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Finite element analysis to determine stress fields at the apex of V-Y flaps

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Abstract After performing a V-Y advancement flap, we observed an unusually shaped necrosis, resembling a keyhole at the apex of the flap. As high closing tensions are an accepted cause of skin necrosis, we developed a mathematical model based on the finite element analysis in order to determine the stress field by simulating the mechanical behavior of human skin during suture and to explain this particular shape of necrosis. For the modeling, a planar nonlinear two-dimensional finite element model was used. The numerical simulation was carried out with Ansys® v12 software. Results are expressed in numerical and graphic form. The shape of the vertical iso-stress line for a stress equal to 18.8 kPa was similar to the necrosis observed in our clinical case. Similarities between the shape of necrosis and the calculated stress field at the apex of the V-Y advancement flap indicate the major role of skin tension in this necrosis. Finite element analysis is an original approach for describing the particular shape of a necrosis. Although many factors can be implicated in skin necrosis, the modeling confirms the role of tension in the necrosis of this particular case.

Level of Evidence: Level V, risk/prognostic study

Keywords V-Yadvancement flap · Necrosis · Finite element analysis · Modeling

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Introduction

High closing tensions are an accepted cause of skin necrosis [1]. For linear scars after elliptical excision, maximum tension is obtained along an axis perpendicular to the scar at the level of maximum excision, and laterally, the tension decreases progressively [2]. In case of necrosis due to too high closing tension, the shape of skin necrosis is then roughly parallel to skin margins.

After performing a V-Y advancement flap, we observed an unusually shaped skin necrosis and skin epidermolysis on either side of the apex of the flap. The shape of this two signs of suffering skin was unusual in that it resembles a keyhole, with the major axis perpendicular to skin margins at the apex

Fig. 1 Skin necrosis and epidermolysis with a keyhole shape at the summit of the flap

of the flap where a corner stitch had been performed (Fig. 1). As there was a lot of tension when suturing, we discuss the possibility that this shape may be explained by determining the stress field with mathematical modeling.

Based in part from a V-Y flap simulated during an abdominoplasty procedure (Fig. 2), we developed a mathematical model based on the finite element analysis (FEA) in order to determine the stress field by simulating the mechanical behavior of human skin during suture.

This study was divided into two parts. The first part of the modeling determines the biaxial initial stress fields representing the in vivo skin tension by inverse method. The second part determines stress fields when suturing the corner stitch. Results are expressed in numerical and graphic form and compared to the clinical case.

Case presentation

An 83-year-old patient presented a dedifferentiated liposarcoma of the lateral chest without metastasis. The major axis measured 10 cm. A wide resection was performed including the primary dominant vascular pedicle of the latissimus dorsi muscle. To cover the defect, a V-Y advancement flap was used, with two lateral expansions according to the Pacman flap (Fig. 3) [3]. The flap was supplied by secondary pedicles from the intercostal and lumbar vessels, and a medial muscle incision was made to allow for an advancement flap (Fig. 4). The angle value of the flap apex was about 50°.

The postoperative period was marked by skin necrosis and skin epidermolysis on one side of the apex. Both have a keyhole shape with the major axis perpendicular to skin margins (Fig. 1). Healing occurred by secondary intention.

Material and Methods

The natural tension of the skin is due to prestress. To determine orthogonal prestress σ_x and σ_y, a rectangular defect was performed in vivo during an abdominoplasty in a 38-year-old woman. Local ethics committee approval and written informed consent were obtained. A rectangular mesh was drawn before skin incision. The dimension of one mesh square was 14×14 mm, and the dimension of the rectangular defect was $d_1 = 42$ mm and $d_2 = 84$ mm. d_1 was parallel to the horizontal direction x, and d_2 was parallel to the vertical direction y (Fig. 2a). Horizontal and vertical skin deformations after incision were due to horizontal prestress field σ_x and to vertical prestress field σ_y, respectively (Fig. 2b). The width d_1 of the rectangle was aligned approximately with Langers lines [4]. For the modeling, a planar nonlinear twodimensional FE model was used. The numerical simulation was carried out with Ansys® v12 software. This numerical simulation was based on Arruda and Boyce's eight-chain material model [5] with parameters taken from and Bischoff et al. [6].

The FEA first established the geometry of the rectangular defect according to Fig. 2a. The dimensions of the modeled defect were identical to the clinical case. It was discretized into triangular finite elements (Fig. 5).

Modelization was divided into two parts: the first part determined the initial stress field of the skin. The stress fields at the boundary of the region under investigation were identified by the inverse method using a finite element calculation by comparing the modeled defect width along the horizontal direction x with the deformed rectangular one (Fig. 2b).

The second part of the modeling process simulated the corner stitch. The FEA thus established the geometry of the V-Y flap just before the corner stitch (Fig. 6). The model was based on the geometry of the V-Y flap used during the abdominoplasty procedure (Fig. 2d). The flap apex angle value is also about 50°. The biaxial prestress fields calculated as described above were incorporated as an additional parameter in the model. The material properties, boundary conditions, and forces were applied to the model, and the results were expressed in numerical and graphic form. To solve the problem of the two-dimensional finite element, the following assumptions were made during the first part of the numerical procedure (Fig. 5):

- The plane stress hypothesis was made for all elements.
- The size of skin sheet was considered to be large with regard to the rectangular defect in order to avoid the influence of the external boundary conditions on the stress field analysis in the neighborhood of the defect.
- In order to have a homogeneous biaxial stress field within the entire skin (without a defect), a prescribed zero displacement of two perpendicular external edges of the in-

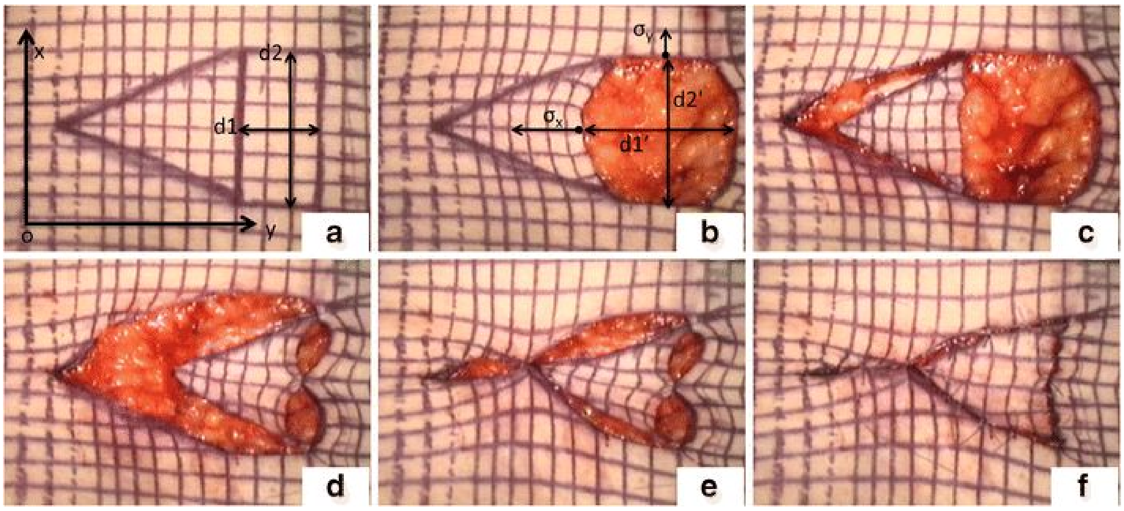

Fig. 2 A rectangular defect and a V-Y advancement flap are performed during an abdominoplasty procedure to characterize skin properties

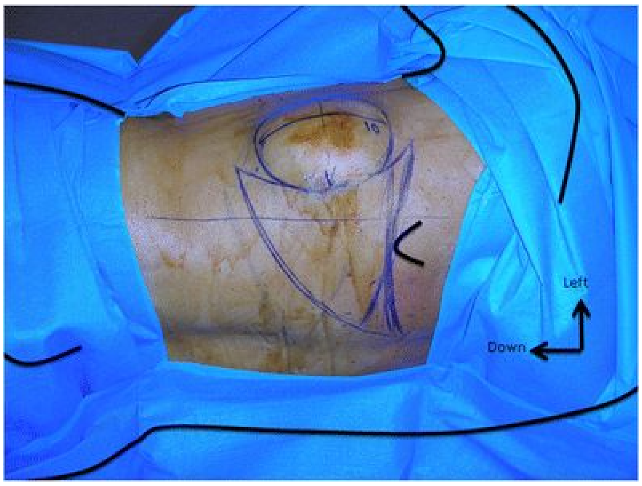

Fig. 3 Latero-thoracic liposarcoma. V-Y flap design (patient positioned in right lateral decubitus position

Fig. 4 V-Y advancement flap with medial latissimus dorsi incision. Apex flap and medial skin are without muscular vascular support

vestigated structure was introduced on left and bottom sides of the skin sheet and a biaxial prestress σ_x and σ_y was, respectively, applied on right and top sides (Fig. 5).
– The mesh around the defect was twice finer than elsewhere.

In the second part of the numerical procedure, new assumptions were made to simplify the modeling procedure (Fig. 6):

– The horizontal symmetry of the model allows half of the domain to be modeled.
– Contrary in Fig. 2d, the flap in Fig. 6 was sutured by only three points; the flap was stuck at the bottom of the loss of substance to design a simplified domain.
– Although in Fig. 2d the flap apex was free-moving, the apex of the flap in Fig. 6 was constrained to zero displacement.
– The stitch point was chosen as the projection of the flap apex N on the wound edge to be moved closer. This point was named M on Fig. 6, and M was moved to the fix point N by a displacement constraint.

Results

In Fig. 2a, the initial dimensions of the rectangle were $d_1 =$ 42 mm and $d2 = 82$ mm. After the incision was made, the orthogonal prestress fields deformed the rectangle and the dimensions of the rectangular defect became $d_1' = 84$ mm and $d_2' = 76$ mm. From inverse FEA using the nonlinear material model, the prestress was found to be $\sigma_x = 6.4$ kPa and $\sigma_y = 0.3$ kPa (Fig. 7).

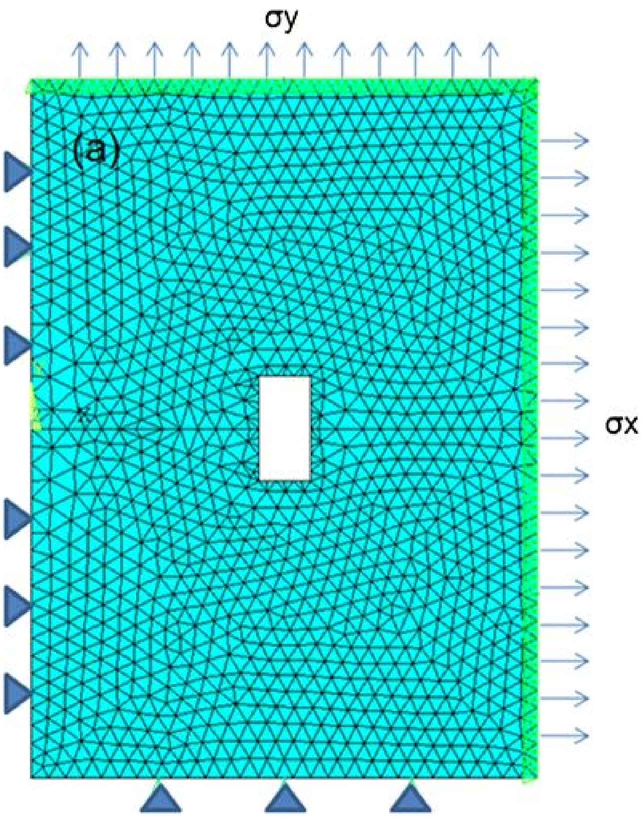

Fig. 5 Geometric model, meshing, and boundary conditions of the domain with rectangular hole

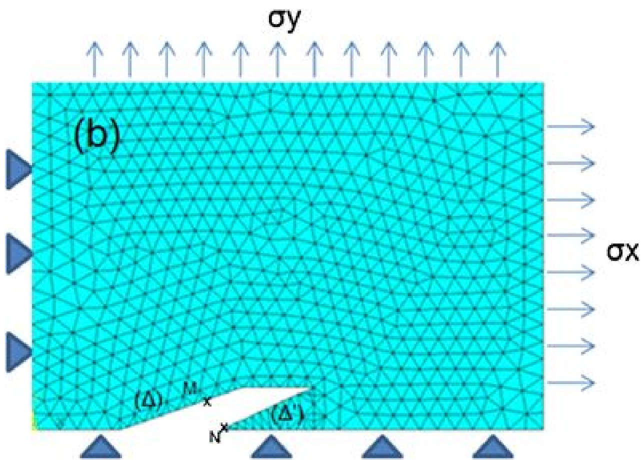

Fig. 6 Geometric model, meshing, and boundary conditions of the V-Y flap

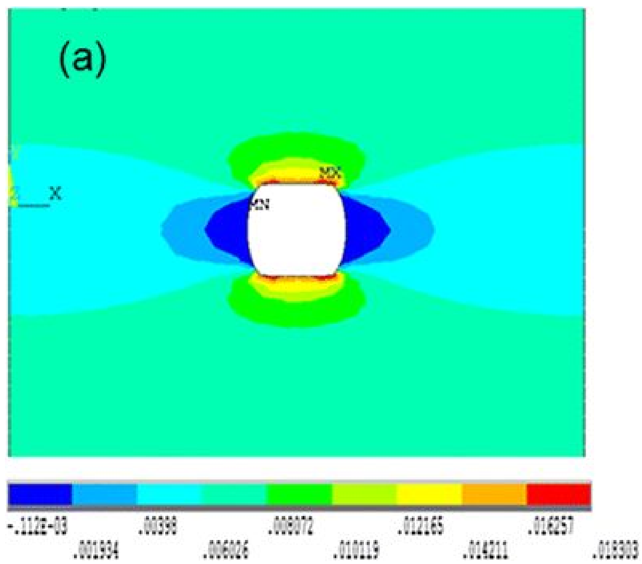

Fig. 7 Zoom of the stress field σ_x on the neighborhood of the defect calculated by inverse method. Values of stress are expressed in megapascals

After incorporating these values in the numerical modelization, biaxial loading determined the maximum stress in the corner stitch. The values of maximum stress were $\sigma_x = 45.3$ kPa and $\sigma_y = 93.4$ kPa. The results were expressed in graphic form with the representation of iso-stress lines at the apex of the flap (Fig. 8). The shape of the vertical iso-stress line σ_y for a stress equal to 18.8 kPa (border of the sky-blue surface) was similar to a keyhole, with a major axis perpendicular to the skin margin. This shape was comparable to the necrosis observed in our clinical case.

Discussion

V-Y advancement flap

The V-Y advancement flap was first described by Dieffenbach in 1845. The purpose of this advancement flap is to substitute a rectangular primary defect adjacent to the base of the triangular flap with two parallelograms(secondary defect) next to each side of the flap (Fig. 2). The incision is shaped liked a V and after closure, like a Y.

We have proposed a simple geometrical analysis of the V-Y advancement flap [7]. This geometrical analysis of the V-Y advancement flap involves simple modeling where the skin is treated as rigid tissue without deformation. Although this does not reflect reality, it helps the surgeon to understand the relationship between the size of the defect before and after V-Y flap advancement according to the value of its apex angle. This simple geometrical analysis also shows that the maximum tension is found at the apex of the flap which is consistent with our clinical case.

Finite element analysis of skin

FEA is a powerful computer-based tool widely used by engineers and scientists to understand the mechanics of physical or biological systems such as the skin [8, 9].

FEA seeks to approximate the behavior of an arbitrarily shaped structure under general loading and constraint conditions with an assembly of discrete regions or domains called

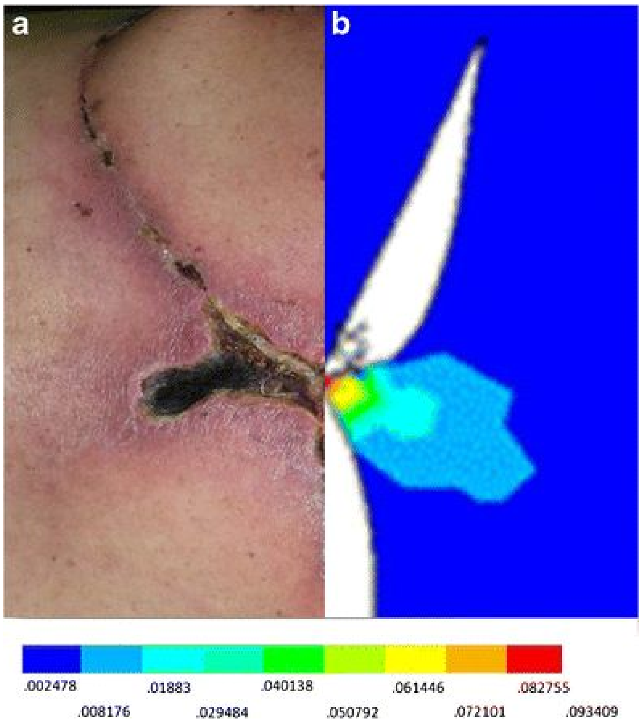

Fig. 8 Comparison between the clinical case and the modeling. a Isostress lines σ_y in kilopascals. b A clinical case of necrosis

elements. These elements have regular geometric shapes with known solutions and are connected at the edges called *nodes*. The behavior of the structure is obtained by analyzing the collective behavior of the elements. Elements are the building blocks of a finite element model and are used to divide a given complex physical domain into simple mathematical representation (simple shapes) with known solutions. One of the benefits of FEA is the integration of the heterogeneity of a domain by allocating a behavior law to each element.

FEA of the skin has many applications such as virtual surgery [10, 11], cutaneous flaps [12, 13], and aging of the skin [14]. It has been used to describe stress fields after simple sutures [15] or after flaps [8].

Two points related to our modeling process should be discussed. First, the mechanical skin properties of the patient with necrosis and the patient used to determine prestress fields were very different. The modeling used data from a 38-year-old woman with excess abdominal skin, while necrosis appeared on the back of an 83-year-old man [16, 17]. Nevertheless, as the aim of the study was to determine the graphic representation of the stress fields when suturing the corner stitch, this is not in itself a problem. It would have been a problem if we had wanted to identify the values of stress responsible for the necrosis. Second, the values of prestress were obtained by inverse method. Values extracted from the literature [16] or experimental methods on the patient such as indentation, suction, torsion tests, wave propagation, and extensometer could also have been used [18]. Nevertheless, the values of prestress calculated in our study were comparable to data in the literature. Although the mechanical behavior law is isotropic, the material response to the moving of the stitch point takes into account the asymmetrical initial prestress ($\sigma_x > \sigma_y$) and then the anisotropic properties of the skin [19, 20].

The particular shape of the necrosis is related to the specific characteristics of the suture at the apex of the V-Y flap. The tension is maximal at this point because the distance to suture is the longest.

Skin tension and necrosis

High closing tensions are an accepted cause of wound slough [1]. The relationship between tension, blood flow, and flap viability is well established [21]. Barnhill et al. [21] demonstrates that tension has significant effects on the superficial dermal microvasculature, resulting in impedance and obliteration of blood flow. An average force of 11.9 N, accompanied by a mean strain of 10.3 %, results in occlusion of all vessels [21].

Two solutions to the problem of closing skin defects under tension are commonly used: undermining [22] and stretching the skin [1]. Undermining has inherent drawbacks because of the damage to the feeding vessels such as skin-edge necrosis and seroma. Undermining leads to decreases in skin blood flow and skin oxygenation [23]. It is necessary to find the right balance between reduced blood flow and decreased tension [24]. Skin stretching reduces wound closing tension. According to Melis et al., the additional advantage of skin stretching over that of undermining alone is clearly shown [2]. Cyclic skin stretching seems even more efficient [25]. In our clinical case, both undermining and excessive tension probably contribute to the necrosis:

- The tension of the suture is maximal at the apex of the V-Y advancement flap.
- In humans, the highest skin stress is found in the back [16].
- Wound edges are undermined to facilitate flap advancement (Fig. 4).

Nevertheless, similarities between the shape of necrosis and the calculated stress field indicate the major role of skin tension.

In order to reduce closing tension in this clinical case, we could have proposed the following:

- A reduction in the value of the angle at the apex of the flap seems to reduce the stress field values. Nevertheless, the longer the flap, the less it is vascularized because the apex has no vascular support (Fig. 4).
- A keystone flap would have been more appropriate because distance to suture around it is smaller and more

homogeneous compared to the advancement of a single V-Y flap. Furthermore, all skin paddles would have been supported by muscles.

Conclusions

In a preceding study, we propose a very simple V-Y flap model with simple mathematical equations. Although only global geometric parameters are considered, this model explains the relationship between the distance to the suture according to the shape of the flap and flap advancement and the specific characteristics of the corner stitch at its apex.

To evaluate stress fields, we developed a mathematical model taking into account hyperelastic properties of the skin to describe stress fields using FEA. The results of the modeling correlate well with the clinical case. Our method is an original approach for describing the particular shape of a necrosis.

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Conflict of interest None

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