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EXPERIMENTAL STUDY

Acellular dermal matrix fenestrations and their effect on breast shape

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Abstract
Background Acellular dermal matrices (ADMs) are increasingly being utilized in primary and secondary breast reconstruction as they confer several advantages, including soft tissue enhancement at the inferolateral pole of the breast. The senior authors have added fenestrations to ADMs to allow for more rapid expansion and improved breast aesthetics. The purpose of this study is to describe the benefits of ADM fenestration using a mathematical formula as a proof of concept for the effects of these modifications on breast shape.
Methods The aggregate effect of symmetrically arranged fenestrations on the ADM's mechanical properties is explained by a uniform reduction in the effective Young's modulus of the graft in a direction perpendicular to the chest wall in the area of graft fenestration. Asymmetric reduction of the Young's modulus is achieved by concentration of the fenestrations at either the cephalic or caudal ends of the ADM.
Results The relaxed Young's modulus facilitates an increased deflection of the ADM from its resting, unaltered state under the weight of the implant or tissue expander and is modeled using a one-dimensional boundary equation. The reduced inferior pole tension allows for enhanced expansion under the weight of the implant or tissue expander. The effects of asymmetrically arranged fenestrations are similarly modeled and appear to afford the surgeon greater precision in controlling inferior pole characteristics.
Conclusions Acellular dermal matrix fenestration improves aesthetic outcome by facilitating greater inferior pole expansion. Mathematical models are provided to describe the modifications and elucidate the mechanism behind their effect on breast shape.
Level of Evidence: Not ratable

Keywords Acellular dermal matrix · Breast reconstruction · Fenestrations · Inferior pole expansion · Mathematical model

Introduction

The use of acellular dermal matrices (ADMs) has become increasingly prevalent in primary (direct-to-implant) and staged breast reconstructions over the last several years [1]. ADMs are derived from cadaveric dermis and are composed primarily of extracellular matrix (ECM) components, which provide a scaffold upon which resident cells can migrate following implantation, facilitating matrix integration [2]. ADMs serve several functions when utilized in breast reconstruction. Most notably, they provide greater soft tissue coverage and suspension within a pocket that may allow for direct-to-implant reconstruction and decrease the time needed to achieve complete expansion in two-stage reconstructions [3–5]. Additionally, when sutured to the chest wall, ADMs can accentuate the infra-mammary fold and lend definition to the lateral mammary contour, which improves symmetry and aesthetic appeal [6–8]. Furthermore, given that the inherent stretch properties of ADMs confer elasticity analogous to normal intact human skin, they function as an expandable sling under the weight of the implant at the inferolateral aspect of the reconstructed breast [6]. By decreasing the tension on an implant, the ADM therefore permits full expansion and improves projection of the lower pole [3, 9, 10].

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Complications in ADM-assisted breast reconstruction are comparable to non-ADM reconstructions, and it has been suggested that ADMs decrease the rate of capsular contracture [1, 4, 11–14]. ADM-assisted reconstructions, however, are associated with a higher incidence of seroma formation, which may stem from the learning curve associated with their use or, more likely, inadequate fluid egress from the subpectoral pocket [15–18].

The authors have used ADMs over the past 8 years in both primary and staged breast reconstruction. We have previously demonstrated that the addition of strategically placed fenestrations in the ADM material leads to improved intra-operative fill volumes, a decreased number of post-operative expansions, and what we believe to be a superior aesthetic result [19]. Furthermore, the fenestrated product appears to reduce our observed complication rate, as seroma formation and capsular contracture are rare in our patient population. The purpose of this study is to describe the aesthetic and functional effects of ADM fenestration in light of our experience and to propose a mathematical model as a proof of concept for these effects on breast shape.

Material and methods

In 2005, Breuing et al. were the first to describe the use of ADMs in breast reconstruction, whereby the ADM acts as an expandable sling supporting the inferior and lateral aspects of the implant or tissue expander [11]. Several factors contribute to the final position of the implant after it settles onto the ADM: the elastic properties of the matrix, the ADM position on the chest wall, and the weight of the implant. Together with the shape, size, and projection of the implant, these variables act in concert to define the expansion and projection of the inferior pole of the breast following implantation. Optimal fenestrations in the ADM act to further improve the coordination of these variables to achieve better aesthetic results.

In an effort to establish a mathematical model that accurately describes the expansion of the ADM under the weight of an implant, the three-dimensional contour of the inferolateral aspect of the reconstructed breast was simplified into a one-dimensional problem. In other words, the final shape of the ADM, which is affected by manipulation of the aforementioned variables, is described simply as the amount of bend, or deflection, of the ADM from its flat, unstressed state. This variable is denoted as u (Fig. 1).

The ultimate result of the fenestrations is dependent upon augmentation of an intrinsic property of the ADM known as Young's modulus (σ). Young's modulus is defined as the inherent stiffness of an elastic material and is mathematically represented by the ratio of stress (pounds per square inch) over strain (dimensionless). Given that the rectangular ADMs have set size and fixed, uniform elastic properties, they have a particular Young's modulus that determines their behavior under stress. A greater Young's modulus predicts that under a given stress, the ADM will demonstrate less deviation (u) compared to a material with a lower σ. By placing fenestrations in the ADM (Fig. 2a, b), we reduce the effective Young's modulus to a lower σ and yield a larger deflection profile (u), consequently improving expansion of the inferior pole and facilitating a more natural shape under the load of the implant.

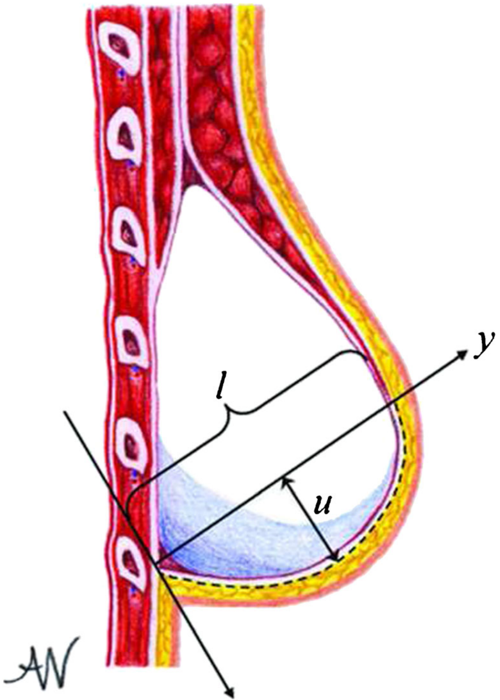

Fig. 1 Parameters of the ADM used to predict the deflection (u) from a flat, unstressed state. y is distance from the chest wall in a posteroanterior direction, and l is the width of the ADM or the distance from the suture point at the chest wall to the point of attachment at the pectoralis major muscle

Reducing the Young's modulus requires that fenestrations be placed perpendicular to a posteroanterior line extending directly from the chest wall, as depicted in Fig. 1 by the vector y, which signifies the distance from the chest wall toward the suture point at the inferior edge of the pectoralis major muscle. Specifically, cuts of a predetermined length are made in the direction of the longest aspect of the rectangular graft. Upon inset of the ADM, these fenestrations assume and maintain an oval shape when exposed to the weight of the implant or tissue expander (Fig. 2c, d). If the fenestrations are regularly spaced and staggered so as to achieve approximately 50−80 % overlap as depicted in Fig. 2a, an approximately uniform effective Young's modulus can be calculated by integrating over the distance from the chest wall to the anterior fixation point of the graft at the pectoralis major muscle (y).

Results

The deflection of the ADM under the weight of an implant can be described using the one-dimensional boundary value

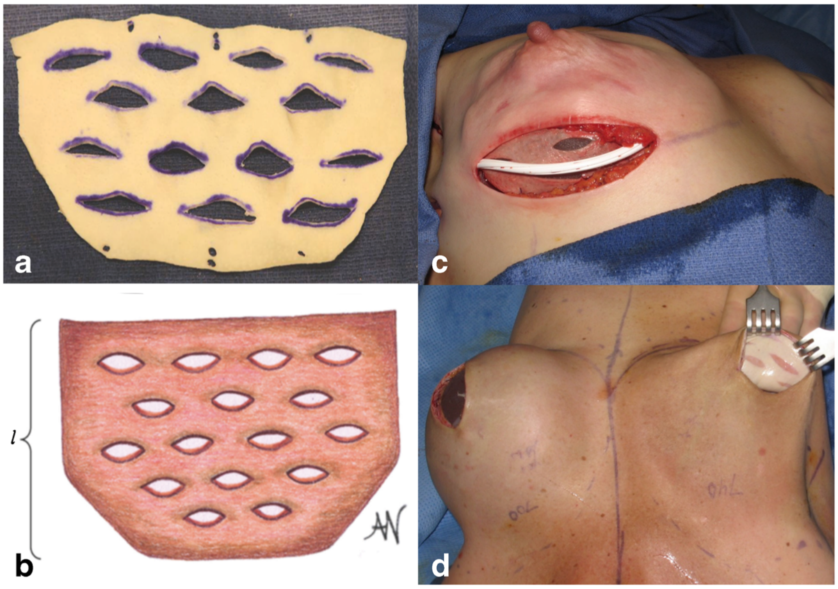

Fig. 2 **a** Preparation of the fenestrated ADM with staggered longitudinal cuts organized in parallel rows where **b** *l* is the width of the ADM. **c** ADM supporting the inferolateral aspect of the reconstructed breast with expanded fenestrations arranged parallel to the chest wall in the medial-to-lateral direction. **d** Maintenance of oval shape at time of implant exchange

problem (Fig. 3a). As previously mentioned, u denotes the deviation of the ADM from its flat, unstressed state. This deflection profile is affected by changes in two variables: y and σ. The variable y must have a value that is bound between 0, which represents the suture point on the chest wall at the level of the infra-mammary fold (IMF), and l, which is the distance from this point to the attachment at the pectoralis major muscle. This is equivalent to the width of the ADM in its unstressed state (Fig. 1). The second variable is the effective Young's modulus, σ, that is relaxed by placing fenestrations in the ADM. The equation in Fig. 3a also includes one additional variable, f, which is the load stemming from the implant and is assumed to be constant. Clinically, the pectoralis major muscle is dynamic in nature in that the inferior edge window shades following implant or expander placement. This phenomenon, however, does not impact our conclusions as the boundaries of our equation include the suture point at the pectoralis, which negligibly adjusts in direct proportion to muscle displacement.

$$\textbf{a}\quad \begin{cases} -\partial_y\left(\sigma \partial_y u\right) = f\,, \quad y \in (0, l)\,, \\ u(0) = 0\,, \\ u(l) = 0\,, \end{cases}$$

$$\textbf{b}\quad \sigma(y) = a + (1 - a)\left[1 + \tanh\left(10(x - 0.5)\right)\right]/2$$

Fig. 3 **a** One-dimensional boundary value problem used to describe the geometry of the ADM where σ represents the Young's modulus of the ADM, u denotes the amount of deviation of the ADM from its flat, unstressed state, f is the load stemming from the implant, y is the distance from the chest wall in a posteroanterior direction, ∂y is the derivative of u in the direction of y, and l is the width of the ADM. **b** Mathematical model describing the asymmetric deflection profile of the ADM following the inhomogeneous placement of fenestrations. The variable a represents the new σ for an asymmetric deviation

It is realistic to assume that this linear elasticity model is valid in practice due to relatively small deflections from equilibrium. Even if the parameters σ, l, and f are unknown, and σ is the only variable that is manipulated, the presence of fenestrations in the ADM will always lead to an enhancement in inferior pole expansion. This is depicted graphically in Fig. 4a where arbitrary values for σ are used to illustrate the inverse relationship between Young's modulus and the deviation of the ADM from its resting, unstressed state.

The equation in Fig. 3a models the situation in which cuts are placed uniformly perpendicular to l, which results in a symmetric deflection between the two suture points at y=0 and y=1. It is conceivable to instead generate an asymmetric deflection profile by concentrating the cuts at the cephalic or caudal portion of the ADM with respect to the chest wall. The resultant shape can be predicted using the function in Fig. 3b in which a represents the new Young's modulus, which is now inhomogeneous across the width of the ADM. For example, if the cuts are not uniformly distributed across the entire width l but are instead symmetrically concentrated within the area h, which denotes the caudal half of l, the effective Young's modulus will no longer be constant over l (Fig. 5). Figure 4b demonstrates the effect of concentrating the fenestrations closer to the chest wall (caudal end of the ADM), resulting in a reduced Young's modulus in this portion of the ADM. This in turn precipitates an asymmetric deflection profile of the ADM with respect to chest wall proximity as seen in Fig. 4c.

Discussion

The utilization of ADMs in primary and staged breast reconstruction has been suggested to improve projection at the

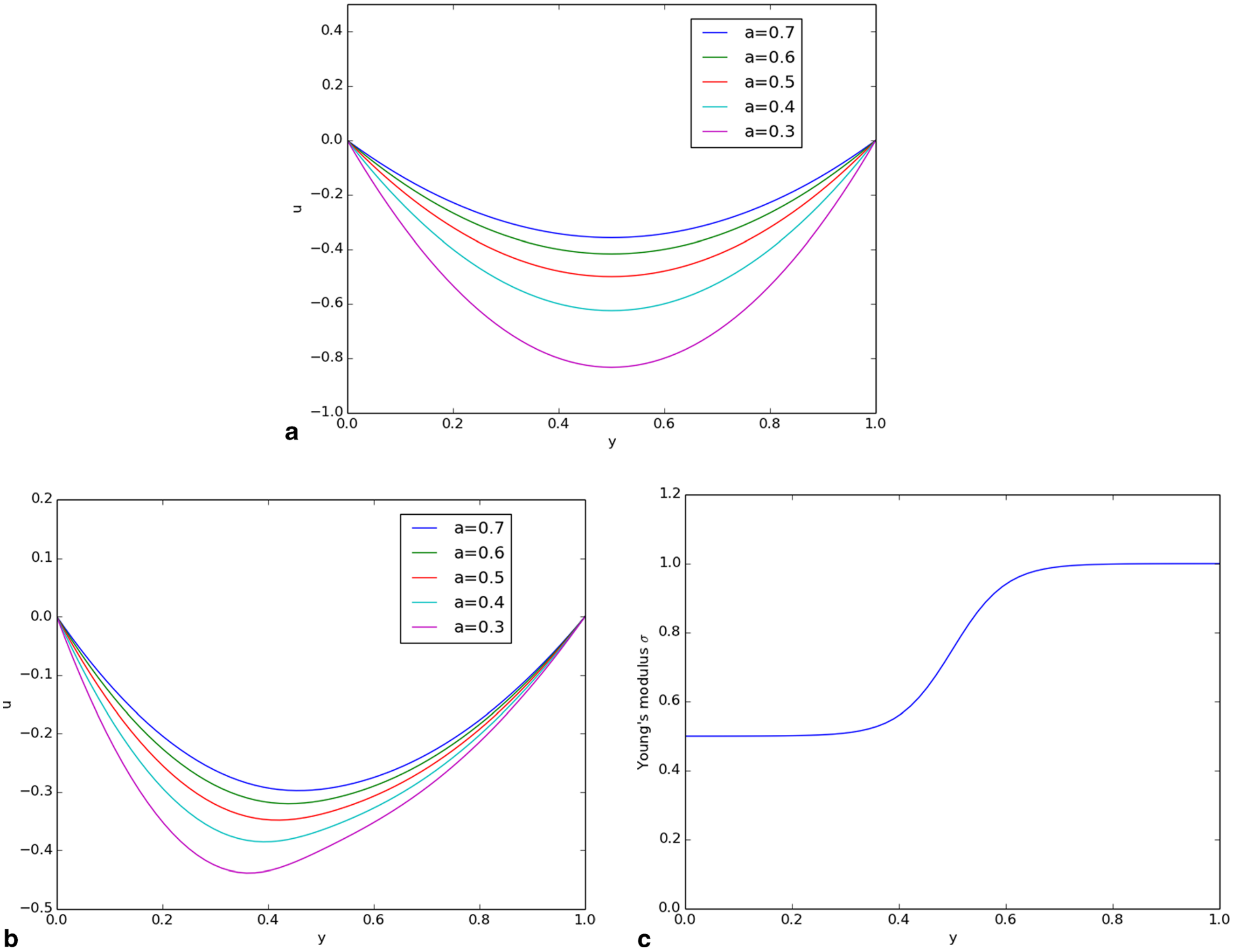

Fig. 4 **a** Graft deflection profiles for values of σ. Fenestrating the matrix decreases σ, thereby enhancing graft deflection from its flat, unstressed state. **b** Profile of Young's modulus (σ) across the length of the ADM following the inhomogeneous placement of fenestrations. Concentrating the fenestrations closer to the chest wall results in a lower Young's modulus in this region of the ADM compared to the unfenestrated portions of the graft. **c** Graft deflection profile for an inhomogeneous Young's modulus as modeled by the equation shown in Fig. 3b. Asymmetric concentration of the cuts from y=0 to y=0.5 confines the deflection of the ADM to a position closer to the chest wall

inferior pole of the reconstructed breast, secondary to an easing of the tension placed on the implant as a result of ADM incorporation [3]. This expansion is accentuated by altering the elastic properties of the ADM through strategically placed fenestrations with appropriate overlap. As cuts in the ADM decrease the effective Young's modulus and consequently increase the deflection of the matrix under a fixed load, the tension on the implant similarly decreases, leading to greater expansion of the inferior breast. We believe that this increased lower pole expansion achieved with fenestration improves breast cosmesis by allowing for a more natural, ptotic breast shape.

The use of meshing to modify the intrinsic properties of grafted material is a time-tested concept. The meshing process was first introduced in 1963 as a method of increasing the surface area coverage offered by conventional skin grafts [20]. Our technique utilizes a similar pattern of precisely staggered cuts arranged into uniform parallel rows over the surface of the ADM. By organizing medial-to-lateral cuts parallel to the long axis of the ADM, the effective Young's modulus is reduced along a vector connecting the fixation points at the chest wall and at the inferior border of the pectoralis major muscle in the posteroanterior direction (y). Given that maximal expansion of a graft occurs when it is pulled perpendicular

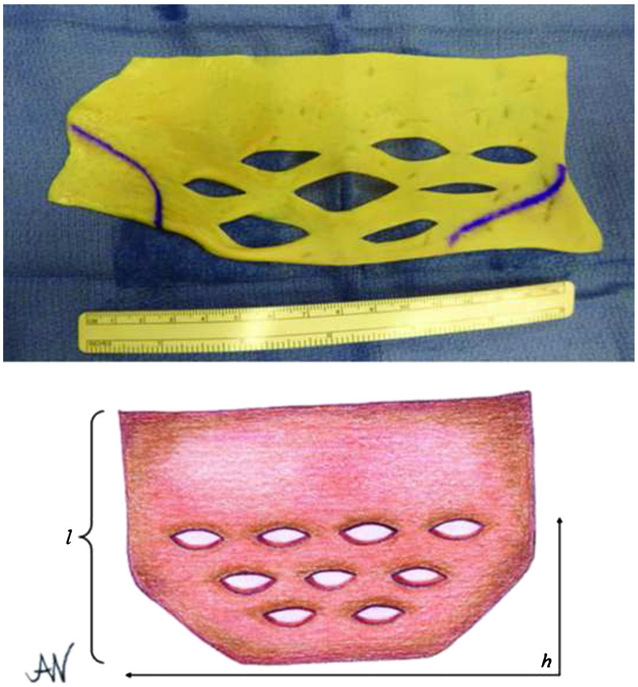

Fig. 5 Concentration of fenestrations on the caudal half of the ADM that is closer to the chest wall, represented by area *h*. This technique allows for the asymmetric deflection profile demonstrated in Fig. 4c

to the length of the cuts, the fenestrated ADM will undergo maximum expansion under the weight of the implant or tissue expander using our technique.

Vandeput et al. proposed a mathematical formula for predicting the theoretical expansion of a graft based on the number of cuts per square inch, the length of the cuts, the vertical distance between each row of cuts, and the distance between the cuts within each row [21]. The authors demonstrated that decreasing the vertical distance between rows of cuts exponentially decreases the amount of graft expansion. Additionally, decreasing the absolute length of the cuts linearly decreases graft expansion. Given that maximal excursion occurs at the center of the fenestration, optimal uniform expansion is achieved when the cuts are staggered in alternate rows to achieve 50–80 % overlap, as designed and implemented by the authors. This also results in the shortest healing time, as the islands of uncut tissue are free to act as bridges to facilitate tissue in-growth. In theory, manipulating these variables may allow the surgeon to control the extent of ADM deviation under the implant and therefore influence the degree of lower pole expansion.

Complications associated with non-fenestrated ADMs are reported to be comparable to reconstructions that do not utilize ADM [1, 18]. However, several studies have also shown increased rates of seroma formation in patients who have undergone AlloDerm-associated (LifeCell Corp., Branchburg, NJ) reconstructions [16, 17, 22, 23], with an incidence ranging from 0 to 9 % in one particular systematic review [1]. Poor contact between the ADM and overlying tissues secondary to irregularity at the soft tissue interface and intentional under inflation of the tissue expander have been cited as reasons for these increased seroma rates [8, 22]. Precise fenestrations with optimal overlap minimize these risk factors. In our patient population, we observed a decreased rate of seroma formation in patients who underwent reconstruction with fenestrated ADMs [19]. It is feasible that enhanced deflection of the ADM secondary to these fenestrations allowed for improved effacement of the tissue expander and ADM with the overlying soft tissue envelope. In addition, the fenestrations create a communication between the subpectoral and subcutaneous pockets, allowing drainage of fluid into the more superficial pocket that can be evacuated with a single drain. Earlier tissue expansion and pressure on the allograft lead to material thinning, earlier vascularization, and greater tissue incorporation due to increased approximation of the graft with the breast flap. This decreases the potential for infectious complications, as there is earlier vascular in-growth into the ADM.

A mathematical formula that describes the effects of fenestration on ADMs in breast reconstruction was proposed as a proof of concept and support for our observations. The model provides a solid foundation for elucidating the underlying mechanism of ADM expansion.

Conclusions

In the preceding discussion, the authors propose a novel material alteration to ADMs for use in breast reconstruction. The authors' application of strategic fenestrations with proper overlap improves aesthetic results by allowing for increased inferior pole expansion with preservation of the natural IMF and shape. This also decreases seroma formation by reducing potential space and providing better drainage of the breast pocket with a single drain. Infectious complications are reduced with rapid incorporation of the ADM due to improved vascular in-growth owing to product thinning with greater immediate expansion. The authors have developed a mathematical model to describe these modifications and elucidate the mechanism behind their effect on breast shape.

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Conflict of interest Authors Garrett A. Wirth, Donald S. Mowlds, Patrick Guidotti, Ara A. Salibian, Audrey Nguyen, and Keyianoosh Z. Paydar declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. For this type of study (retrospective), formal consent is not required.

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