if not glottalic stops is precluded in Tigrinya, however, since there is no strong positive correlation between larynx height and Fo for the oral stops in that language either.

It should be noted that unlike the languages examined by Hombert, Ohala, and Ewan, Fo at the onset of a vowel following a voiced stop in Tigrinya was not markedly lower than it was

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after a voiceless stop. After both kinds of stops in this language, Fo rose gradually, much as it did after ejectives. The absence of marked differences in Fo following the three kinds of stops in Tigrinya compared to more noticeable differences observed in English, for example, suggests that stops which are phonologically identical, i.e. voiced, voiceless, etc., may be phonetically quite different in different languages or even for different speakers (see Caisse (1982) for a demonstration of crosslinguistic differences in Fo perturbations following voiceless unaspirated stops). Phonetic variability of this sort provides a means of explaining sound changes or rules which appear to be anomalous from a strictly phonological point of view.

The shared goal of the discussions in chapters 2 and 3 has been to show that larynx movement is not a particularly significant articulation, since it appears to be incapable of affecting either Po or Fo.

In chapter 4, the discussion turns away from the focus on larynx movement of the two preceding chapters to a more general discussion of the ways laryngeal and glottal articulations are coordinated with oral ones. It is suggested there that in stops, where the oral articulation completely obstructs the flow of air out of the mouth, glottal articulations are more tightly bound to oral ones than in fricatives or sonorants, where the oral articulation does not

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obstruct air flow completely. The articulatory event to which the glottal articulations accompanying stops are bound is the release of the stop, an acoustically salient event which is absent in fricatives and sonorants. As a result of binding the glottal articulations to the stop release, their acoustic effects will be packed into the short interval surrounding it. The glottal articulations which accompany the production of fricatives and sonorants will vary more in when they occur viz-a-viz the oral maneuvers of the consonant because of the lack of a salient anchor point. Their acoustic effects are therefore more likely to be distributed across the consonant and the glottal articulation is more likely to shift off the consonant entirely onto the surrounding vowels.

Since stops are more likely to be released before vowels than after them, it more likely that glottal articulations will be distinctive on prevocalic than postvocalic stops, or in structural terms in syllable onsets rather than syllable codas. Evidence is presented from Klamath that glottal contrasts for stops are only maintained when the stop precedes a vowel or sonorant and are neutralized elsewhere. So long as a complex onset consisting of a stop followed by a sonorant is allowed by the syllable canon of this language, then stops can be shown to contrast for glottal features only when they

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occur in syllable onsets. However, if the neutralization of glottal contrasts is sensitive to whether the stop is in an onset or not, then Klamath words must be syllabified twice. The first syllabification is quite uniform; only a single consonant of any type is allowed in an onset. In other words, no complex onsets occur. A rule deleting reduced vowels when they occur in open syllables applies to the output of this initial, uniform syllabification. Crucially, this rule is blocked when the reduced vowel is followed by a sequence consisting of a stop followed by a sonorant, which indicates that at this stage in the derivation the syllable boundary falls between rather than before the two consonants. Following the application of vowel deletion, such sequences are resyllabified, creating the one type of complex onset allowed in the language. The functional contrast between the deep and surface syllabifications and the two rules which are sensitive to them, vowel deletion and neutralization of glottal contrasts, is quite clear. Vowel deletion is sensitive to syllable weight, specifically, the presence of at least one tautosyllabic consonant following the reduced vowel. It is completely irrelevant just what this consonant is, all that is needed to block vowel deletion is for one nonsyllabic to follow the reduced vowel in the same syllable. The syllabification which precedes vowel deletion is equally indifferent

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to the kind of consonant it applies to; all that matters is that the potential onset segment is nonsyllabic. The second syllabification and the neutralization of glottal contrasts which it conditions is instead sensitive to the content of the following feature matrix. A stop can shift from the coda of the preceding syllable to the onset of the following one and thereby escape neutralization just so long as the following segment is + sonorant .

Because of the constraints on the occurrence of glottal contrasts for stops in Klamath, in clusters of stops in this language only the last stop can bear a distinctive glottal feature; glottal contrasts are neutralized on all the other stops in the cluster. Since at most a single stop can occur in a syllable onset, the neutralization of glottal contrasts for nonfinal stops in such clusters is a result of their occuring in a syllable coda. The neutralization of glottal contrasts for nonfinal stops in stop clusters is simply one of the manifestations of the binding hypothesis. Equally common is assimilation or agreement in glottal features among the members of the cluster, as in Russian, Kabardian, and Attic Greek.

Somewhat rarer is the situation found in Cambodian, where the consonants in a cluster disagree in glottal features. Consonants in this language exhibit a three-way contrast in glottal

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aperture: [+ spread] /p^h, t^h, c^h, k^h, s, h/; [- spread, - constricted], obstruents /p, t, c, k/ and sonorants /m, n, ɲ, ŋ, r, l, w, y/; and [+ constricted] /b, d, ʔ/. In clusters in this language where the first consonant is not a sonorant, the constituents of the cluster disagree in the size of the glottis. As in Klamath, it appears that it is the prevocalic consonant which shows a contrast for glottal aperture, while the size of the glottis for the nonprevocalic consonant is predictable. Therefore, as in Klamath, it is unnecessary to independently specify the the glottal features of each consonant in a cluster in Cambodian.

In the second half of chapter 4, three examples are presented of the relative instability of the association of glottal features to oral ones in continuants, i.e. fricatives and sonorants, compared to noncontinuants, i.e. stops.

First, in Makah and Nitinat, the glottalized sonorants still found in closely related Nootka have lost their glottalization. Glottalization has disappeared without a trace in all positions, except when the originally glottalized sonorant followed a short vowel, where the loss of glottalization is is compensated by lengthening the vowel. This suggests that glottalized sonorants were reanalyzed in Makah and Nitinat

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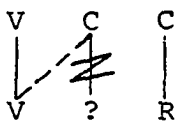
as a sequence of a glottal stop followed by a sonorant. The glottal stop is lost in all positions except when the preceding syllable nucleus dominates just a single segment. In this environment, the glottal stop itself is also lost, but its slot is preserved by extending an association line from the preceding vocalic segment to it; i.e.

(1)



Deglottalization with compensatory lengthening persists as a synchronic process in Makah and Nitinat since there is a set of suffixes which glottalize the final segment of a stem. In all the Wakashan languages these suffixes create ejectives when attached to stems ending in stops and they create glottalized sonorants in Nootka and Kwakw'ala when attached to stems ending in fricatives -- glottalization is accompnaied by deobstruentization in such stems. The glottalized sonorants created from stem-final fricatives in Makah and Nitinat have, like original glottalized sonorants, deglottalized, again with compensatory lengthening of a preceding short vowel.

Second, in the various Yokuts dialects glottalized sonorants also behave as though they consisted of a sequence of a glottal stop followed by a sonorant in that they cannot occur word-initially or after another consonant -- no consonant clusters

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occur at the beginnings of words and at most two consonants may occur between vowels in this language. On the other hand, although long vowels are normally shortened before consonant clusters, they remain long before glottalized sonorants. The ambiguous behavior of this class of segments can be resolved through the use of a two-tiered representation consisting of a single consonant slot in the CV skeleton dominating two segments in the segmental melody, i.e.

(2)

Finally, the structural constraints on the development of tones in Athabaskan languages are considered. In these languages, one tone, high or low, called the "marked" tone by Leer (1979) and Krauss (1979), appears on stems with short vowels that originally ended in a glottal stop or ejective, while the opposite tone, low or high, called the "unmarked" tone, appears on stems which ended in an oral obstruent. It is suggested that glottalization is detached from the final consonant and reattached to the preceding syllable nucleus in stems where the marked tone appears. The reattachment of glottalization to the syllable nucleus is blocked, however, in stems with long vowels, apparently because the nucleus can only have two branches, both of which are attached to a segment when the stem vowel is

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long. As a result, the unmarked tone appears on such stems. However, if the stem-final ejective is spirantized, the marked tone develops on stems with long vowels as well. The marked tone also appears on stems which originally ended in glottalized sonorants, regardless of whether the stem vowel is long or short, so it appears that glottalization is so loosely linked to continuants in these languages that the fact that both nucleus slots are linked to a segment cannot deter the reattachment of glottalization to the nucleus. Reattachment is only constrained so long as the stem-final consonant remains a stop.

In each of the three cases outlined above, it has been shown that glottalized continuants tend to behave phonologically as a sequence of a glottal stop followed by the continuant consonant. As a consequence, the glottal stop is subject to rules which detach the glottal stop from its consonant slot which do not affect the continuant. Glottalized noncontinuants, i.e. ejectives, occur in all three of the language groups discussed, but glottalization remains tightly bound to the oral articulation in all of them.

The binding hypothesis and its various corollaries is only a small part of a complete theory of the coordination of glottal articulations with oral ones and the hypothesis will undoubtedly undergo extensive revision as the theory develops. However, it

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appears likely that the most basic assumption of this hypothesis, that oral articulations anchor glottal ones, will survive revision. To be more precise, any oral maneuver which rapidly changes the shape of the vocal tract and as a result rapidly modulates the acoustic properties of the signal is a potential anchor for a glottal articulation. It is the salience of the interval of rapid acoustic modulation that makes the oral maneuvers effective anchor points for the timing of glottal articulations.

Since the change in signal characteristics which can be acheived by changing the state of the glottis can be as salient as that accomplished by oral articulations, the question arises as to why oral articulations are not anchored by glottal ones. It is easy to find answers to this question, but all are fatally flawed. First, in many languages more paradigmatic distinctions are carried by oral features such as place than by glottal features such as voicing. For example, Kwakw'ala distinguishes five places of articulation for stops: bilabial, alveolar, palatal, velar, and uvular, but there is only a three-way contrast for glottal features: voiceless aspirated, voiced, and ejective. However, in Yuchi only three places of articulation are distinguished for stops: bilabial, alveolar, and velar, while there is a four-way contrast in glottal features: voiceless unaspirated,

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voiceless aspirated, voiced, and ejective. Second, it may be the case that oral features change value syntagmatically with greater frequency than glottal features do, i.e. an entire string may be voiced, but it is certainly possible to find strings where glottal features change value as frequently as oral ones do. At a more microscopic level, it should be noted that even though an entire string may be voiced, this does not mean that the state of the glottis remains unchanged throughout the string since segment-by-segment adjustments of the vocal folds appear to be necessary to keep voicing going behind different oral articulations. Finally, certain glottal features, particularly those representing Fo, i.e. tone and intonation features, are frequently prosodies; that is, they are properly features of entire strings rather than single segments. This is perhaps the most compelling justification for the difference between oral and glottal features with respect to their binding capability since it implies that glottal features in general require oral anchors if they are to be aligned properly with a string. However, a number of strictly oral prosodies, i.e. vowel and nasal harmony, are found in a wide variety of languages, so oral features as a class are no more nonprosodic than glottal ones. Because of the flaws in each of these three attempts to explain why oral articulations anchor glottal ones rather than vice versa, this assumption will have to be taken

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as an axiom in the theory of articulatory coordination, or perhaps simply as a yet unproven conviction.

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References

Abbreviations

ANLC RP = Alaska Native Language Center Research Papers.

Ann. Bull. RILP. Tokyo = Annual Bulletin of the Research Institute of Logopedics and Phoniatrics. Tokyo.

Haskins SR = Status Report of Haskins Laboratories.

IJAL = International Journal of American Linguistics.

JASA = Journal of the Acoustical Society of America.

JP = Journal of Phonetics.

LI = Linguistic Inquiry.

LTBA = Linguistics of the Tibeto-Burman Area.

QPR PLE MIT = Quarterly Progress Report. Research Laboratory in Electronics. Massachusetts Institute of Technology.

UCB RPL = University of California, Berkeley. Reports of the Phonology Laboratory.

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