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Model to Estimate Threshold Mechanical Stability of Lower Lateral Cartilage

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Abstract

IMPORTANCE—In rhinoplasty, techniques used to alter the shape of the nasal tip often compromise the structural stability of the cartilage framework in the nose. Determining the minimum threshold level of cartilage stiffness required to maintain long-term structural stability is a critical aspect in performing these surgical maneuvers.

OBJECTIVE—To quantify the minimum threshold mechanical stability (elastic modulus) of lower lateral cartilage (LLC) according to expert opinion.

METHODS—Five anatomically correct LLC phantoms were made from urethane via a 3-dimensional computer modeling and injection molding process. All 5 had identical geometry but varied in stiffness along the intermediate crural region (0.63–30.6 MPa).

DESIGN, SETTING, AND PARTICIPANTS—A focus group of experienced rhinoplasty surgeons (n = 33) was surveyed at a regional professional meeting on October 25, 2013. Each survey participant was presented the 5 phantoms in a random order and asked to arrange the phantoms in order of increasing stiffness based on their sense of touch. Then, they were asked to select a single phantom out of the set that they believed to have the minimum acceptable mechanical stability for LLC to maintain proper form and function.

MAIN OUTCOMES AND MEASURES—A binary logistic regression was performed to calculate the probability of mechanical acceptability as a function of the elastic modulus of the LLC based on survey data. A Hosmer-Lemeshow test was performed to measure the goodness of

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Study concept and design: Kim, Wong.
Acquisition, analysis, or interpretation of data: All authors.
Drafting of the manuscript: All authors.
Critical revision of the manuscript for important intellectual content: Kim, Wong.
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fit between the logistic regression and survey data. The minimum threshold mechanical stability for LLC was taken at a 50% acceptability rating.

RESULTS—Phantom 4 was selected most frequently by the participants as having the minimum acceptable stiffness for LLC intermediate care. The minimum threshold mechanical stability for LLC was determined to be 3.65 MPa. The Hosmer-Lemeshow test revealed good fit between the logistic regression and survey data ($\chi_3^2=0.92$, P = .82).

CONCLUSIONS AND RELEVANCE—This study presents a novel method of modeling anatomical structures and quantifying the mechanical properties of nasal cartilage. Quantifying these parameters is an important step in guiding surgical maneuvers performed in rhinoplasty.

LEVEL OF EVIDENCE—5.

In rhinoplasty, techniques used to change the shape of cartilaginous structures in the nose often compromise the physical stability. Traditional methods for changing nasal and suturing techniques. Apart from suture approaches, all other nasal tip cartilage approaches require the careful, limited destruction or removal of specific regions in the cartilage and thus alter overall mechanical stability.[1,2] Although newer, less invasive methods for cartilage reshaping, such as cartilage thermoforming and electromechanical reshaping, can achieve shape change without requiring actual incisions to the cartilage, they alter the chemical composition of the cartilage and create some degree of tissue injury.[3–7] Shape change always comes at the expense of tissue injury or requires the use of a material to counteract the forces that resist deformation.

It is well understood that cartilage tissue can be excised or damaged to produce shape change, but equilibrium shape is difficult to predict; these approaches may take years to master.[8–10] Rhinoplasty surgeons rely on their experience and expertise and use clinical judgment to gauge the degree of tissue destruction required to maintain adequate structural integrity to support the overlying soft tissue, resist contracture forces produced by wound healing, and overcome gravity. This process is inexact and highly dependent on the intuition of each surgeon. No mechanical correlate for the minimum acceptable stiffness of cartilaginous structures in the human nose has been defined. Furthermore, previous attempts to quantify the mechanical properties of nasal cartilage have used a variety of different techniques and subsequently yielded a wide range of results, giving an imprecise estimate of how stiff nasal cartilage is or should be.[11–15] Most studies[11,12,14,15] confuse intrinsic material properties of the tissue with the integrated response of a structure to deformation that also depends just as much on the object form factor (shape). This study presents a novel method of quantifying the stiffness of nasal cartilage based on the experience and expertise of surgeons and aims to identify the minimally adequate level of stiffness required for lower lateral cartilage (LLC) to maintain proper form and function in a human nose.

Methods

Five anatomically correct mechanical phantoms modeling native human LLC were created via an injection molding process using a synthetic elastomer material that has a similar look and feel to human cartilage (Figure 1). All 5 phantoms had identical geometry and material properties in the medial and lateral ends but varied in stiffness around the intermediate crural area to simulate changes in mechanical properties due to surgical modifications, such as partial thickness crushing. Elastic modulus was calculated to quantify the stiffness of each phantom. The set of phantoms was created to have elastic moduli that spanned a range of values consistent with elastic moduli values for nasal cartilage calculated in previous studies (Table).[11–15] The elastic modulus for the medial and lateral ends of all phantoms was 30.6 MPa.

To create anatomically correct models, a real sample of LLC was harvested from a cadaver. The cartilage sample was then flattened and the outline was traced. The outline was imported into 3-dimensional (3D) computer modeling software (Solidworks, Dassault Systèmes Solidworks Corp, and 3DS-max, Autodesk Media and Entertainment), bent into a geometry consistent with the original LLC sample, and rendered into a 3D model (Figure 2).

The 3D model was converted into a negative mold, thus forming a hollow cavity that matched the shape of the original LLC model. A 3D printer (MakerBot) was used to create physical versions of the mold out of a clear, flexible polylactic acid plastic (Figure 3A).

The phantoms were cast via an injection molding process using a liquid polyurethane prepolymer and polyol-plasticizer mix (Smooth-On Inc). The synthetic materials were selected to create the phantoms because they yielded models with a look and feel similar to human nasal cartilage while giving the ability to control and quantify the mechanical properties of each phantom. The stiffness of each phantom was controlled by adding a phthalic acid, benzyl butyl ester softener (Smooth-On Inc), in different proportions with the liquid polyurethane mixture to interfere with cross-linking at varying degrees.

The LLC phantoms were created via a 2-stage injection molding process. For each phantom, the same liquid polyurethane mixture was injected into the medial and lateral ends of the LLC mold and allowed to partially cure during a 24-hour period. After the medial and lateral ends had partially cured, a mixture with a specific ratio of liquid polyurethane to softener was injected into the intermediate crural area. A unique ratio of liquid polyurethane to softener was used for each phantom to allow for differing elastic moduli in the intermediate crural area of each phantom. The phantoms were then allowed to fully cure for 48 hours (Figure 3B–D). After the elastomer material had fully cured, the thin plastic mold was peeled away off the LLC phantom (Figure 3D).

To calculate the elastic modulus of each phantom, rectangular samples (1 × 1 × 12 cm) were cast using the same polyurethane mixture to softener ratios used to cast each corresponding phantom. Because of the irregular shape and geometry of the LLC phantoms, obtaining accurate measurements via direct mechanical testing was not possible. Elastic modulus is an intrinsic material property that is independent of specimen geometry. Thus, mechanical testing on rectangular samples cast from equivalent materials is an accurate method of determining the elastic modulus for each corresponding LLC phantom. Each rectangular test sample underwent a tensile test using a mechanical testing platform (EnduraTEC ELF 3200, Bose Corporation). The elastic modulus for each sample was calculated from the resulting stress-strain curves and correlated with the appropriate phantom (Table).

To determine the minimum acceptable stiffness for human LLC, 33 facial plastic surgeons, plastic surgeons, and otolaryngologists who perform rhinoplasty were surveyed at a regional professional meeting on October 25, 2013. Study participants were tested individually and were masked to all other participants. Each participant was asked to self-rate his or her expertise in rhinoplasty as low, moderate, or high. Only participants who rated their expertise in rhinoplasty as moderate or above were included in the study. Each surgeon was presented all 5 phantoms in a random order and asked to place the mechanical phantoms in order of increasing stiffness based on his or her sense of feel and touch. Participants were allowed to examine and mechanically manipulate the samples in any way. Each participant was given an accuracy rating based on how correctly he or she was able to arrange the phantoms in order of increasing stiffness. After the participant had organized the phantoms in order of increasing stiffness to the best of his or her ability, he or she was asked to select a single phantom of the 5 that they believed to have the minimum acceptable stiffness for LLC (intermediate crura) to still maintain proper shape and function in a human nose. Each participant's response was weighted according to his or her accuracy rating. Oral informed consent was received from all study participants.

On the basis of the survey data, the rate of acceptability was calculated for each phantom. A binary logistic regression between mechanical acceptability and unacceptability for each phantom was performed to calculate a minimum acceptable stiffness for LLC. The data were best fit to a logistic equation curve in the form of $p(x) = 1/(1+e^{-(a + bx)})$, where x represents the elastic modulus and a and b are constants characterizing the curve. The minimum acceptable stiffness for LLC was taken at a 50% acceptability rating. The Hosmer-Lemeshow test was used to evaluate the goodness of fit between the data and the binary logistic regression.

Results

The number of times each LLC phantom was selected as having the minimum acceptable stiffness of the intermediate crura is outlined in Figure 4. Phantom 4, with a modulus of 3.97 MPa, had the highest frequency of selection. A binary logistic regression was performed to create a curve specifying the probability of mechanical acceptability as a function of elastic modulus of the intermediate crus (Figure 5). With this model, the minimally adequate elastic modulus of human LLC was determined to be 3.65 MPa. The Hosmer-Lemeshow test revealed a good fit between the survey data and the logistic regression ($\chi^2_3=0.92$, $P = .82$).

Discussion

Quantifying the minimum acceptable stiffness of nasal cartilage is an important step in guiding surgical maneuvers used to reshape nasal cartilage. All methods of cartilage reshaping, both traditional and new, will result in some degree of loss of structural integrity in exchange for shape change.[1–7] This loss has important implications for rhinoplasty because the cartilaginous structures in the nose must be stable enough to counteract collapsing forces that act on the nose and maintain the nasal airway. It is well known that excessive damage to the mechanical stability of nasal cartilage structures can cause functional and aesthetic complications.[8,9] Yet, it is unknown what threshold of mechanical stability must be maintained to preserve proper form and function in the nose.[9,10] Thus, quantifying the minimum stiffness required for nasal cartilaginous structures would help surgeons determine the optimal balance between sufficient shape change and acceptable loss in stability.

Quantifying these characteristics of nasal cartilage also has important implications for tissue engineering. Autologous cartilage grafts harvested from the nasal septum, ear, or ribs have been used for a variety of rhinoplasty procedures.[16] However, there are limitations to the use of autologous cartilage grafts because of possible donor site morbidity, limited quantities of harvestable tissue, and unpredictable behavior of the graft after being placed.[16] Alloplastic grafts offer some advantages over autologous grafts, such as unlimited availability and simplicity of insertion, but pose potential complications of infection or foreign-body reaction.[17] Artificially grown cartilage grafts can, in theory, be created to have the specific biomechanical properties desired for different surgical applications while eliminating many of the potential complications of autologous and alloplastic grafts.[18–22] It is necessary to quantify the biomechanical properties of nasal cartilage before we can identify the ideal parameters for artificially grown cartilage grafts. In addition, the stiffness of artificially grown cartilage is directly correlated with manufacturing time and cost. Identifying a minimum target stiffness is a critical step for cost-effective tissue engineering. Notably, this minimum value for tissue stiffness may be lower than the mechanical properties of native tissue. This reduction would certainly be the case with specimens classically modified using techniques such as partial thickness crushing, scoring, or cross-hatching.

This study concludes that the LLC should maintain a minimum elastic modulus of 3.65 MPa to maintain proper form and function in a nose. Currently, estimates of elastic moduli for nasal cartilage presented in the literature vary greatly among studies and testing methods. Values for the elastic modulus of human septal cartilage presented in previous studies[11,12] have ranged from approximately 0.5 to greater than 30 MPa. Similarly, values for the elastic modulus of human LLC have ranged from 2 to 25 MPa.[9,12] These differences have largely been attributed to inconsistencies among different testing methods and materials. Richmon et al[14] found that the orientation of deformation affects the measured elastic modulus. Similarly, Westreich et al[12] have suggested that different methods of sample preparation can affect results. Furthermore, small specimen sizes and irregular geometries make it difficult to obtain consistent test samples and accurate measurements.

The estimate of elastic modulus for human LLC presented in this study is limited because of several factors. First, actual human nasal cartilage is an anisotropic, viscoelastic material that consists of several phases that interact to give cartilage its unique biomechanical properties. Ideally, this experiment would be performed with actual cartilage samples instead of with models made from synthetic materials. However, such a study would be impossible because of problems regarding geometric consistency, storage, and accurate measurements of biomechanical properties. Second, surgeons rarely consider LLC alone in clinical practice. There are several other components (thickness of the surrounding skin and soft tissue and specific geometry and orientation of the LLC) that contribute to the look, function, and feel of a nose.

This study presents a novel method of evaluating nasal cartilage mechanics that uses the experience and expertise of surgeons rather than mechanical testing on actual cartilage specimens. By using computer modeling software and 3D printing, we were able to create anatomically correct models of nasal structures with specific mechanical properties. Use of these models to survey surgeons allows us to infer the desired mechanical properties of nasal cartilage based on expert opinion, with at least some analytic rigor.

Conclusions

Oversoftening or compromising the structural stability of nasal cartilage structures when performing surgical maneuvers may result in poor long-term aesthetic and functional outcomes. It is unknown what minimum mechanical stability must be preserved for various cartilaginous structures in the nose to maintain proper form and function. Previous attempts to quantify the biomechanical properties of human nasal cartilage have yielded a wide range of results. Using our model, this study concludes that human LLC should maintain a minimum elastic modulus of 3.65 MPa. For further research, this method of modeling anatomical structures and surveying experts can be used to identify mechanical thresholds for other cartilaginous structures.

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Figure 1. Five Lower Lateral Cartilage (LLC) Phantoms Used for the Survey

Each phantom was marked with distinct patterns to allow phantom identification while allowing masked evaluation by surveyed surgeons.

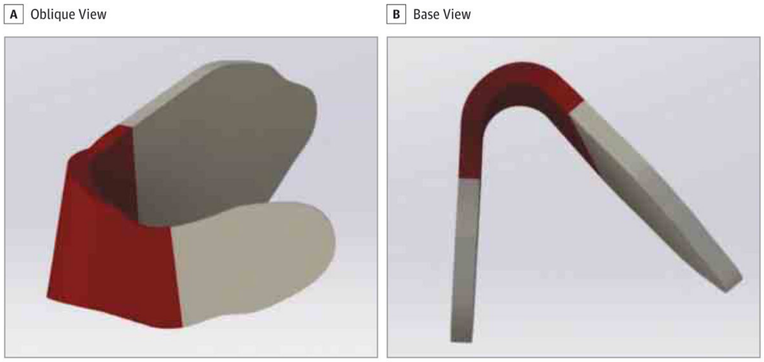
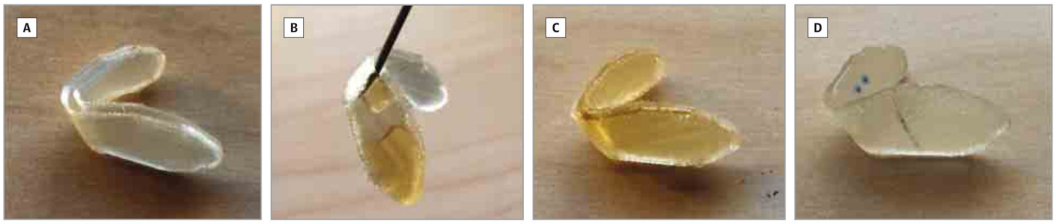


Figure 2. Three-Dimensional Rendering of the Lower Lateral Cartilage Computer Model

The area in red highlights the portion of the intermediate crus that varies in elastic modulus among phantoms.



A, Empty mold made of thin polylactic acid plastic. B, Injection of elastomer mixture into the mold. C, Lower lateral cartilage model while the elastomer is curing inside the plastic mold. D, Lower lateral cartilage model after being removed from the plastic mold.

Figure 3. Physical Versions of the Mold

A, Empty mold made of thin polylactic acid plastic. B, Injection of elastomer mixture into the mold. C, Lower lateral cartilage model while the elastomer is curing inside the plastic mold. D, Lower lateral cartilage model after being removed from the plastic mold.

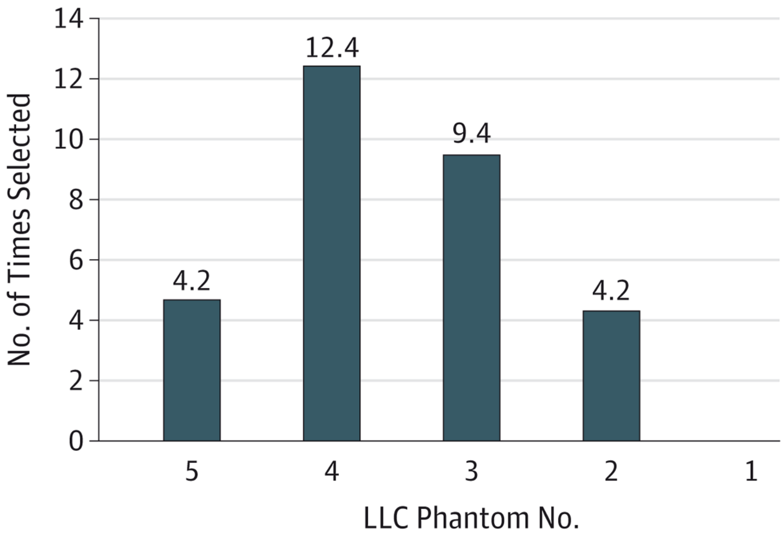


Figure 4.

Raw Survey Data for the Number of Times Each Lower Lateral Cartilage (LLC) Phantom Was Selected as Having the Minimum Acceptable Stiffness for LLC Intermediate Crura

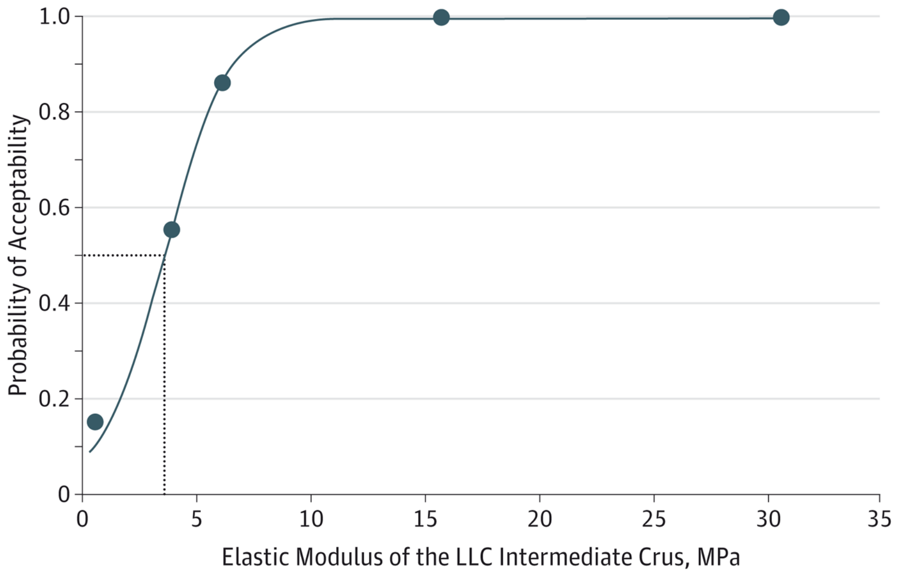


Figure 5. Probability Density for Mechanical Acceptability vs Phantom Stiffness

Plotted points represent the rate of acceptability calculated for each phantom based on survey data. The curve represents the probability of mechanical acceptability as a function of elastic modulus of the lower lateral cartilage (LLC) intermediate crus.

Table

Elastic Moduli Values for the Intermediate Crus of Each Lower Lateral Cartilage Phantom

Phantom No.	Elastic Modulus, MPa
1	30.60
2	15.70
3	6.24
4	3.97
5	0.63