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Title

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Permalink

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Journal

Archives of facial plastic surgery, 13(4)

ISSN

1521-2491

Authors

Foulad, Allen
Manuel, Cyrus
Wong, Brian JF

Publication Date

2011-07-01

DOI

10.1001/archfacial.2011.8

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Peer reviewed

Published in final edited form as:

Arch Facial Plast Surg. 2011 ; 13(4): 259–265. doi:10.1001/archfacial.2011.8.

Practical Device for Precise Cutting of Costal Cartilage Grafts to Uniform Thickness

Allen Foulad, BS, Cyrus Manuel, BS, and Brian J. F. Wong, MD, PhD

Beckman Laser Institute and Medical Clinic (Mssrs Foulad and Manuel and Dr Wong) and Department of Biomedical Engineering, Samueli School of Engineering (Dr Wong), University of California, Irvine, Irvine; and Department of Otolaryngology–Head and Neck Surgery, University of California, Irvine, Orange (Mr Foulad and Dr Wong).

Abstract

Objectives—Costal cartilage is becoming increasingly popular as a graft source for facial reconstruction. However, carving methods have not changed in decades and continue to primarily rely on detailed maneuvers with a scalpel. There are few reports of mechanical devices for shaping costal cartilage, and to our knowledge their accuracy and precision have not been reported. We describe a simple costal cartilage slicing device that facilitates the production of sections having uniform, user-defined thicknesses.

Methods—The design included laboratory research using 200 porcine and 2 cadaveric human *ex vivo* costal cartilage slices. A 2-component apparatus was constructed consisting of a mechanism to secure the costal cartilage and a double-bladed device to cut the rib graft through a central cross-section. Optimizing blade characteristics and static forces that secure the cartilage were critical design challenges. The device was used to obtain slices 0.8, 2.1, and 4.1 mm in thickness, with lengths up to 4.0 cm and a width of 1.0 cm. To confirm uniformity, thickness was measured at 8 fixed regions per section using a digital micrometer.

Results—All costal cartilage slices appeared to be extremely uniform on visual and manual inspection. The absolute difference between the largest and smallest thickness measured for each individual sample ranged from 0.04 to 0.13 mm, 0.06 to 0.14 mm, and 0.10 to 0.21 mm for the 0.8-, 2.1-, and 4.1-mm-thick groups, respectively.

Conclusions—Our study demonstrates the precision of using a mechanical slicing device to section costal cartilage to a clinically relevant and uniform thickness. This mechanized technology

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Correspondence: Brian J. F. Wong, MD, PhD, Beckman Laser Institute and Medical Clinic at University of California, Irvine, 1002 Health Sciences Rd E, Irvine, CA 92612 (bjwong@uci.edu)..

Author Contributions: *Study concept and design:* Foulad, Manuel, and Wong. *Acquisition of data:* Foulad and Manuel. *Analysis and interpretation of data:* Foulad, Manuel, and Wong. *Drafting of the manuscript:* Foulad, Manuel, and Wong. *Critical revision of the manuscript for important intellectual content:* Foulad, Manuel, and Wong. *Statistical analysis:* Foulad and Manuel. *Obtained funding:* Wong. *Administrative, technical, and material support:* Foulad and Wong. *Study supervision:* Wong.

Financial Disclosure: None reported.

Previous Presentation: This study was presented at the Triological Society Combined Sections Meeting; February 6, 2010; Orlando, Florida.

may increase accuracy and reduce carving time required for using costal cartilage tissue in head and neck reconstruction.

Costal cartilage is a valuable graft source for nasal and facial reconstruction. Providing for a relatively abundant supply of cartilage, the costal margin is the only practical option for autogenous cartilage grafts when auricular and septal cartilage are depleted or if a considerable amount of cartilage is required for extensive framework reconstruction. However, grafts harvested from peripheral regions of costal cartilage have the potential disadvantage of warping after graft placement.¹ This undesirable effect is minimized and theoretically eliminated by obtaining balanced cross-sections from the central core of the rib.²⁻⁴ Such considerations demonstrate that the harvesting technique critically affects the shape dynamics and outcome of costal cartilage grafts, particularly in applications such as reconstructive rhinoplasty.

Techniques for carving cartilage have had modest progress over the past several decades. In the operating room, the scalpel remains the preferred instrument of choice. However, this method is hindered by imprecise and time-consuming maneuvers. Obtaining flat grafts of uniform thickness using a scalpel requires skill and expertise, especially for thinner slices such as spreader grafts used for rhino-plasty. The ability to harvest uniform cartilage specimens is important because these specimens have a wide range of applications in nasal reconstruction.⁵

Several cartilage cutting devices have been described or alluded to in the literature. Generally, these devices adhere to a common design of 2 parallel blades that are separated by a specific distance using a spacer at both ends (**Figure 1A**). The piece of rib is first cut to a length that is no greater than the distance between the spacers. Then, the double-bladed device is pushed through the rib segment, producing a slice having approximately the same thickness as the spacer (Figure 1B and C). Specifically, Harris et al⁶ used a guillotine-type device fashioned from a traditional paper cutter lever using 2 parallel blades. These blades were swung down to section a rib segment. Wong et al⁷ developed a cartilage cutting guillotine using razor blades, in conjunction with securing the rib with gentle compression in a vise mechanism. Lopez et al⁴ adapted the guillotine concept by using 4 parallel blades to obtain a central slice and 2 peripheral slices. Although these devices offer a simple and rapid cutting approach alternative to the traditional scalpel, the accuracy of these devices is not reported, and the literature is sparse with respect to reports of other devices.

Our objective was to create a cutting device that creates costal cartilage sections of user-defined, highly uniform thickness. We describe our design effort and systematic examination of cutting mechanisms and designs and then describe our prototype device and its performance capabilities.

METHODS

PRELIMINARY INVESTIGATION

Extensive preliminary investigations were performed using numerous cutting tools, blades, and mechanisms:

No. 11 surgical scalpel
 Pathology sectioning blades
 Commercial rotary meat slicer
 Culinary mandoline
 Planer
 Double-bladed device
 Double-beveled blade
 Single-beveled blade
 Clamped specimen
 Nonclamped specimen
 Specimen under tension
 Microtome
 Vibratory dermatome

The most uniform and clinically relevant slices, at lengths up to 4 cm, were obtained using cutting devices that implemented a double-bladed design, in which 2 parallel blades are separated by spacers at the ends (Figure 1). However, to obtain the most consistent and uniform slices, optimization of the double-bladed model was required. Specifically, it was deemed critical to optimize 3 important performance specifications: (1) the type of blade bevel, (2) blade length, and (3) method of cartilage stabilization during cutting.

The bevel characteristic of a blade considerably affects uniformity of the resulting cut cartilage slice. Thousands of blades for commercial and industrial purposes are available from innumerable vendors. In general, most blades are typically beveled on both sides of the cutting edge forming a “V” shape. This provides a thin, sharp edge for cutting. The concern of using a double-beveled design in a double-bladed cutting device is that the distance between the beveled cutting tips of the blades is greater than the distance between the bodies of the blades (**Figure 2A**). Therefore, as a slice is being cut, the thickness of the slice is forced through the smaller region between the bodies of the blades and causes the blades to diverge. This leads to an even greater thickness of cartilage to be cut, and the cycle self-perpetuates, leading to creation of a wedge-shaped specimen (Figure 2B and C). Correspondingly, thicker blades would cause increased wedging due to a more prominent bevel and thus an even greater distance between the tips of the blades compared with the distance between the bodies of the blades. Therefore, thinner blades will reduce this effect but will not entirely eliminate the wedging. Furthermore, extremely thin blades will introduce the potential of blade flexure unless expensive stainless steel alloys or exotic aerospace industry materials are used. A more practical alternative is to use single-beveled blades with the bevel facing outward, which eliminates the source of wedging (Figure 2D).

Increasing the blade length results in flexure during guillotine sectioning and considerably reduces specimen thickness uniformity. To minimize blade flexure, stiffer and thicker blades

can be used, but at a higher cost. To circumvent the necessity of using longer blades, the rib can simply be cut through its long axis instead of being cut longitudinally through its short axis (**Figure 3**). This not only minimizes the blade length but also allows any arbitrary length of cartilage to be cut using this reduced blade length. Interestingly, we were not able to identify any costal cartilage cutting devices in the literature that used this approach.

Stabilization of the cartilage during cutting is important to prevent specimen movement, facilitate user safety, and provide proper positioning so that precise cuts can be made at specific regions. Ideally, the method of stabilization would also straighten curved pieces of rib, so that the blade can precisely traverse the center of the rib with simple downward force. Securing the cartilage using a clamp is a simple option that can provide stabilization (**Figure 4A**). However, the compressive forces generated by clamping not only increase the difficulty of pushing the blades through the cartilage but also can potentially decrease the uniformity of the sliced specimens. In theory, applying a compressive force to costal cartilage results in a varying amount of compression at different regions of the cartilage due to its anisotropic structure. Therefore, a slice cut from cartilage that is under compression would have an increased thickness at regions that were more compressed. An alternative method to secure the cartilage is through tension. Sutures placed on opposing sides of the cartilage can provide tension in a fashion that secures it in proper position (**Figure 4B**).

Various minor factors must also be considered when using a double-bladed cutting device. First, any fasteners, such as bolts and set screws, used to hold a guillotine blade device together should go through the spacers of the device. Furthermore, the spacer should surround the entire perimeter of the fastener. Therefore, as the fasteners are tightened, there will be a uniform application of force along both the spacer and blades, resulting in less potential blade distortion. Second, the device should be used with sharp blades, because dull blades will lead to reduced uniformity in the specimens. Third, under ideal circumstances, curved rib should be straightened as much as possible during section. The force from pushing the cutting device onto curved rib can lead to increased flexure of the rib, causing the blade to track away from the central core.

DEVICE CONSTRUCTION

Preliminary investigations using prototype cutting devices and approximately 200 porcine costal cartilage specimens were performed in order to delineate tissue behavior and device limitations during cutting. These observations were distilled to engineer a prototype using computer-assisted design with SolidWorks (2008; Dassault Systèmes, Concord, Massachusetts), and subsequently the construction of the device described herein (**Figure 5**). At the core of the cutting device are 2 parallel single-beveled blades (American Cutting Edge, Centerville, Ohio). Aluminum spacers were placed between the ends of the blades to keep them separated by a distance equal to the thickness of the specimen desired. The spacers were placed 1 cm apart, therefore limiting the cartilage cutting portion of the blade to this same length and minimizing blade flexure. A blade holder was constructed to clamp the blades and spacers tightly together and provide sufficient grip for holding and maneuvering the device. At each end of the device, a bolt was passed through the blade holder, spacer, and blades in order to fasten the components of the device together.

An apparatus was constructed to stabilize the cartilage in position and provide a guide for the cutting device. Two vertical bars provide the support required to secure the cartilage in proper position. The guide is capable of sliding forward and backward by loosening a bolt, enabling proper device positioning for making cuts at precise locations of the rib.

EXPERIMENTAL STUDY

Porcine ribs were obtained from a local packing house, and the cartilaginous region of the second through fifth ribs was extracted. In addition, cadaveric human costal cartilage from the fifth and sixth ribs of a formaldehyde-embalmed 61-year-old man was obtained through the University of California, Irvine, Willard Body Program. A utility knife was used to remove the tissue surrounding the cartilage. The perichondrium was stripped only from regions that the blades of the cutting device would traverse because the perichondrium is a relatively tough tissue (more so in a porcine model) and can lead to blade flexure during slicing. The remainder of the perichondrium was left intact because suture can be easily and effectively passed through this type of tissue when stabilizing the specimen. The length of the rib was cut a few centimeters longer than the length desired. The bottom 1 cm of the rib was then clamped in the stabilization apparatus to position it upright. In order to provide sufficient support, the remainder of the rib was secured using tension from sutures as illustrated in **Figure 6**. If there was curvature in the rib, the suture tension was adjusted in the necessary regions to straighten the rib. The cutting device was then placed against the guide of the stabilization apparatus and was slowly pushed straight down through the center of the rib. This guide provides a means by which the sectioning unit can reliably traverse the specimen. A central slice of desired thickness was then obtained, and the length and width of the slice were trimmed with a razor blade to the desired length and width.

For the porcine cartilage, slices were cut using spacers of thicknesses 0.8 mm (n=20), 2.1 mm (n=10), and 4.1 mm (n=10). For each thickness, half the specimens were cut at a length of 2.5 cm and the remaining half of the specimens were cut at a length of 4.0 cm. All slices were 1.0 cm in width. For the human cartilage, slices were obtained using a spacer with a thickness of 2.1 mm (n=2). The specimens were cut at a length of 4.0 cm and a width of 1.0 cm.

A digital caliper (Absolute Digimatic; Mitutoyo, Aurora, Illinois) was used to measure the thickness at 8 regions along all 4 sides of the slices. Specifically, measurements were obtained from 3 points equally spaced along each length and from 1 point at the center of each width. The percent difference for each sample was calculated by dividing the difference between the largest thickness and smallest thickness by the average of the smallest and largest thicknesses.

RESULTS

On visual and manual inspection, all the costal cartilage slices obtained using the cutting device were taken from the center of the rib and were highly uniform in thickness (**Figure 7** and **Figure 8**). The **Table** describes the thickness uniformity of the sliced porcine specimens in detail. The absolute difference between the largest and smallest thicknesses measured for each individual sample ranged from 0.04 to 0.13 mm, 0.06 to 0.14 mm, and 0.10 to 0.21 mm

for the 0.8-mm, 2.1-mm, and 4.1-mm spacer groups, respectively. The mean thicknesses for all the samples measured were 0.68 mm, 1.95 mm, and 3.91 mm for the 0.8-mm, 2.1-mm, and 4.1-mm spacer groups respectively. The percentages of thickness for each individual sample ranged from 6.5% to 19%, 3.0% to 7.3%, and 2.5% to 5.4% for the 0.8-mm, 2.1-mm, and 4.1-mm spacer groups, respectively.

The uniformity in the thickness of the sliced human specimens was comparable with that of the porcine specimens. The mean thickness of the 2 human samples was 2.0 mm, and the absolute difference between the largest and smallest thickness measured for the samples ranged from 0.09 to 0.13 mm. Pronounced islands of calcification were observed in both specimens (**Figure 9**).

COMMENT

There has been a growing trend in the use of costal cartilage for both functional and cosmetic rhinoplasty. Costal cartilage slices of uniform thickness are useful for many reconstructive applications, such as spreader grafting, septal replacement and reconstruction, lateral crural struts, and caudal extension grafts.⁵ In parallel with the increased use of costal cartilage, it is necessary to expand the sparse literature regarding the biophysical properties of this tissue.⁸ Therefore, the value and need for uniformly thick cartilage slices is evident, as these slices are required for biophysical studies on costal cartilage mechanical behavior to attain accurate and reproducible results.

The scalpel remains the preferred tool of choice for cutting cartilage. However, cutting thin cartilage slices of highly uniform thickness using a scalpel requires skill, expertise, and time. Hence, several studies have used and described variations of a double-bladed device for cutting cartilage slices with increased speed and accuracy.^{4,6,7} Nevertheless, to our knowledge, the uniformity of the thickness of the cartilage specimens cut by these devices has not been reported and analyzed to date.

Cartilage can be thought of as a charged polymer hydrogel in which resistance to compression is generated by Coulombic repulsion forces produced by the negatively charged proteoglycan subunits within the tissue matrix. Because of the extensive negative charge, electrical neutrality is achieved via the presence of counterions in the interstitial fluids, chiefly Na^+ (sodium) and Ca^{2+} (calcium). Owing to this subsequent increase in osmolarity, there is an influx of water into the cartilage tissue. In turn, this swelling is counteracted by a collagen type II meshwork, which under physiologic conditions is under tension. Water flow through the matrix during loading contributes to tissue mechanical behavior as well and complicates the description of cartilage behavior during stress and strain, despite extensive and detailed modeling efforts.⁹ This is relevant with respect to cutting cartilage because these biophysical effects collectively contribute not only to the warping process but also to the imprecision achieved in fashioning grafts using conventional techniques. The tissue simply shrinks, swells, and distorts during cutting.

Our group constructed a double-bladed device to cut costal cartilage and devised an apparatus that appropriately secures the cartilage during cutting. The device can be easily

adjusted to cut specimens of any desired thickness by using spacers of the corresponding size. Further more, the present design can cut any arbitrary length of cartilage without adjustment. In order to obtain slices of highly uniform thickness, the device was constructed incorporating measures to address the 3 fundamental problems we identified. First, a single-beveled blade was used to prevent wedging of the cut specimen. Second, the specimen was oriented orthogonal to conventional techniques to reduce the required blade length and prevent flexure during cutting. Finally, the use of tension rather than compression was used to secure the specimen during cutting.

The results demonstrated that the double-bladed device, when optimized, yields cartilage slices that are highly uniform in thickness. The absolute difference between the smallest and largest thickness of each sliced specimen remains small, on the order of a tenth of a millimeter, and fairly constant among various thicknesses cut. Accordingly, the percentage difference in thickness decreases as specimen thickness is increased because the imprecision of the device is finite and does not depend on specimen thickness. Specifically, slices cut to 2 mm in thickness had a percentage difference in thickness that was less than 7.3%. These differences are difficult to detect on visual and manual inspection.

In contrast to the porcine specimens, the human cartilage specimens contained many islands of calcification. Nonetheless, the resulting sliced human specimens demonstrated uniformity in thickness that was comparable with that of the porcine specimens. Intuitively, there is a threshold of calcification above which the attainment of adequate slices is no longer feasible. However, it is reasonable to theorize that if a stand-alone blade can cut through the rib using simple orthogonal force without extreme pressure, then the double-bladed device is capable of producing successful slices.

The most involved step in using the cutting device is preparation of the specimen. It was imperative to strip the perichondrium from any regions of the cartilage that the blade of the slicing device would traverse. Removal of the perichondrium is necessary because it is a very tough tissue to cut, especially in a porcine model, and if left attached it would lead to specimens having decreased uniformity in thickness and also cause the blade to list away from the central core of the rib. An option is to use blades that are sharper than the stainless steel blades used in our design, or to use a mechanism that vibrates the blades in order to emulate a sawing motion. This escalates cost and complicates the device construction for only a presumed modest improvement. In certain cases, preparation of the rib also required using a scalpel to shape the bottom region of the cartilage that was to be clamped with the securing apparatus. This bottom region was shaped in order to remove any curvature so that the cartilage would stand in an ideal position after clamping. Finally, several minutes of preparation time are required for suturing of the rib. An enhanced method of stabilizing the rib, such as the use of specially constructed graspers or the use of magnets to hold the sutures to the posts without the need for tying knots, may decrease preparation time, and continues to be a focus of our design efforts.

There are limitations regarding the use of the described design. There is currently no commercially available model of this device. However, emphasis was placed on simplifying the design so that it can be custom constructed easily and economically by virtually any

machinist. Of significant note, collaborative efforts are currently under way to make the device available through a major medical supply company. Once the device is constructed, there still is modest skill involved during the cutting process. Although practice or demonstration is required, the learning curve is minimal. We have asked undergraduate students at our institute who are not involved in this research effort to section specimens after being provided instruction for its operation, and they have produced uniform specimens with ease. Sections could be readily performed by nursing and surgical staff that have a higher skill level, though we believe this still remains the responsibility of the surgeon. In addition, porcine or bovine rib can be easily attained from a local meat market to test the device and the user's skill prior to official use. Finally, the average thicknesses of the cut specimens were slightly smaller than the thickness of the spacer used. This may be due to dehydration effects, although measurements were taken immediately after slicing. Nevertheless, it may be ideal to use a spacer slightly thicker, on the order of 0.10 mm, than the thickness of the specimen required.

Adhering to several guidelines will ensure successful cuts with the use of the device. First, although it is advised to remove or thin the perichondrium from areas through which the blade of the device will traverse, it is highly favorable to preserve the perichondrium at areas that will be sutured to the posts. The perichondrium is easily pierced with a needle but can withstand extreme tensional forces without tearing. This allows the needle to be run through more peripheral regions, even through the plane between the perichondrium and cartilage, without risk of the suture tearing through the specimen. Second, obtaining a central slice through the entire length of the cartilage requires any curvature to be straightened by increasing the tension on the cartilage at appropriate regions using the sutures. A ruler can be used during this securing stage to ensure that the center of the specimen's width is the same distance from the post along the entire length of the cartilage. Of note, once the cut is made and the tension is released, the resulting slice from the core will demonstrate the same curvature as the native cartilage. Third, securing the cartilage to the posts with more sutures will increase the stability of the cartilage during cutting. This minimizes the chance of error and prevents listing of the blade away from the core of the cartilage. Therefore in critical settings, it is recommended to use at least 1 suture per 1 cm of cartilage length per post. Fourth, pushing the cutting device through the cartilage at a slower rate will minimize the force on the cartilage and thus reduce listing of the blade. It is recommended to attempt the initial use of the device using these guidelines in a noncritical setting.

The characteristics of the rib are an important consideration during harvesting. Cartilage with minimal curvature simplifies cutting with the device. In addition, ideal cartilage possesses a large enough thickness so that the blades of the device are at least 5 mm from the periphery of the cartilage during cutting. Therefore, if the device slightly lists away from the cartilage core the blades will not veer through the side of the specimen. In this study, we used the fifth and sixth ribs of a human cadaver to cut central slices 4 cm in length with success. Although the technique was not investigated in the current study, the cutting device can also be used freehand without using the securing platform. This method increases the skill required to cut flat and uniform grafts but gives the operator full control of the path of the blades and enables cutting of nonideally shaped ribs.

The double-bladed cutting device provides a practical method to obtain costal cartilage specimens in both the operating room and the research setting. The device reduces the skill and time required to fashion cartilage slices while increasing the uniformity of the cut specimens. Furthermore, via an adjustable guide, slices can be obtained precisely from the central core of the rib. Although this study investigated specimen lengths up to 4 cm, longer lengths can be attained without modification of the device. In addition to the experimental work, the device has since been used in the operating room to produce a columellar power strut for a nasal reconstruction procedure. Future work will investigate simple and economical mechanisms to reduce the time required to secure the cartilage.

Through systematic assessment of various cutting methods, this study concludes that the double-bladed design provides an excellent model for constructing a costal cartilage cutting device that slices specimens of highly uniform thickness. Several factors were identified that affect the accuracy of the design, such as blade characteristics and method of securing the cartilage while cutting. The device is economical to construct and allows for cuts of arbitrary thicknesses and lengths. The mass production of this design will further reduce costs and potentially allow for a more efficient design.

Acknowledgments

Funding/Support: This study was funded by the Department of Defense Deployment Related Medical Research Program (DR090349) and the National Institute for Dental and Craniofacial Research (1R21DE019026).

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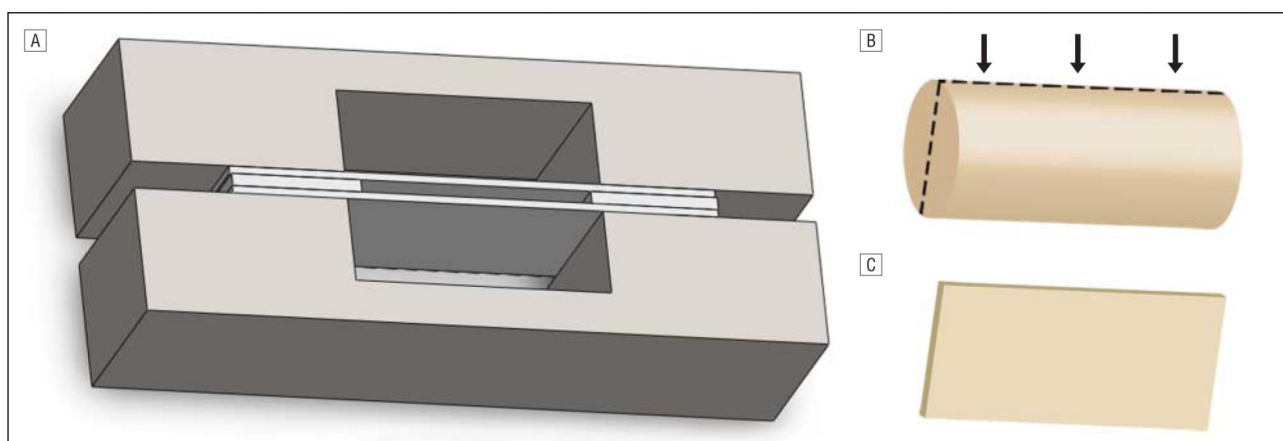


Figure 1.

Basic design of a double-bladed cartilage cutter. A, Two parallel blades are separated by spacers at the ends. B, The cutting device is pushed straight down (arrows) through the costal cartilage piece. C, Flat cartilage specimens are obtained.

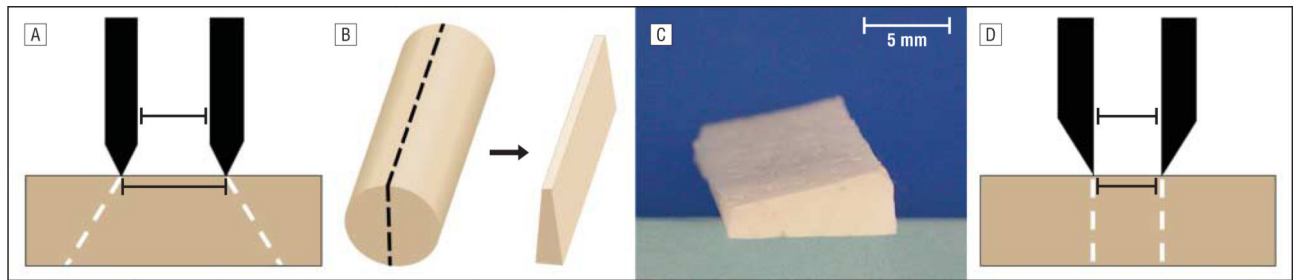


Figure 2.

Optimization of blade bevel design (black bar) in double-bladed cartilage cutters. A, The distance between the cutting tips of the double-beveled blades is greater than the distance between the bodies of the blades. Therefore, as the cartilage is being cut, the thickness of the slice is forced through the relatively smaller distance between the bodies of blades and thus pushes the 2 blades apart. B, The divergence of the blades contributes to wedge formation (arrow). C, A cartilage specimen cut using a 0.5-mm-thick double-beveled blade has an observable wedge shape. D, The use of single-beveled blades with the bevel facing outward reduces the potential for wedge formation.

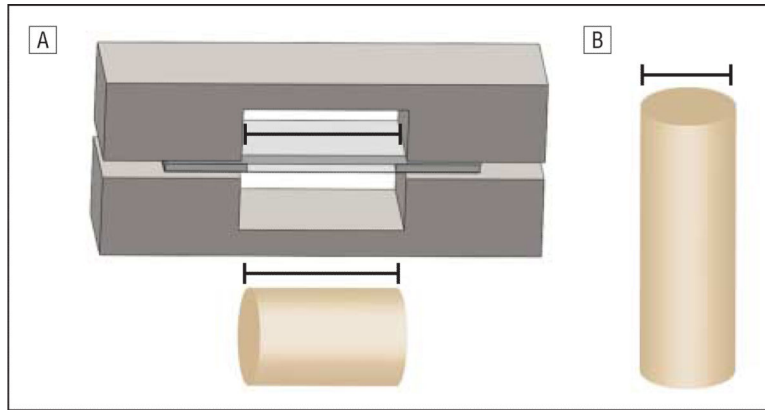


Figure 3.

Impact of blade length on specimen sectioning. A, Cutting cartilage longitudinally, through its short axis, necessitates the length of the blade to be as long as the cartilage length required. B, Cutting the rib through its long axis enables the use of short length of blade to cut any arbitrary length of cartilage and thus minimize blade flexure.

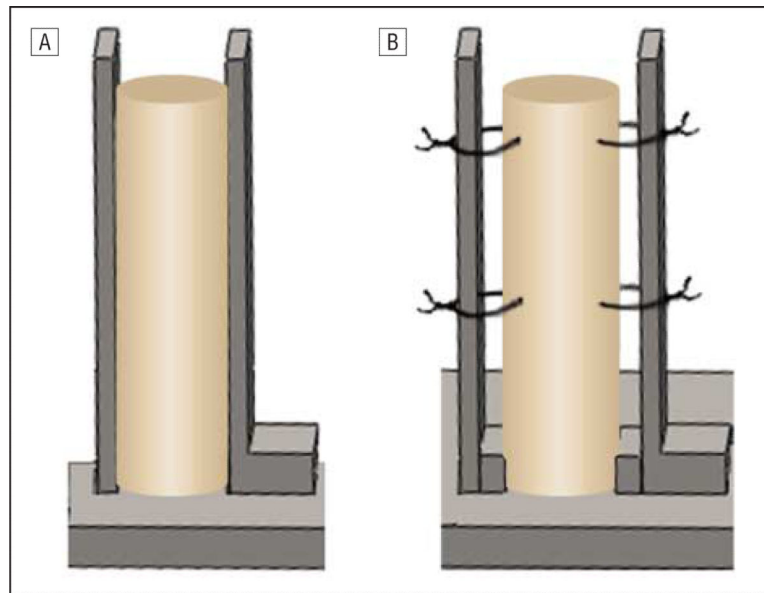


Figure 4. Cartilage stabilization during sectioning. A, Clamping (compressive deformation) is the simplest method to secure the cartilage in proper position during cutting. B, Tension is the recommended method to secure the cartilage, as this leads to slices having greater uniformity in thickness.

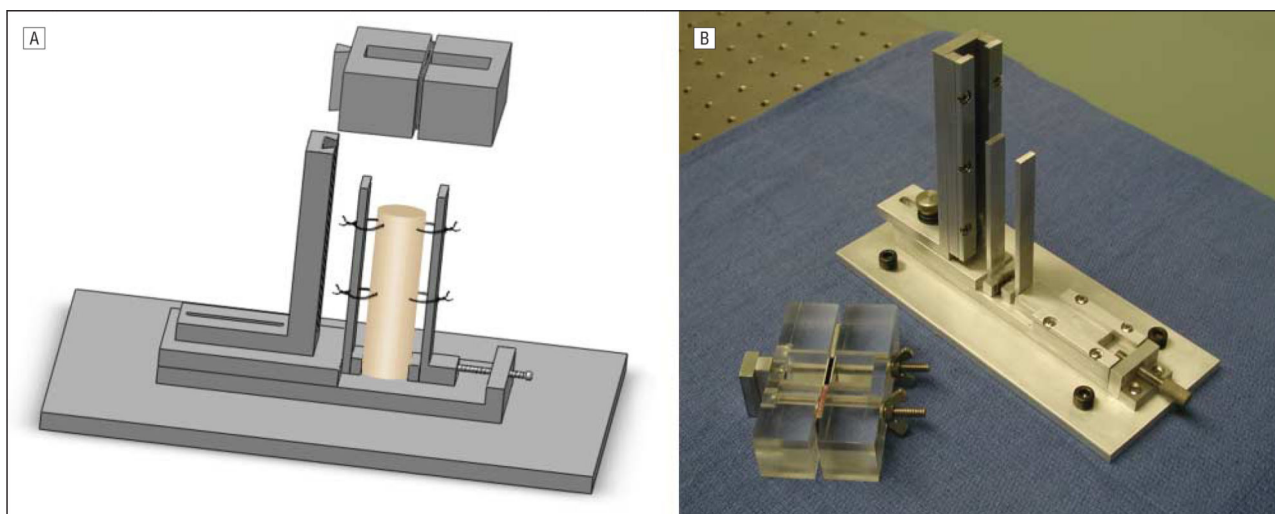


Figure 5. Optimized double-bladed cartilage cutter. A, Computer-assisted design rendering of the cutting device and stabilization apparatus. B, Actual cutting device constructed.

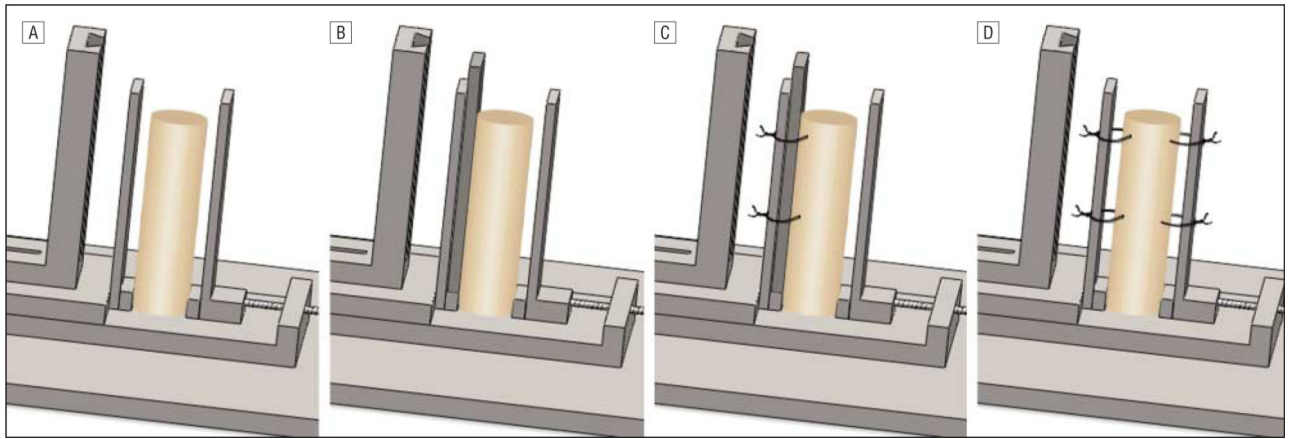


Figure 6.

Method used to secure the cartilage in proper position. A, The bottom of the cartilage is clamped to hold it upright during suturing. B, A bar is placed between the cartilage and the securing post to prevent contact during suturing. C, The cartilage is tied to the securing post. D, The opposite side of the cartilage is tied to the second securing post, and the bar is removed.



Figure 7.
Cartilage after being cut by the device. The cut slice is from the central core of the cartilage.

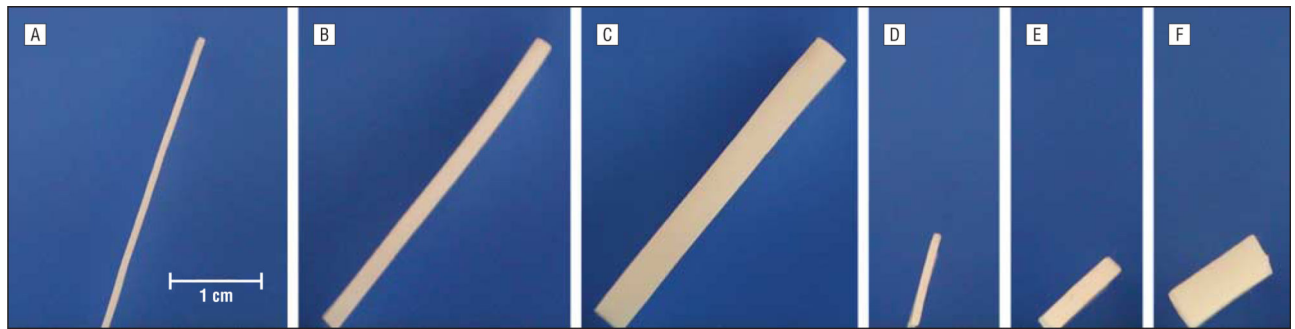


Figure 8.

Specimens obtained using the double-bladed cutter and viewed from the edge. Panels A and D, panels B and E, and panels C and F correspond to slices obtained with a spacer thickness of 0.8 mm, 2.1 mm, and 4.1 mm, respectively. All specimens are 4-cm long and 1-cm wide. A-C, Photographs of the edge that forms the length. D-F, Photographs of the edge that forms the width. All images are scaled identically.



Figure 9.
Human costal cartilage slice with pronounced islands of calcification that was obtained using double-bladed device.

Table

Thickness Calculations of Porcine Cartilage Slices Cut With the Double-Bladed Device

Thickness of Spacer, mm	Width × Length of Specimen, cm	Absolute Difference, mm ^a	Percentage Difference, % ^b	Thickness, Mean (SD), mm
0.8	2.5 × 1.0	0.04-0.10	6.5-15.2	0.68 (0.05)
0.8	4.0 × 1.0	0.06-0.13	7.7-19.3	0.68 (0.04)
2.1	2.5 × 1.0	0.06-0.13	3.1-6.7	1.94 (0.03)
2.1	4.0 × 1.0	0.06-0.14	3.0-7.3	1.95 (0.02)
4.1	2.5 × 1.0	0.10-0.19	2.5-4.9	3.93 (0.02)
4.1	4.0 × 1.0	0.13-0.21	3.3-5.4	3.89 (0.06)

^aThe difference between the smallest and largest thickness of each sample. The range for all samples is given.

^bThe percentage difference of thickness among each sample. The range for all samples is given.