Three-Dimensional Geometry of the Heineke–Mikulicz Strictureplasty

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Background: The objective of this study was to assess the regional geometry of the Heineke–Mikulicz (HM) strictureplasty. The HM intestinal strictureplasty is commonly performed for the treatment of stricturing Crohn's disease of the small intestine. This procedure shifts relatively normal proximal and distal tissue to the point of narrowing and thus increases the luminal diameter. The overall effect on the regional geometry of the HM strictureplasty, however, has not been previously described in detail.

Methods: HM strictureplasties were created in latex tubing and cast with an epoxy resin. The resultant casts of the lumens were then imaged using computed tomography. Using 3-dimensional vascular reconstruction software, the cross-sectional areas were determined and the surface geometry was examined.

Results: The HM strictureplasty, while increasing the lumen at the point of the stricture, also results in a counterproductive luminal narrowing proximal and distal to the strictureplasty. Within the model used, cross-sectional area was diminished 25% to 50% below baseline. This effect is enhanced when 2 strictureplasties are placed in close proximity to each other.

Conclusions: The HM strictureplasty results in alterations in the regional geometry that may result in a compromise of the lumen proximal and distal to the location of the strictureplasty. When 2 HM strictureplasties are created in close proximity to each other, care should be undertaken to assure that the lumen of the intervening segment is adequate.

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Crohn's disease is a chronic intestinal inflammatory condition of unknown etiology that typically affects the small intestine and colon. Inflammation from small bowel Crohn's disease is often multifocal in nature and can give rise to multiple nonadjacent areas of localized intestinal stricturing. Patients with chronic obstructive symptoms from multifocal strictures are often treated with intestinal strictureplasty. The most commonly applied strictureplasty technique is the Heineke–Mikulicz (HM) strictureplasty.[1] This procedure is named after the pyloroplasty technique from which it is derived. The procedure involves creating an antimesenteric incision along the long axis of the intestine[2] (Fig. 1) This incision is centered over the focal area of narrowing and is extended into relatively normal tissue both proximal and distal to the stricture. This longitudinal incision is then closed in a transverse fashion. With this, the HM strictureplasty draws tissue from areas proximal and distal to the stricture to add to the circumference at the stricture site. Because tissues proximal and distal to the site are shifted, changes in the regional geometry away from the stricture itself are likely. Although it is widely recognized that the HM strictureplasty is effective at relieving the narrowing of a Crohn's stricture, a detailed analysis of the effects on the regional geometry of the HM strictureplasty has yet to be described. The following study was undertaken to provide an experimental model in which to study the geometry of intestinal strictureplasties and to elucidate the geometric character and regional effects of the HM strictureplasty.

METHODS

To precisely and accurately study the geometry of a single HM strictureplasty and the interaction between pairs of strictureplasties, we designed a robust elastic model. Latex tubing with 2 cm inner diameter and 0.15 cm wall thickness (McMaster-Carr, Elmhurst, IL) was used to model the baseline cylindrical intestinal geometry. The HM procedure was carried out on the tubing: linear incisions were made along the long cylindrical axis, closed transversely using interrupted 4-0 Polysorb suture (Tyco, Norwalk, CT) taking care that the incision vertices were well approximated. The suture lines were made water tight by

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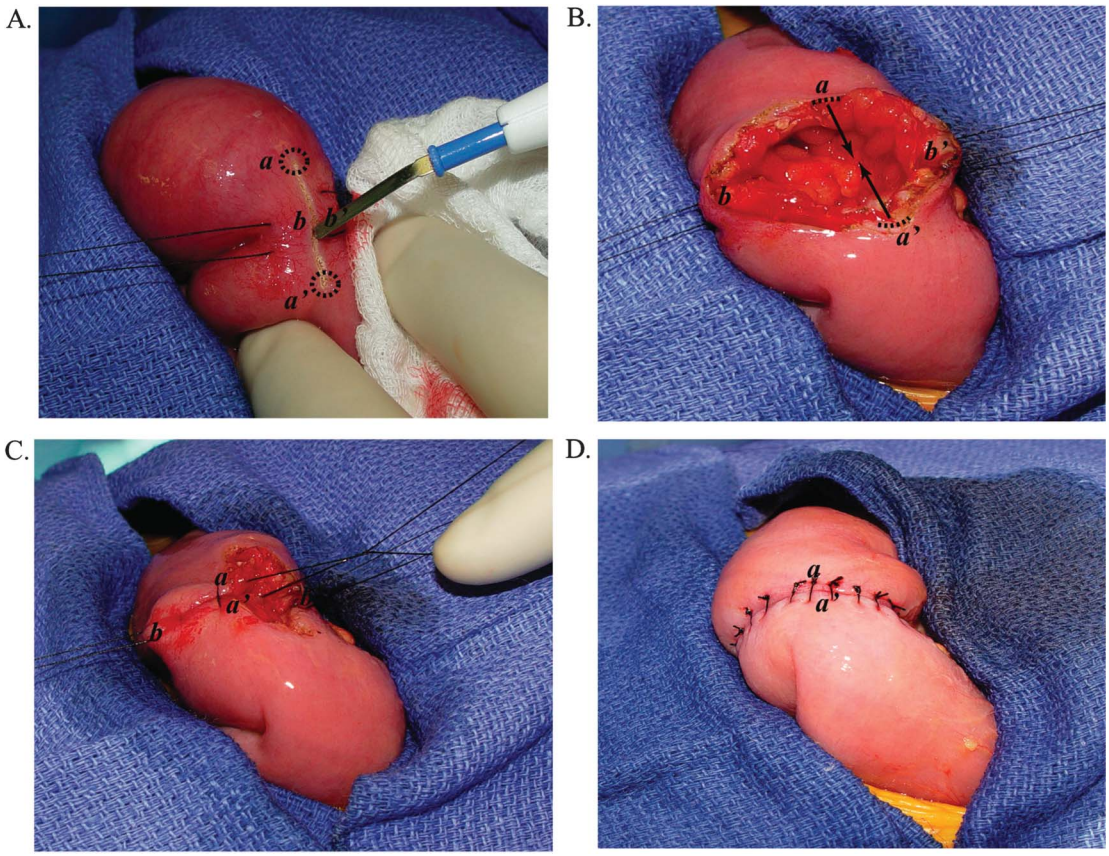

FIGURE 1. HM strictureplasty procedure performed in a patient with focal stricturing. A, Linear incision is made along the antimesenteric boarder, extending proximally (*a*) and distally (*a*′) across the stricture into healthy bowel. B and C, The incision is closed transversely with the approximation of vertex points *a* and *a*′, which initially were separated by the length of the incision. D, Completed HM strictureplasty.

external application of silicone rubber 732 multipurpose sealant (Dow Corning, Midland, MI). The postprocedure tubing was cast with EpoFix cold setting embedding epoxy resin (Electron Microscopy Sciences, Hartfield, PA). EpoFix requires no heating thus assuring the rubber mold would not deform during the casting process. A setting time of 36 to 48 hours was used at room temperature. To obtain geometric parameters, the epoxy casts were imaged with computed tomography in a Phillips iCT256 scanner using 0.9 mm slice thickness, 0.045 mm slice increments (V = 120 kV, I = 37 mA, mAs = 30 mAs). The digitalized imaging allowed for calculation and analysis of the cross-sectional area by commercial Philips 3D vascular reconstruction software (see Fig. A, Supplemental Digital Content 1, http://links.lww.com/IBD/A78 which demonstrates the digital reconstruction of the strictureplasty; see Video, Supplemental Digital Content 2, http://links.lww.com/IBD/A79, which demonstrates 3-dimensional reconstruction of a HM strictureplasty; see Video, Supplemental Digital Content 3, http://links.lww.com/IBD/A80, which demonstrates 3-dimensional reconstruction of 2 HM strictureplasties in series; see Video, Supplemental Digital Content 4, http://links.lww.com/IBD/A81 which demonstrates 3-dimensional reconstruction of a Michelassi strictureplasty). The epoxy casts were also imaged using a Nikon DX90 camera. The camera was controlled externally by the Nikon Capture Control software. All data analyses were performed using MATLAB (Mathworks, Natick, MA).

For the single strictureplasties, 3 enterotomy lengths were studied: 2, 3, and 4 cm. For the double strictureplasty models, the procedure was the same except that 2 linear enterotomies were initially created (2 and 3 cm enterotomies were studied). Care was taken so that the 2 incisions were along the same longitudinal axis. Furthermore, the separation between 2 strictureplasties was measured as the shortest linear distance between the incisions (see Fig. B, Supplemental Digital Content 1, http://links.lww.com/IBD/A78, which demonstrates measurements of separation between strictureplasties). The separation distances studied ranged from 1 to 7 cm in 1-cm step sizes. To model the Michelassi strictureplasty, a 20-cm incision was made, the tube was then transected, beveled and sutured in the standard method.

Advanced mathematical analysis of the resultant geometry of the HM strictureplasty was undertaken by considering the outermost lumen layer as an idealized 2-dimensional surface and studying its intrinsic geometry. The intrinsic geometry of a surface consists of the collection of all distances between points as

measured on the surface.[3] The connection between the intrinsic geometry of a surface and the configuration it assumes in space is not trivial and is provided by the Gaussian curvature. (see Text, Supplemental Digital Content 5, http://links.lww.com/IBD/A82 which provides a detailed description of the mathematical principles).

In general, when an initially flat (or cylindrical) surface is cut and reconnected along straight lines, the resulting intrinsic geometry remains flat almost everywhere and contains only conical defects in which Gaussian curvature is condensed in points.[4] The magnitude of a Gaussian curvature condensation can be identified with the opposite of the angle excess in the cone. A birthday hat–like structure, which is constructed by cutting out a wedge of head angle α from a disk and reconnecting the free edges of the disk, corresponds to a positive Gaussian curvature condensation of magnitude α at the vertex (see Fig. A, Supplemental Digital Content 6, http://links.lww.com/IBD/A83 which demonstrates the described curvature). Similarly, if a wedge of head angle β is now connected to the cut sides, then the resulting Gaussian curvature condensation is of magnitude $\alpha - \beta$ (see Fig. B and C, Supplemental Digital Content 6, http://links.lww.com/IBD/A83 which demonstrates the described curvature). It is important to emphasize that the condensation of Gaussian curvature to a point does not mean that the geometry was changed only at a point; in the above examples, a whole wedge of material was either introduced or eliminated to generate the desired Gaussian curvature condensation.

RESULTS

In this model, the HM strictureplasty, depending on the length of the enterotomy, increases the luminal cross-sectional area by 50% to 150% above the baseline lumen at the point of the strictureplasty (Fig. 2). Regional distortions from the strictureplasty, however, generated a decrease in luminal cross-sectional area of 25% to 50% below baseline just proximal and distal to the strictureplasty site. This compromise of the residual lumen was dramatically increased when 2 strictureplasties were placed in close proximity (Fig. 3).

For a detailed analysis of the geometry of the HM strictureplasty, we began with the model of the single strictureplasty in isolation (Fig. 2A). We identify 3 locations of Gaussian curvature condensation. First, there is the small central region in which the enterotomy end points (a and a' in Fig. 1) are sutured together. In our physical models, this corresponds to the midpoint along the suture line (black open circle in Fig. 2A bottom panel). Geometrically, the strictureplasty procedure in this point corresponds to taking 2 full circles and joining them along a radial cut as shown in Figure 4A, where the centers of the circles map onto points a and a', and the joined centers give rise to a surface geometry similar to

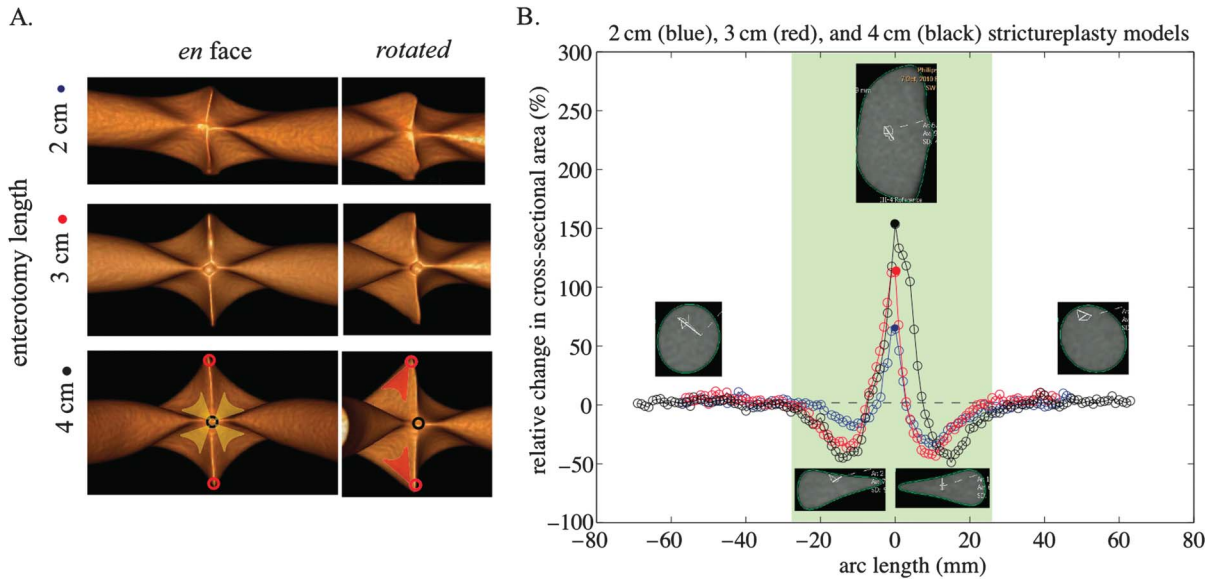

FIGURE 2. Models of single enterotomy strictureplasties of varying length. A, computed tomography–derived 3-dimensional reconstructions of final HM geometries generated from 2, 3, and 4 cm linear enterotomies. The shading in the last set of images highlights the different geometric structures discussed in the main text. B, The relative cross-sectional areas $((A - A_0)/A_0$, where A_0 is the area of the undeformed tube) of the 3 models from distal to proximal ends and across the strictureplasty sites as a function of arc length (l). Two regimes are identified: regime I: $+d \leq l$ and $-d \geq l$ (outside the green box) where A is equal to that of the undeformed cylinder and regime II $-d \leq l \leq +d$ (inside the green box) where A deviates strongly and represents the region most strongly affected by the HM procedure; in both cases, $d = 20$ mm and is the diameter of the undeformed tube. Regime II can further be subdivided into a *central area of strong dilation*, where A $(l = 0) \approx (1.5 - 3)\ A_0$ and the degree of dilation increases proportionally with increasing enterotomy length, and *flanking areas of contraction* just proximal and distal to the point of dilation, where A $(l = \pm d/2) \approx 1/2\ A_0$ and the degree of narrowing dependents less strongly on enterotomy length.

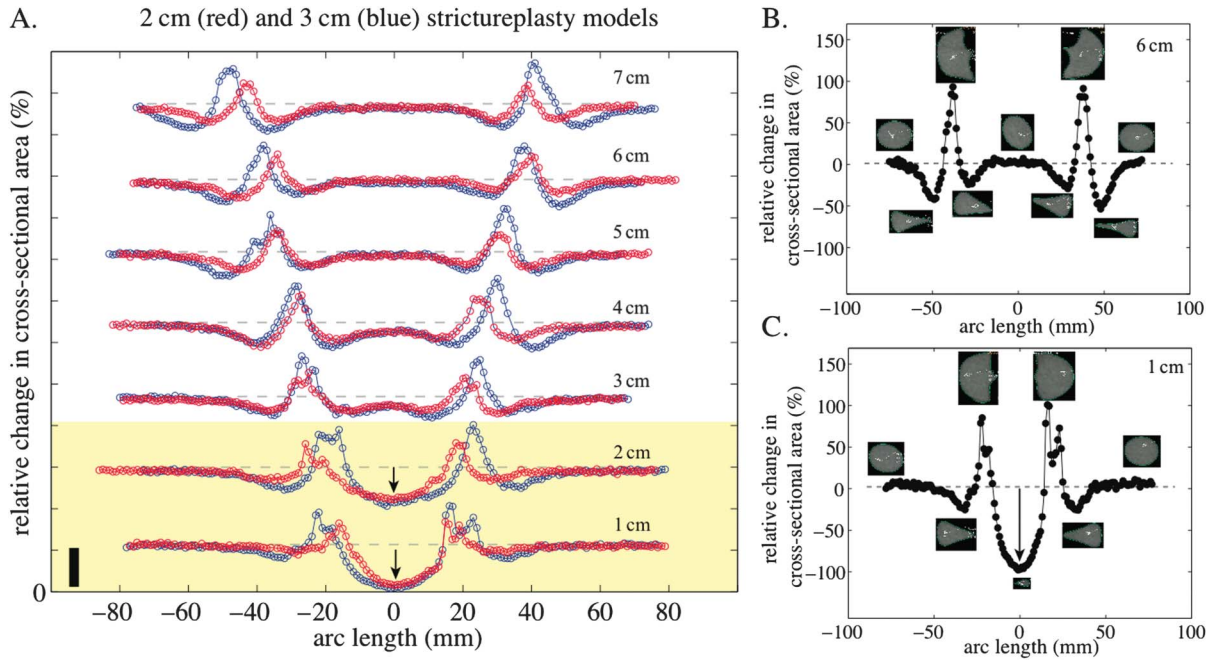

FIGURE 3. A, computed tomography–derived cross-sectional areas of model double strictureplasties as a function of enterotomy length, 2 cm (red data) and 3 cm (blue data), and strictureplasty separation (1–7 cm). The curves are offset for each separation distance and centered at the midpoint for clearer visualization. The baseline in each set is drawn in as the dashed gray horizontal line and corresponds to a cross-sectional area identical to the undeformed tube A_0 (solid black bar corresponds to a 100% change in cross-sectional area). Two regimes are identified: a weak interaction regime occurring for separation distances more than 1 tube diameter (white background data in (A) and representative set with computed tomography cross-sectional images in (B)) and a strong interaction regime when strictureplasties are placed within 1 tube diameter (yellow background data in (A) and representative set with computed tomography cross-sectional images in (C)). Within the weak interaction regime, the 2 strictureplasties sites have the same local structure as that of the single strictureplasties in Figure 2: central dilation with flanking contractions; however, beyond each strictureplasty the cross-sectional area returns to baseline: $A\ (l = 0) \approx A_0$. Within the strong interaction regime, the 2 strictureplasties strongly interact causing a very severe collapse of the cross-sectional area between the 2 sites: $A\ (l = 0) \approx 0$.

that seen in Figure 4B. This central point carries a negative Gaussian curvature condensation of -2π (saddle-like structure). The ridges of the saddle are separated by 4 valleys (shaded in yellow in Fig. 2A) and also clearly seen in different projections of the mathematical models in Fig. 4D–F.

A second set of curvature condensation points flank the central -2π region. These points arise from the transverse closure of the enterotomy at the ends of the suture line (b and b' in Fig. 1 and red open circles in Fig. 2A). Geometrically, the structure of each of these flanking corners corresponds to connecting the 2 radial lines in a semicircle to generate a cone of Gaussian curvature condensation of $+\pi$. The fact that the Gaussian curvature condensations sum up to 0 (2 of $+\pi$ and 1 of -2π) is not coincidental and is associated with the fact that far from the strictureplasty site the geometry remains unchanged. Further details of these concepts are contained within the Text, Supplemental Digital Content 5, http://links.lww.com/IBD/A82. In summary, the geometry of the HM strictureplasty is set by the linear enterotomy and transverse closure that generates 3 points of curvature condensation: a central saddle-like structure and 2 flanking cones.

The observed geometry of the single strictureplasty is strongly dominated by the -2π Gaussian curvature condensation. Within the model, cutting out the points of positive Gaussian curvature condensations and introducing various cuts to the antimesenteric side does not alter the geometry significantly. This conclusion is also supported by Figure 4 where an elastic model of the negative Gaussian curvature condensation alone (excluding both the cylindrical geometry and the positive Gaussian curvature condensation) (Fig. 4B) successfully reproduces the shape of the corresponding region in the HM strictureplasty as it appears in Figure 4C (see Video, Supplemental Digital Content 7, http://links.lww.com/IBD/A84 which demonstrates how the model successfully reproduces the shape of a HM strictureplasty).

We next investigate what impact this geometry has on luminal cross-sectional area of our models. Figure 2B presents the computed tomography–derived cross-sectional areas A as a function of curved distance along the poststrictureplasty model (i.e., arc length l). We center our data along the transverse suture line and define this plane as $l = 0$; furthermore, we use the undeformed tube diameter d as our internal length scale. In the case of all 3 enterotomy lengths (2, 3, and 4 cm), 2 regimes are immediately definable. Regime I, away from the enterotomy, and defined by $l \leq -d$ or $+d \leq l$ (outside the green box in Fig. 2B) where A is equal to A_0, the area of the undeformed cylinder, and

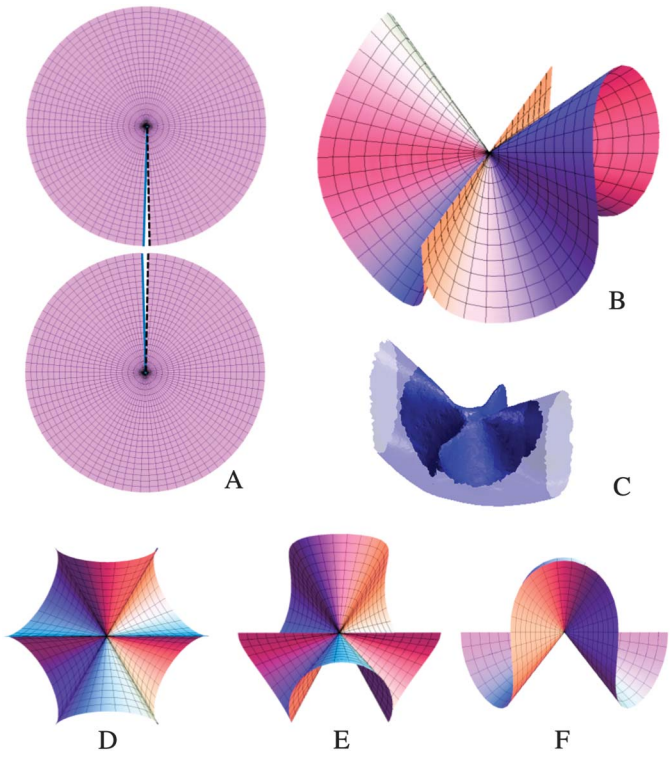

FIGURE 4. The geometry of a single HM strictureplasty is dominated by the -2π Gaussian curvature condensation at the center of the strictureplasty site. A, The enterotomy ends, marked a and a' in Figure 1 can be considered as the centers of 2 identical circles whose radii are half the enterotomy length. Within this framework, it is obvious how the suturing of the 2 circles one to the other generates a 2π angle excess that corresponds to a -2π Gaussian curvature condensation. B, The configuration obtained by minimizing the elastic bending energy of the 2 connected disks forming a -2π Gaussian curvature condensation. The suture lines are assumed to have no bending rigidity, and the disks are not allowed to self-intersect. C, The scanned 3 cm enterotomy length model (shown in Fig. 2A) with a region of distance <1.5 cm around the central vertex marked in dark blue (see Video, Supplemental Digital Content 7, http://links.lww.com/IBD/A84 which demonstrates how the model successfully reproduces the shape of a HM strictureplasty). D, Top; (E) diagonal; and (F) side views of the elastic bending minimizing configuration. The triangular opening visible in (F) accounts for the proximal and distal cross-section area decrease visible in Figure 2B.

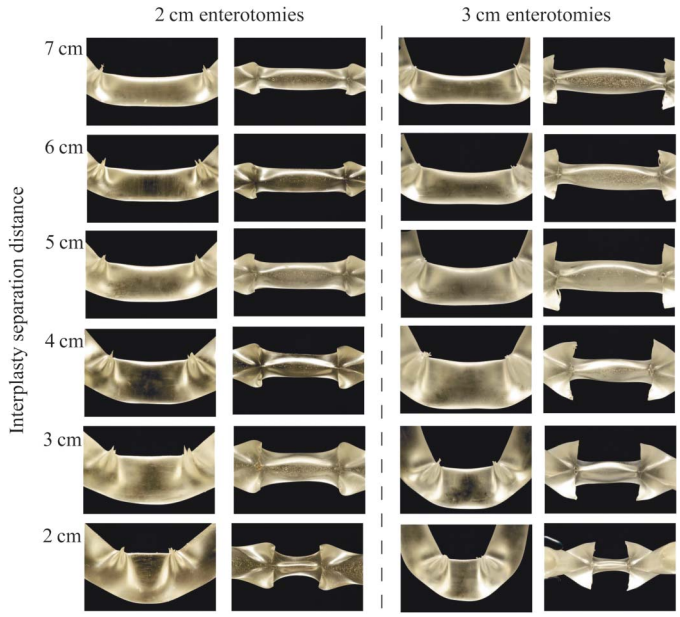

FIGURE 5. Cast models of 2 strictureplasties (2 and 3 cm enterotomies) separated by 2, 3, 4, 5, 6, or 7 cm. The interplasty separation is measured as the distance between the inner vertices of the 2 strictureplasties in the undeformed tubes (see Fig., Supplemental Digital Content 1, http://links.lww.com/IBD/A78). The images clearly show that as 2 strictureplasties approach within 1 tube diameter (2 cm), a strong change in global geometry occurs.

the corresponding relative change in cross-sectional area $(A - A_0)/A_0$ is 0. Significant deformation fields induced by the strictureplasty geometry are confined to the vicinity of the enterotomy extending 1 tube diameter in each direction, $-d \leq l \leq +d$. We define this as regime II (inside the green box in Fig. 2B). In this region both area dilation and area contracture are observed. Centrally located under the suture line is an area of strong dilation: $A\ (l = 0) \approx (1.5 - 3)\ A_0$. However, this dilated region does not smoothly connect to the undeformed cylinder of regime I but rather is flanked by regions of area contracture both distally and proximally: $A\ (l = \pm d/2) \approx 1/2\ A_0$. It is these flanking regions that make the reconnection to the undeformed cylinder. The existence of strong dilation is not surprising as the procedure is successful in dilating strictured bowel. However, the luminal compromise within the flanking regions has not been previously described.

We note that the existence of both dilated and contracted regions within the strictureplasty is consistent with its saddle-like geometry discussed above. Figure 4 shows the geometric shapes generated by fussing 2 circles in different projections. The dilated region exists directly under the suture line and corresponds to the region around the horizontal ridge where the circles were sutured together. The size of the area underneath the ridge clearly depends on its length, which is simply the length of the initial enterotomy in our models. Indeed, the data in Fig. 2B show that the dilation increases with enterotomy length. Moreover, Figure 4E and F clearly show that just proximal and distal to the horizontal suture line, the sheet is pinched inward. The 4 valleys radiating from the midpoint of the suture line (condensation point) drive this inward displacement. In fact, by comparing the cross-sectional images of our model strictureplasties in the contracture area (see Fig. 2B bottommost images), it is easily appreciated that the structure is nearly triangular in agreement with the triangular opening seen in Fig. 4F. Geometrically, the degree of pinch-off is independent of circle radius or the length of the suture line, as long as there is sufficient length for the tube to close on the mesenteric side. Again, our data are in agreement, showing that the degree of contracture is less sensitive to enterotomy size than the degree of dilation. In summary,

we conclude that the dilation (50–150% increase in cross-sectional area) is simply driven by the transverse closure of the enterotomy; however, the strong condensation of negative Gaussian curvature that occurs during this closure induces regions of area compromise (~25–50% decrease relative to undeformed tubing).

The second part of our study focuses on how the global geometry and luminal area change as multiple strictureplasties are placed in series. Figure 5 shows images for a set of 2 and 3 cm enterotomies with enterotomy separation varying from 1 to 7 cm (at 1-cm intervals). Visually, it is apparent that below a separation of 3 cm, a transition occurs. To more precisely characterize this transition, we follow the cross-sectional area of the different models using computed tomography. The data in Figure 3 can be divided into 2 regimes. A *weak interaction regime* for $\lambda > d$, where is the strictureplasty separation length (see Fig. B, Supplemental Digital Content 1, http://links.lww.com/IBD/A78 for further definition). In this regime, the 2 strictureplasties have the same geometry as in the single enterotomy cases studied above: central area of dilation flanked by areas of contracture. Beyond each strictureplasty, the cross-sectional area returns to that of the undeformed cylinder: $A\ (l = 0) \approx A\ (l = \pm\infty)$. The conclusion here is that if separated by atleast 1 tube diameter, the geometry of multiple strictureplasties is independent of one another. A rather dramatic transition occurs once the enterotomies are placed within 1 tube diameter: $\lambda \leq d$. Within this *strong interaction regime*, the 2 strictureplasties strongly interact causing a very severe collapse of the cross-sectional area between the two sites: $A\ (l = 0) \approx 0$. The nearly total collapse of the interstrictureplasty area is far beyond the milder contracture encountered with single strictureplasties, where the decrease in area was on the order of 25–50% versus >85% encountered when 2 strictureplasties are placed in close proximity (see Video, Supplemental Digital Content 8, http://links.lww.com/IBD/A85 which demonstrates a virtual flythrough of the lumen of 2 strictureplasties placed in proximity).

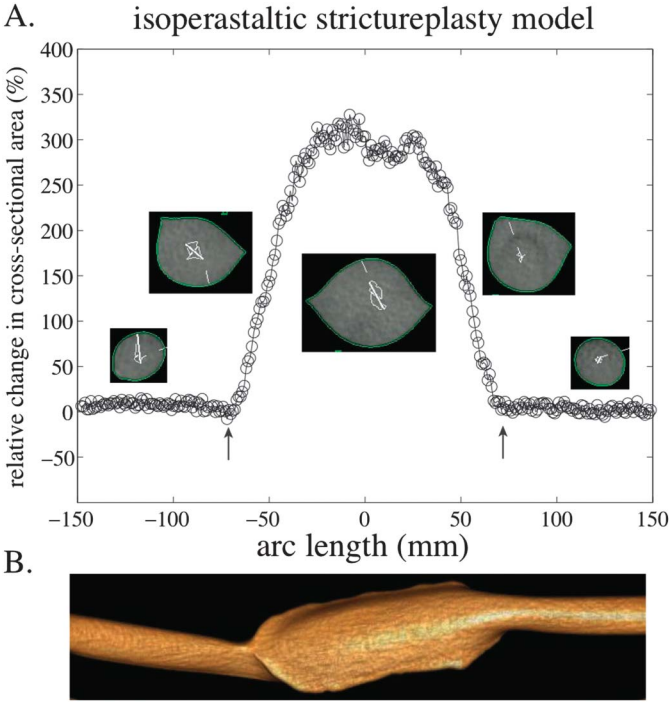

FIGURE 6. Cross-sectional area data for a model Michelassi strictureplasty (A) and the computed tomography 3-dimensional reconstruction of the model (B). The data show central dilation by a factor of 4 over the undeformed tube consistent with radius doubling in the reconstructed section. Importantly, the connection between the dilated region and the undeformed (region indicated by black arrows) is smooth with no proximal or distal contracture as in the HM.

As detailed in the Introduction, multiple strictures can surgically be treated with either several HM procedures or alternatively with the Michelassi isoperistaltic strictureplasty. We studied 1 model of the Michelassi (Fig. 6). Our data show that the procedure leads to a nearly 4-fold increase in luminal area, consistent with the doubling of the luminal diameter. Furthermore, the beveling effect at the end points releases some of the Gaussian curvature condensation. This likely plays a role in alleviating any proximal or distal contracture that would otherwise occur. Unlike the circle-to-circle geometry that is inherent in the HM, the wedges presented in Figure B and C (Supplemental Digital Content 6, http://links.lww.com/IBD/A83) capture the Michelassi end point geometry more clearly. Note that some curvature condensation still occurs; however, it is decreased by the amount of angle removed during wedge creation.

Lastly, we carried out experiments on tubes of different thickness and diameters to better understand the above observed luminal collapse between 2 strictureplasties. A phase diagram of double enterotomy/strictureplasties as a function of tube thickness (t), tube diameter (d), enterotomy length, and strictureplasty separation distance (λ) is given in Figure (Supplemental Digital Content 9, http://links.lww.com/IBD/A86), a phase diagram of double strictureplasties as a function of tube thickness, diameter, enterotomy length, and strictureplasty separation). Briefly, 3 dimensionless parameters are defined: $\psi = \lambda/d$, α = tube thickness/enterotomy length, and ϕ = enterotomy length/d. And our data show that the criteria for placing 2 HM strictureplasties within the strong interaction regime are $\psi < 1$, $\phi \geq 1$, and $\alpha \leq 0.1$.

DISCUSSION

With our model for intestinal strictureplasty we found a 25% to 50% decrease in the normal residual cross-sectional area just proximal and distal to an isolated HM strictureplasty. For the strictureplasties performed in isolation, the length of the enterotomy correlated with the cross-sectional area at the point of the strictureplasty. Larger enterotomies resulted in greater increases in the cross-sectional area at the point of the strictureplasty, whereas the degree of luminal compromise proximal and distal to the strictureplasty was less dependent upon the length of the enterotomy. That is to say, increasing the length of the enterotomy for a strictureplasty performed in isolation results in a significant increase in the lumen at the point of the stricture without much in the way of an increase in the compromise of the lumen proximally and distally.

When 2 strictureplasties are created in close proximity to each other, the compromising affect on the lumen is dramatically increased. This additive effect becomes prominent when the strictureplasties are positioned within a distance equal to or less than the diameter of the normal undistorted lumen. Given that the HM strictureplasty is designed to increase luminal diameter at the point of stricturing by shifting tissues normally located above and below the stricture, some degree of narrowing of the lumen proximally and distally could have been anticipated. Yet, the degree to which this happens, at least with our model, was surprising. The effect seen when 2 strictureplasties are placed in close proximity is dramatic.

It is important to note that the distance between strictureplasties is different from the distance between the strictures themselves. The distance between strictureplasties is a function of the distance between the strictures and the length of the enterotomy that is used to create the strictureplasty. For example, if 2 focal strictures located 7 cm apart in a segment of intestine with a baseline diameter of 3 cm are managed with HM strictureplasties each performed with a 4-cm enterotomy, the resultant strictureplasties would be 3 cm apart and thus within the range where significant luminal compromise of the segment between the strictureplasties may occur. Increasing the length of enterotomy for strictureplasties placed in series will shorten the distance between the strictureplasties themselves and thus potentially increase the collapse generated by the interaction between the 2 strictureplasties. In other words, making enterotomies that are excessively long will result in strictureplasties that ultimately will lie closer to each other and hence excessively long enterotomies may have a counterproductive effect that decreases the lumen in between the 2 strictureplasties. However, as mentioned above, shortening the enterotomy for a HM strictureplasty in isolation will not significantly affect the degree of narrowing proximally and distally to the strictureplasty. Either way decreasing the length of the enterotomy will decrease the expansion of the lumen at the stricture sites.

The safety and effectiveness of HM strictureplasties in the management of stricturing Crohn's disease of the small intestine has been well-established.[1,5–8] The technique is an effective means of alleviating the symptoms of chronic partial obstruction while at the same time preserving intestinal length and functional absorptive surface area. From the excellent short-term results reported in multiple case series, it is reasonable to conclude that any luminal compromising that may occur in proximity to the HM strictureplasty is not likely to result in postoperative obstructive symptoms in the short term. The long-term consequences on luminal narrowing, however, may prove to be more troubling. Much attention has been paid to the consequences that the postsurgical residual intestinal lumen after intestinal anastomosis may have on the recurrence rates for Crohn's disease. Considerable literature has been devoted to how varying anastomotic techniques would affect the likelihood of recurrence.[9–13] So far, no such consideration has been applied to strictureplasty techniques. It has been suggested that anastomotic techniques that result in diminished or compromised luminal cross-sectional areas may result in earlier recurrences of inflammation and/or symptoms from recurrent Crohn's disease.[11,13,14] Some have contended that stasis of luminal contents may generate or aggravate the inflammatory response.[11,13,15] Clinical observations have also suggested that alleviation of stasis may result in improvement in disease activity.[15,16] Even if residual lumen size were to have no effect on the activity of inflammation, it would seem possible that an already compromised lumen would more readily constrict to a critical diameter that leads to earlier development of obstructive symptoms.

It is interesting to note that some authors have found that upon reexploration for recurrent Crohn's disease in those patients who had undergone previous intestinal strictureplasty, the strictureplasty sites themselves are often free of recurrence.[16,17] Recurrences, however, are commonly noted to be in the same general region of the initially treated disease. In other words, recurrences may not typically occur at the strictureplasty site but rather in the regions proximal or distal to the previous site. It is also been reported that recurrences are higher when multiple strictureplasties are used compared with strictureplasties performed in isolation.[18]

Surgeons with experience in treating Crohn's disease have advised against placing HM strictureplasties in close proximity. These recommendations are based upon concerns regarding tension on the suture lines and possible compromise of the blood flow to the tissues in between suture lines that are placed in close proximity. We believe this study provides additional reasons for concern when performing HM strictureplasties that are separated from each other by relatively short distances. Under such circumstances, it may be advisable to use alternative techniques such as resection, the Finney strictureplasty, or the Michelassi strictureplasty. The Michelassi strictureplasty seems to be well suited for managing multiple strictures located in close proximity. Our model demonstrated that this technique resulted in dramatic increase in the lumen throughout the length of the strictureplasty without any significant compromise of the natural lumen on either the proximal or distal ends.

The detailed mathematical analysis of the 3-dimensional geometry of the HM strictureplasty is both complex and challenging. Such detailed analysis, however, is more than a theoretical endeavor. Through such analysis and modeling, it may be possible to propose modifications to the surgical technique that could ameliorate the effects described; hence, the detailed mathematical analysis is included in this article.

The main limitation of this study is that the model is created from inanimate materials and thus it cannot compensate or predict the variables that may occur in living tissue, such as motility, variable compliance, remodeling, and tissue growth compensation. The model, however, does provide for the consistency and reproducibility necessary for accurate measurement and analysis. Another limitation of this study is that all the experiments were performed in tubes without focal stricturing. This was done for the sake of consistency, but the absence of a focal stricture should not affect the key observations made. Because the surgical procedure

extends both proximally and distally beyond the strictured area, the global hyperbolic geometry caused by negative Gaussian curvature condensation at the central point will be dominated by tissue properties at the ends of the enterotomy. These ends exist in normal tissue. Although the stricture tissue could potentially impact how the flanking conical structures develop, these areas are not relevant to the geometric issues that are the focal point of this study.

In summary, our model suggests that the HM strictureplasty results in compromise of the lumen proximal and distal to the strictureplasty site. This effect is greatly increased when to strictureplasties are placed in close proximity to each other. Care should be undertaken when performing multiple HM strictureplasties to assure that the intervening lumen is adequate.

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