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Kinematic analysis of mandibular motion before and after mandibulectomy and mandibular reconstruction in dogs

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OBJECTIVE

To evaluate and quantify the kinematic behavior of canine mandibles before and after bilateral rostral or unilateral segmental mandibulectomy as well as after mandibular reconstruction with a locking reconstruction plate in *ex vivo* conditions.

SAMPLE

Head specimens from cadavers of 16 dogs (range in body weight, 30 to 35 kg).

PROCEDURE

Specimens were assigned to undergo unilateral segmental ($n = 8$) or bilateral rostral (8) mandibulectomy and then mandibular reconstruction by internal fixation with locking plates. Kinematic markers were attached to each specimen in a custom-built load frame. Markers were tracked in 3-D space during standardized loading conditions, and mandibular motions were quantified. Differences in mandibular range of motion among 3 experimental conditions (before mandibulectomy [ie, with mandibles intact], after mandibulectomy, and after reconstruction) were assessed by means of repeated-measures ANOVA.

RESULTS

Both unilateral segmental and bilateral rostral mandibulectomy resulted in significantly greater mandibular motion and instability, compared with results for intact mandibles. No significant differences in motion were detected between mandibles reconstructed after unilateral segmental mandibulectomy and intact mandibles. Similarly, the motion of mandibles reconstructed after rostral mandibulectomy was no different from that of intact mandibles, except in the lateral direction.

CONCLUSIONS AND CLINICAL RELEVANCE

Mandibular kinematics in head specimens from canine cadavers were significantly altered after unilateral segmental and bilateral rostral mandibulectomy. These alterations were corrected after mandibular reconstruction with locking reconstruction plates. Findings reinforced the clinical observations of the beneficial effect of reconstruction on mandibular function and the need for reconstructive surgery after mandibulectomy in dogs. (*Am J Vet Res* 2019;80:637–645)

Malignant or benign but locally destructive tumors of the mandible can have a substantial impact on the quality of life of affected dogs.^{1,2} Therefore, it is generally accepted that when possible, mandibular tumors should be promptly removed by means of mandibulectomy.¹⁻³ Other treatment modalities such as radiation therapy and intralesional chemotherapy may also be used, either to complement mandibulectomy or as a sole treatment, depending on the tumor type.⁴ However, the excision of bone and soft tissue structures of the mandible, as occurs with mandibulectomy, disrupts continuity of the mandible, and the associated critical-size bone defect severely compromises mobility of the remaining mandibular segments.^{2,5}

ABBREVIATIONS

TMJ Temporomandibular joint

The intact support of the TMJ and the masticatory forces on the unaffected side in dogs undergoing mandibulectomy result in the intact mandible typically drifting away from the median plane and toward the excised side without deliberate muscular guidance. The nature of such mandibular drift is typically dependent on the site of mandibulectomy.^{1,2,5,6} Specifically, unilateral segmental and bilateral rostral mandibulectomy result in mandibular instability and drift and may result in difficulty in eating and drinking. Moreover, the drift and instability of the mandible may result in stress on the muscles of mastication and the TMJ as the dog attempts to reposition the jaw to its normal position.^{7,8} In the long term, mandibular drift may result in irreversible changes such as TMJ osteoarthritis.⁹

Over the past decade, a regenerative approach to mandibular reconstruction in companion dogs

has been reported by our group and others.^{6,10-14} The main goals of mandibular reconstruction in dogs are the restoration of dental occlusion, mandibular stability, and normal function, which includes physiologic mouth opening and closing and minimal lateral movement (ie, laterotrusion).^{6,10,15} People undergoing mandibular reconstruction after mandibular tumor excision have superior function, aesthetics, and quality of life, compared with those who do not undergo mandibular reconstruction,¹⁶⁻²⁰ and our experience performing mandibular reconstruction suggests that results are similar for dogs.

An understanding of normal jaw motion and the effects of mandibulectomy on that motion can provide clinically relevant insight into the complex masticatory changes that occur after mandibulectomy.²⁰⁻²² To our knowledge, no studies have been reported regarding mandibular kinematics in dogs, the effects of mandibulectomy on those kinematics, or the kinematic outcome of restoring mandibular stability in dogs by means of internal fixation. Therefore, the purpose of the study reported here was to evaluate the motion of intact canine mandibles, the kinematic behavior of mandibles treated with unilateral segmental or bilateral rostral mandibulectomy, and the kinematic behavior of mandibles treated with unilateral segmental or bilateral rostral reconstruction. We hypothesized that mandibular kinematics in dogs would be adversely affected (ie, significant deviation from the motions of the intact mandible) by unilateral segmental or bilateral rostral mandibulectomy. We further hypothesized that reconstructive surgery, which restores the continuity after mandibulectomy, would restore normal mandibular kinematics. We believed the findings would allow evaluation of the kinematic benefits of mandibular reconstruction to enhance surgical techniques.

Materials and Methods

Specimens

Head specimens were obtained from the cadavers of 16 dogs (range in body weight, 30 to 35 kg) that were skeletally mature, had been euthanized for reasons unrelated to the study, and were assigned for unrestricted use. These cadavers had been previously frozen immediately after euthanasia, then thawed for use in the study.

Study design

The study was designed such that each head specimen was evaluated in 3 experimental conditions in the following order: before mandibulectomy (ie, intact mandibles; control treatment), after mandibulectomy, and after mandibular reconstruction. Eight specimens were arbitrarily selected to

undergo unilateral segmental mandibulectomy and reconstruction, and the remaining 8 were assigned to undergo bilateral rostral mandibulectomy and reconstruction.

Specimen preparation

A custom-built load frame was connected to each head specimen while allowing the mandibles to move freely during kinematic testing (**Figure 1**). Two 4.0-mm-diameter threaded fixation pins^a were secured into the dorsal aspect of the cranium to fix the specimen onto the apparatus. Threaded fixation pins measuring 1/8 inch (3.17-mm) in diameter^a were drilled into the mandibles at the level of the maxillary third premolar teeth bilaterally (**Figure 2**). Two spherical reflective kinematic markers were attached to each pin in the mandibles and were used to collect data for displacement changes of the mandibles. A set of 3 orthogonal pins was attached into the nasal bone by use of a 1/8-inch (3.17-mm) threaded pin to provide a skull-based reference frame. To apply movement to the mandibles, an eyebolt was drilled in each mandible at the level of the mandibular fourth premolar tooth. The eyebolts were used to pull the mandibles in different directions. Once a head specimen was secured and leveled, the kinematic markers were placed on it and a black cloth was draped over the specimen to provide contrast for easy and reliable tracking of the kinematic markers.

Kinematic testing and experimental conditions

Traction was applied to the mandibles at a standard load of 6 kg to determine the extent of displacement change in multiple directions. To achieve this, a standardized weight was attached to an eyebolt in

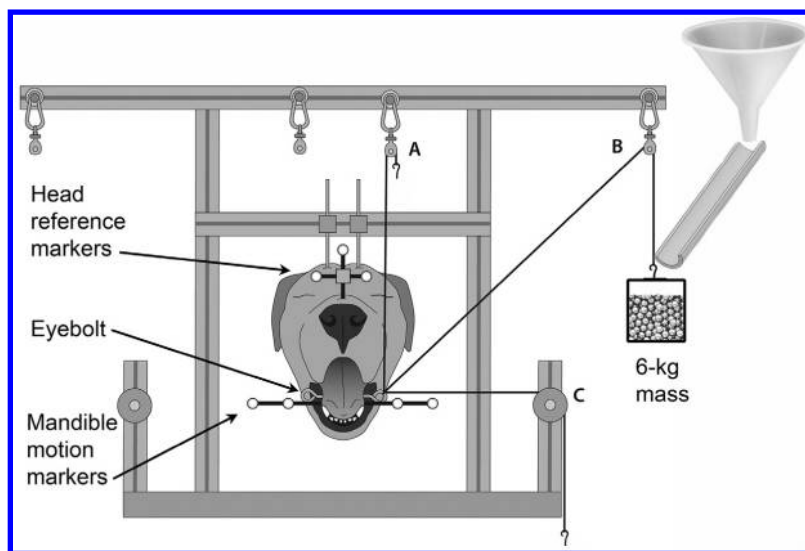


Figure 1—Diagram of the setup used for kinematic testing of canine mandibles in various conditions. A head specimen from a canine cadaver was mounted in a custom-built load frame, and the mandible was pulled in 3 directions on both the left and right sides. Directions for the left side are illustrated and included dorsal traction (A), dorsolateral traction at 45° (B), and lateral traction (C). The pulley positions are in the transverse plane at the level of the eyebolts.

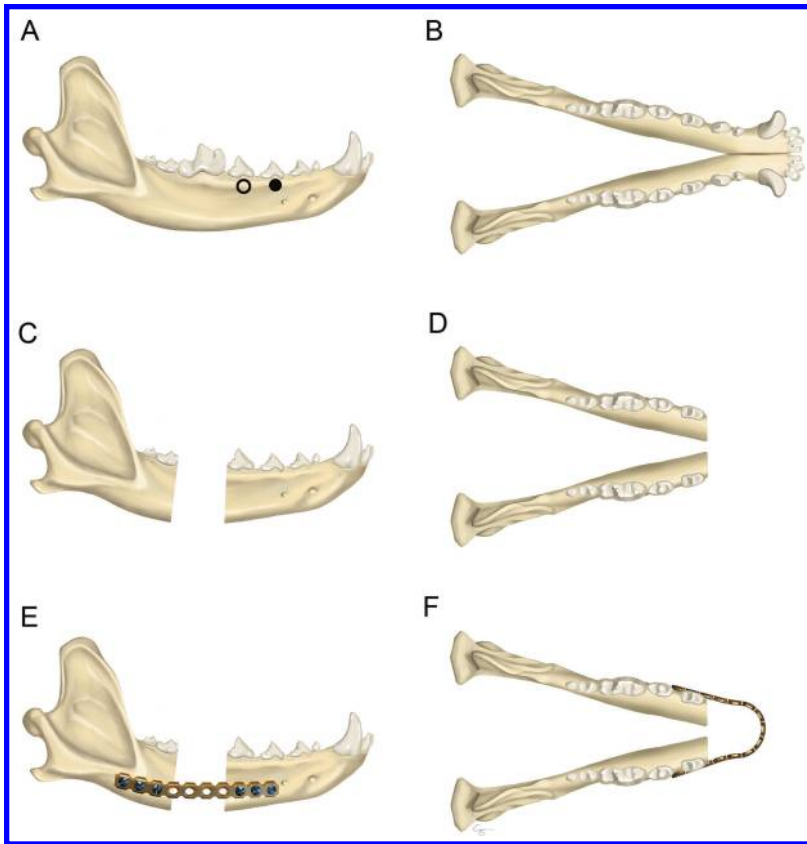


Figure 2—Diagram indicating the mandibulectomy sites and techniques and subsequent mandibular reconstructions subjected to kinematic analysis in the study. Mandibular kinematic analysis was performed on intact mandibles (A and B) first and then on the same mandibles after right unilateral segmental mandibulectomy (C) or bilateral rostral mandibulectomy (D) was performed. The mandibles were then reconstructed accordingly (E and F) and retested. The location of the motion tracking pin (black circle) and the eyebolt (open circle) is shown in panel A.

the left and right mandibles at the level of the fourth premolar tooth. The mandibles were pulled separately in lateral, dorsolateral, and dorsal directions, to the left and right sides, by attachment of a wire to the eyebolt in the mandible and a system of pulleys (Figure 1). Tests were initiated with the jaw in an open position.

The magnitude of the traction load was standardized as well as the loading profile. The magnitude of weight was determined in preliminary tests that involved increasing weights to find a load associated with a plateau in displacement at which the mandibles no longer displaced with increasing loads. The loading rate profile was kept consistent by pouring 6 kg of 2.8-mm-diameter copper-coated lead balls through a tube of standard diameter (25 mm) into a container hanging at the end of the wire. Before each load application, the mandibles were reset to a standard start position determined by the position that the intact mandibles hung naturally owing to gravity in the intact condition, then allowed to hang unrestricted. The order of the direction of load application (dorsal, dorsolateral, or lateral) in each head specimen was changed for each successive specimen so that the effect of load direction order on the results was minimized in the statistical analysis. However, the load

direction order remained the same for the treatments within a specimen. Motion of the mandibles from a neutral position to each extent was recorded by 2 high-resolution monochrome 60-Hz video cameras^b that were calibrated in a 3-D space.

After kinematic testing of the intact mandibles, right unilateral segmental or bilateral rostral mandibulectomy was performed (Figure 2). For unilateral segmental mandibulectomy, the mandibular segment containing the first molar tooth was removed as described elsewhere.²³ For bilateral rostral mandibulectomy, the mandibular segments rostral to the third premolar teeth were removed to reflect the clinical scenario.¹⁰

After kinematic testing of the mandibulectomy condition, either a 10-hole, 2.4-mm locking reconstruction titanium locking plate^c was appropriately contoured and secured to the right buccal (abaxial) surface of the mandible, just dorsal to the mandibular canal and ventral to the tooth roots, with three 3-mm locking screws^d on either side of the defect (unilateral segmental mandibulectomy), or a 14-hole long plate^c was contoured to the rostral portion of each mandible and secured with 3-mm screws (bilateral rostral mandibulectomy; Figure 2).²³ Kinematic testing was then performed on the reconstructed

specimens.

Kinematic data were reduced by use of kinematic software^e that digitized the locations of mandible markers relative to reference markers on the head specimen (Figure 3). Virtual markers were created at the insertion sites of the mandible marker pins on the lateral aspect of the mandibles. Linear displacements of the virtual markers (ie, left or right mandible) were calculated in the mediolateral, rostrocaudal, and dorsoventral directions for each direction of loading (left dorsal, right dorsal, left lateral, right lateral, left dorsolateral, and right dorsolateral). The intermandibular distance was measured as the distance between the left-lateral and right-lateral virtual markers. Amount of mandible separation was defined as the jaw width relative to the initial intact condition.

Statistical analysis

Mixed-model ANOVA^f was used to identify significant differences in kinematic data among the 3 experimental conditions (intact mandibles, after mandibulectomy, and after mandibular reconstruction), stratified by traction direction (dorsal, dorsolateral, and lateral). Mandibulectomy technique (unilateral segmental or bilateral rostral) was treated as a fixed effect. Head

specimen was treated as a random effect, and the repeated measurements within specimens were accounted for in the analyses. Normality of the distributions of the displacement data for the mandibles, stratified by traction direction, was evaluated^{f,g} by use of the residuals from the ANOVA. If the Shapiro-Wilk statistic was < 0.90, then group comparisons were made by performance of post hoc pairwise comparisons on the ranked values. If data were normally distributed, group comparisons were performed by testing for differences in least squares mean values.

The degree of displacement of the mandibles in the unloaded condition was assessed without stratifying by pull direction. These data were normally distributed, so ANOVA was performed and differences were reported as least squares mean ± SE. For all statistical tests, differences were considered significant at a value of *P* < 0.05.

Results

Specimens

Head specimens assigned to undergo unilateral segmental mandibulectomy originated from 5 Bull

Terriers, 1 German Shepherd Dog, and 2 mixed-breed dog. Mean ± SD jaw width between the insertion points of the kinematic markers was 38.0 ± 14.1 mm, and mean distance from the TMJ center to the eyebolt in the mandible was 102.1 ± 10.4 mm.

Head specimens assigned to undergo bilateral rostral mandibulectomy included 7 mixed-breed dogs and 1 Bull Terrier. Mean ± SD jaw width between the insertion points of the kinematic markers was 47.7 ± 6.6 mm, and mean distance from the TMJ center to the eyebolt in the mandible was 96.9 ± 10.0 mm.

Intact mandible kinematics in traction (grouped right and left mandibles)

Data for the left and right mandibles combined for all 16 head specimens were summarized to show the extent of motion that resulted from loading of the mandibles in each direction before mandibulectomy was performed (ie, with the mandibles intact; **Table 1**).

Mandible kinematics in the resting (unloaded) state

Right unilateral segmental mandibulectomy—Right

unilateral segmental mandibulectomy affected mandibular position in the resting state. Both mandibles drifted significantly mediolaterally to the left (left mandible by a mean of 4.2 mm and right mandible by a mean of 6.5 mm; **Table 2**). After reconstruction, the left mandible position was not significantly different from that of the intact left mandible, but the right still retained a left mean drift of 4.8 mm.

Mandibulectomy resulted in significant caudal and ventral displacement in both mandibles. After reconstruction, there was no significant difference in rostrocaudal or dorsoventral position, compared with positions in intact mandibles.

Bilateral rostral mandibulectomy—

After bilateral rostral mandibulectomy, both mandibles drifted laterally in respective abaxial directions. The left mandible drifted a mean of 11.6 mm and right mandible a mean of -3.4 mm (**Table 2**). After reconstruction, no significant difference in left mandible po-

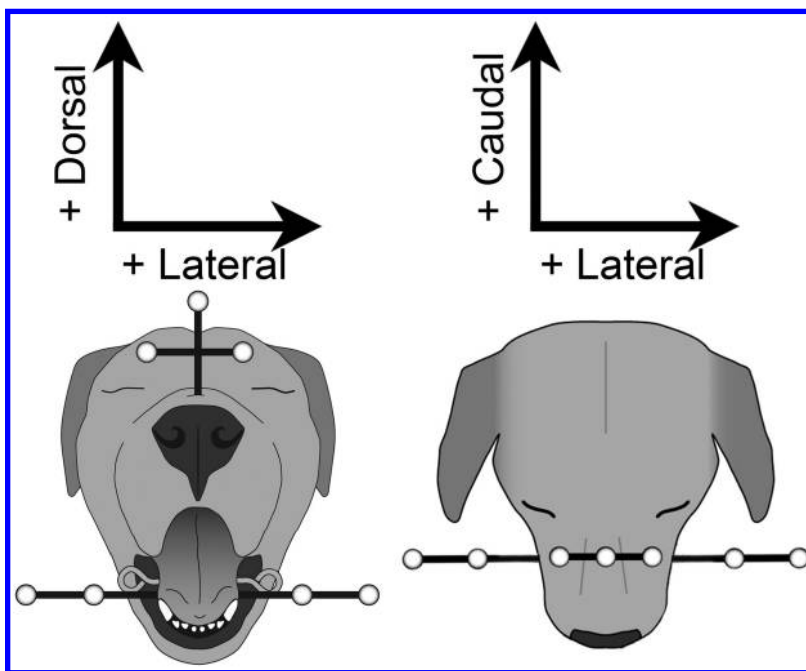


Figure 3—Diagram of the coordinate system used for position directions in the study.

Table 1—Median (interquartile [25th to 75th percentile] range) displacement values (mm) for mandibular motion resulting from loading in different directions of both the left and right sides in head specimens from canine cadavers (*n* = 16) evaluated with the mandibles intact.

Traction direction	Lateral displacement	Dorsoventral displacement*	Rostrocaudal displacement†
Lateral	8.5 (6.7–12.4)	5.8 (3.3–7.8)	-2.1 (-5.2 to -0.4)
Dorsolateral	4.5 (1.6–8.8)	29.6 (22.4–35.1)	-11.7 (-13.6 to -7.5)
Dorsal	2.4 (1.0–6.8)	32.7 (27.7–41.6)	-13.6 (-17.2 to -10.2)

*Positive values indicate dorsal displacement, and negative values indicate ventral displacement. †Positive values indicate caudal displacement, and negative values indicate rostral displacement.

Table 2—Least squares mean \pm SE displacement values (mm) for mandibular motion resulting from loading in different directions in the resting position for each mandible in head specimens from canine cadavers before (intact) and after right unilateral segmental mandibulectomy (n = 8) or bilateral rostral mandibulectomy (8) and subsequent mandibular reconstruction.

Mandibulectomy type	Mandible	Direction of displacement	Mandible condition		
			Intact	After mandibulectomy	After reconstruction
Unilateral segmental	Left	Lateral	0.5 \pm 0.8 ^a	4.2 \pm 0.8 ^b	1.3 \pm 0.9 ^a
		Rostrocaudal	0.4 \pm 1.0 ^a	3.3 \pm 0.9 ^b	1.7 \pm 1.0 ^{a,b}
		Dorsoventral	-0.7 \pm 1.8 ^a	-8.5 \pm 1.7 ^b	-4.6 \pm 1.8 ^{a,b}
	Right	Lateral	0.3 \pm 0.7 ^a	6.5 \pm 0.7 ^b	4.8 \pm 0.8 ^b
		Rostrocaudal	0.6 \pm 0.8 ^a	2.9 \pm 0.8 ^b	1.9 \pm 0.8 ^{a,b}
		Dorsoventral	-1.0 \pm 1.8 ^a	-10.6 \pm 1.8 ^b	-4.1 \pm 1.8 ^a
Bilateral rostral	Left	Lateral	0.8 \pm 0.6 ^a	11.6 \pm 0.6 ^b	2.4 \pm 0.6 ^a
		Rostrocaudal	0.2 \pm 0.8 ^a	4.0 \pm 0.8 ^b	2 \pm 0.8 ^{a,b}
		Dorsoventral	1.0 \pm 0.6 ^a	-8.4 \pm 0.6 ^b	-1.9 \pm 0.6 ^c
	Right	Lateral	1.6 \pm 0.7 ^a	-3.4 \pm 0.7 ^b	5.3 \pm 0.7 ^c
		Rostrocaudal	-0.8 \pm 0.6 ^a	3.3 \pm 0.6 ^b	1.9 \pm 0.6 ^b
		Dorsoventral	0.3 \pm 0.6 ^a	-6.7 \pm 0.6 ^b	-3.1 \pm 0.6 ^c

^{a-c}Within a row, values with different superscript letters differ significantly ($P < 0.05$).

Table 3—Least squares mean \pm SE intermandibular distance (mm) in the head specimens of Table 2 before (no traction [ie, resting state]) and at peak traction in various directions.

Mandibulectomy type	Traction direction	Mandible condition		
		Intact	After mandibulectomy	After reconstruction
Unilateral segmental	None	0.08 \pm 0.09 ^a	0.86 \pm 0.09 ^b	-0.20 \pm 0.09 ^c
	Left lateral	0.93 \pm 0.53 ^a	0.36 \pm 0.58 ^a	1.32 \pm 0.53 ^a
	Left dorsolateral	0.35 \pm 0.40 ^a	1.08 \pm 0.40 ^a	0.09 \pm 0.40 ^a
	Left dorsal	0.41 \pm 0.29 ^a	0.68 \pm 0.29 ^a	0.14 \pm 0.35 ^a
	Right lateral	0.58 \pm 0.39 ^a	1.30 \pm 0.39 ^a	1.51 \pm 0.39 ^a
	Right dorsolateral	0.32 \pm 0.33 ^a	1.29 \pm 0.33 ^a	0.38 \pm 0.33 ^a
	Right dorsal	0.41 \pm 0.26 ^a	0.63 \pm 0.26 ^a	0.02 \pm 0.28 ^a
Bilateral rostral	None	-0.69 \pm 0.57 ^a	15.45 \pm 0.57 ^b	-3.21 \pm 0.57 ^c
	Left lateral	0.04 \pm 1.59 ^a	22.47 \pm 1.59 ^b	-1.43 \pm 1.59 ^a
	Left dorsolateral	-0.40 \pm 1.76 ^a	19.50 \pm 1.76 ^b	-2.73 \pm 1.91 ^a
	Left dorsal	-0.48 \pm 1.46 ^a	13.61 \pm 1.46 ^b	-3.29 \pm 1.46 ^a
	Right lateral	-0.29 \pm 1.41 ^a	20.04 \pm 1.41 ^b	-2.43 \pm 1.41 ^a
	Right dorsolateral	-0.44 \pm 1.48 ^a	17.38 \pm 1.48 ^b	-3.00 \pm 1.48 ^a
	Right dorsal	-0.64 \pm 1.74 ^a	12.26 \pm 1.74 ^b	-3.49 \pm 1.74 ^a

Values represent the difference between intermandibular distance at each state and the intermandibular distance at the first intact state before any traction occurred.

See Table 2 for remainder of key.

sition was observed in any direction, compared with positions of the corresponding intact mandible. After mandibular reconstruction, the right mandible differed in position from the corresponding intact mandible by a mean shift of 5.3 mm left laterally, 1.9 mm caudally, and -3.1 mm ventrally.

Mandible kinematics in traction

After mandibulectomy was performed, mandibles displaced significantly farther in all traction directions, but particularly in the lateral directions, than did intact mandibles, regardless of mandibulectomy technique. After reconstruction, mandibles displaced less than after mandibulectomy, and displacement after reconstruction approached that of intact mandibles (**Supplementary Figures S1–S4**, available at avmajournals.avma.org/doi/suppl/10.2460/ajvr.80.7.637).

Right unilateral segmental mandibulectomy—After reconstruction, no significant differences in lateral or rostrocaudal displacements from the positions of the intact mandibles were observed in any traction direction. With left and right lateral traction applied after mandibulectomy, mandibles maximally displaced laterally significantly farther than when intact (mean displacement, 26.9 and 14.7 mm, respectively) or after reconstruction (mean displacement, 23.5 and 13.9 mm, respectively; **Supplementary Figures S1 and S2**). The amount of displacement was less when traction was applied to reconstructed mandibles, compared with the amount after mandibulectomy (**Supplementary Table S1**, available at avmajournals.avma.org/doi/suppl/10.2460/ajvr.80.7.637). With left and right dorsolateral traction applied, no differences in lateral displacement were observed among the 3 experimental

conditions. With dorsal traction applied on the left mandible, after mandibulectomy (on the right side), the left mandible displaced left laterally significantly farther (mean displacement, 6.5 mm) than it did after mandibular reconstruction, but with dorsal traction applied to the right mandible, no difference in lateral displacement was observed among the 3 experimental conditions.

With right lateral traction applied, mandibles after mandibulectomy displaced caudally significantly farther than when intact or reconstructed (mean difference, 10.3 and 10.4 mm, respectively), but with left lateral traction applied, no difference in caudal displacement was observed among these conditions. With dorsolateral or dorsal traction applied, no differences in rostrocaudal displacement were observed among conditions.

Bilateral rostral mandibulectomy—After mandibular reconstruction, no significant differences in lateral or rostrocaudal displacement from values for the intact mandibles were identified in any traction direction, except for a difference in the left mandible with left lateral displacement from left-lateral traction (mean difference, 8.9 mm).

With left and right lateral traction applied, mandibles after mandibulectomy maximally displaced laterally significantly farther than did intact mandibles (mean difference, 33.4 and 29.8 mm, respectively) and reconstructed mandibles (mean difference, 24.5 and 28.9 mm, respectively). With left and right dorsolateral traction applied, mandibles after mandibulectomy maximally displaced laterally significantly farther than did intact mandibles (mean difference, 25.1 and 22.1 mm, respectively) and reconstructed mandibles (mean difference, 26.0 and 26.0 mm, respectively). With right or left dorsal traction applied, no difference in lateral displacement was observed among the 3 experimental conditions.

With right lateral traction applied, a significantly larger caudal displacement was observed for mandibles after mandibulectomy than for intact mandibles (mean difference, 6.1 mm), but no difference in caudal displacement was observed with left lateral traction. No significant differences in caudal displacement were observed among experimental conditions when dorsolateral or dorsal traction was applied.

Intermandibular distance

Mean \pm SE intermandibular distance was 27.0 ± 6.3 mm for head specimens in which unilateral segmental mandibulectomy had been performed and 45.3 ± 3.6 mm for specimens in which bilateral rostral mandibulectomy had been performed. Unilateral segmental mandibulectomy resulted in a larger mean intermandibular distance and the reconstruction a smaller distance in the resting state, compared with the distance in intact mandibles (**Table 3**). With traction applied, no significant differences were identified among the 3 experimental conditions.

Similar to the other mandibulectomy technique, bilateral rostral mandibulectomy resulted in a larger mean intermandibular distance and the reconstruction a smaller distance, compared with the distance in intact mandibles in the resting state. However, with traction applied, there was larger intermandibular distance in all directions due to mandibulectomy but no difference in intermandibular distance owing to the reconstruction, compared with values for the intact mandibles.

Discussion

To our knowledge, the present study was the first to evaluate mandibular kinematics in dogs and to demonstrate several clinically important aspects of mandibular kinematics in intact mandibles as well as after mandibulectomy and reconstruction. First, the extent of laterolateral motion (ie, laterotrusion) of the mandibles of dogs was confirmed and quantified. Second, unilateral segmental and bilateral rostral mandibulectomy significantly altered the normal mandibular kinematics in unloaded conditions. In addition, under lateral traction, both mandibulectomy techniques significantly altered the mandibular kinematics; however, there were no significant differences among the experimental conditions (intact mandibles, after mandibulectomy, and after mandibular reconstruction) under dorsal or dorsolateral traction. Finally, for both mandibulectomy techniques, reconstruction largely resulted in restoration of mandibular kinematics that was indistinguishable from the kinematics of intact mandibles.

Dogs have mandibles that are joined rostrally in a fibrocartilaginous union to form the intermandibular joint or mandibular symphysis and articulate caudally with the temporal bone to form the TMJs.^{24,25} Each mandible rotates about a common transverse axis that passes through the center of each condylar process. The general movement of the TMJ in dogs is hinge-like, and minimal translation motion may be observed in 50% of dogs.²⁶ Results of the present study confirmed the clinical observation that a small amount of lateral movement (ie, laterotrusion) may occur that is limited by the TMJ lateral ligaments and the normal occlusal relationship of the maxillary and mandibular caudal premolar and molar teeth.²⁵ In addition, we demonstrated that the mean passive motion without occlusion of the teeth was 8.5 mm in the lateral, 5.3 mm in the dorsal, and 2.1 mm in the caudal directions. This passive motion is clinically important when assessing mandibular motion in dogs suspected to have TMJ disorders, dogs with head trauma, or dogs with altered mandibular range of motion. Information regarding the normal kinematics of the mandibles would be important for evaluating the mandibular range of motion and effects of mandibulectomy and mandibular reconstruction.^{3,20}

In an unloaded (resting) condition, mimicking the clinical scenario of a dog with only passive mandible motion (ie, not eating, drinking, or barking), unilat-

eral segmental and bilateral rostral mandibulectomy in the present study significantly altered the normal mandibular kinematics. This was in agreement with previous clinical observations that mandibular drift (ie, medial displacement of the intact mandible) can be expected following mandibulectomy,^{2,3,5,6,10,11,27,28} and such alterations occur because the remaining intact mandible has inadequate contralateral support. As observed in the present study, unilateral segmental mandibulectomy resulted in more pronounced mandibular motion in the unloaded condition than did bilateral rostral mandibulectomy. That occurred because the medial aspects of the 2 mandibles after rostral mandibulectomy are close to each other and may even have direct contact.⁵

However, unlike the clinical situation in a live dog, the unloaded testing in the present study measured only the natural tendency of the mandibles to drift without the effect of contraction of the muscles of mastication.^{29,30} A substantial difference may exist between the *ex vivo*, experimental conditions of our study and the clinical situation given that the tendency of the intact mandibles to drift is believed to occur because of the action of the muscles of mastication, particularly the medial pterygoid muscle. Contraction of the medial pterygoid muscle pulls the intact mandible medially (lingually), leading to malocclusion.¹⁹ In the present study, a mandibular drift was also noted to the side contralateral to the mandibulectomy site, which is typically not readily observed in live dogs. Again, that finding may have been due to the natural tendency of the mandibles to drift without the effect of muscles pulling. The present study added to our understanding because it showed that a displacement or drift of the mandibles occurs even without the action of muscles of mastication and such displacement is likely to be exacerbated in the presence of contracting muscles (ie, in a live dog). Even a minimal amount of malocclusion in dogs can cause trauma to the hard palate owing to the impingement of the mandibular canine teeth and challenges with prehension.^{5,6,10,28} Degenerative TMJ disease may also occur with long-lasting malocclusion or mandibular drift.³⁰

When loading the mandibles to their maximal extent in the study reported here, we demonstrated that, particularly with lateral traction, both bilateral rostral and unilateral segmental mandibulectomy significantly altered the kinematics of the mandibles. That was in agreement with previous clinical observations that mandibular drift is exacerbated during eating and drinking, effectively challenging the quality of life of the dogs and their owners.^{3,5,6,10,11} In addition, unilateral segmental mandibulectomy, and less so bilateral rostral mandibulectomy, may disrupt the muscle attachments, adding to the adverse effect of mandibulectomy on the stability of the mandibles. Alterations in mandibular kinematics have a pronounced effect on the way dogs eat, drink, groom themselves, and breathe and may cause traumatic

malocclusion, pain or discomfort during mastication, and long-lasting adverse effects on the TMJ.

When traction was applied to the mandibles to simulate mouth closure in a dorsal or dorsolateral direction, no significant differences were evident among the experimental conditions in the present study. The lack of differences was likely related to interdigitation of the maxillary and mandibular premolar and molar teeth. Once the mandibular teeth engaged the maxillary teeth, the maxillary teeth guided the mandibular teeth and, by proxy, mandibles into an interlocking, appropriate occlusion. The result was that the specimens had no noticeable mandibular drift in that condition. The clinical implications were that once dogs close their mouths beyond the point that the mandibular teeth engage the maxillary teeth, mandibular drift would be minimized.

Both mandibulectomy techniques significantly altered the space between the mandibles that forms the floor of the mouth. In both situations, subsequent reconstruction returned that intermandibular space to premandibulectomy measurements, with a less pronounced alteration in the segmental mandibulectomy under traction. The mandibles have a fundamental functional role in supporting the floor of the mouth, which in turn supports vital functions such as support of the tongue, swallowing, and breathing.^{17,19} Although available information related to the function of dogs after mandibulectomy is based on clinical observations,^{2,3,6,10} observations for people that underwent mandibulectomy indicate they have a reduction in their ability to use the tongue and to eat food that does not require substantial chewing.^{31,32} Moreover, such people can also develop dysphagia.³² Therefore, the findings that mandibular reconstruction assisted in restoring the floor of the mouth were clinically relevant as dogs receiving reconstruction after mandibulectomy are likely to have restored functions of the floor of the mouth and the tongue, allowing easier eating, drinking, and swallowing. Reconstruction is likely to allow dogs to return to normal, long-term function faster and better than no reconstruction.

Bite forces in dogs are important indicators of the functional state of the masticatory system and the ability to generate a sufficient bite for eating, protection, and playing.³³ The jaw adductor muscles, TMJ, and teeth contribute to mastication. Although no bite forces were measured in the present study, reports from human kinematic studies^{17,20} indicate that bite force in patients undergoing mandibular reconstruction surgery is significantly higher than the bite force in those who undergo no reconstruction. Moreover, people who undergo no reconstruction following mandibulectomy partially compensate for the loss of mandibular continuity and mandibular drift with stiffening of the masticatory muscles of the opposing side.¹⁷ When mandibular continuity is reestablished, dental occlusion is also restored and greater occlusal stability allows for more efficient masticatory function. Therefore, it is likely that restoration of conti-

nity and normal kinematics by reconstruction after mandibulectomy in dogs allows the masticatory muscles to function more efficiently.

Findings of the study reported here should be interpreted in the context of the study limitations. Because cadaveric specimens were used, voluntary mandibular motion was lacking. Furthermore, masticatory forces could not be measured. Consequently, the action of the masticatory muscles and its potentially positive effect in stabilization of the mandibles, particularly following unilateral segmental mandibulectomy, could not be assessed. However, the study provided a novel controlled kinematic evaluation of the skeletal aspects of unilateral segmental and bilateral rostral mandibulectomy and mandibular reconstruction with precise quantification of these elements. Evaluation of these elements in live dogs would have been challenging and unreliable, as was observed during bite force measurements in live dogs in another study.³⁴

To the authors' knowledge, the present study was the first to evaluate the kinematic aspects of the mandibles in dogs under 3 conditions: before mandibulectomy, after unilateral segmental or bilateral rostral mandibulectomy, and after mandibular reconstruction. Inspired by our clinical experience, we demonstrated that mandibulectomy has adverse effects and beneficial reconstruction effects on mandibular kinematics that can affect oral functions and quality of life in dogs. Therefore, for dogs undergoing mandibulectomy, the mandibular function, long-term prognosis, and potential adverse effects should be discussed with owners and reconstruction options should be offered.

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Footnotes

- a. IMEX Veterinary Inc, Longview, Tex.
- b. S-PRI, AOS Technologies AG, Baden, Switzerland.
- c. VPT4120.24, DePuy Synthes Vet, a division of DePuy Orthopaedics Inc, West Chester, Pa.
- d. VST311.014, DePuy Synthes Vet, a division of DePuy Orthopaedics Inc, West Chester, Pa.
- e. Motus 10, Contemphas, Kempen, Germany.
- f. PROC MIXED, SAS, version 9.4, SAS Institute Inc, Cary, NC.
- g. PROC UNIVARIATE, SAS, version 9.4, SAS Institute Inc, Cary, NC.

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