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Research Paper

On skin expansion

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ABSTRACT

This article discusses skin expansion without considering cellular growth of the skin. An *in vivo* analysis was carried out that involved expansion at three different sites on one patient, allowing for the observation of the relaxation process. Those measurements were used to characterize the human skin of the thorax during the surgical process of skin expansion. A comparison between the *in vivo* results and the numerical finite elements model of the expansion was used to identify the material elastic parameters of the skin of the thorax of that patient. Delfino's constitutive equation was chosen to model the *in vivo* results. The skin is considered to be an isotropic, homogeneous, hyperelastic, and incompressible membrane. When the skin is extended, such as with expanders, the collagen fibers are also extended and cause stiffening in the skin, which results in increasing resistance to expansion or further stretching. We observed this phenomenon as an increase in the parameters as subsequent expansions continued. The number and shape of the skin expanders used in expansions were also studied, both mathematically and experimentally. The choice of the site where the expansion should be performed is discussed to enlighten problems that can lead to frustrated skin expansions. These results are very encouraging and provide insight into our understanding of the behavior of stretched skin by expansion. To our knowledge, this study has provided results that considerably improve our understanding of the behavior of human skin under expansion.

1. Introduction

The present work intends to describe and raise considerations about the surgical procedure of skin expansion. Skin expansion is a physiological process based on the ability of human skin to increase its superficial area in response to a stress (Van Rappard et al., 1988). The surgical procedure is performed by implanting skin expanders under the subcutaneous tissue. Skin expanders are silicon bags of different shapes and sizes, which are infiltrated with a saline solution. The skin relaxes after a period of time, and if the imposed deformation is maintained, the resulting stress, and consequently the internal pressure, decreases. The physiology of skin expansion considers both the stretching of the skin and the relaxation process used to obtain an extra flap of skin that possesses the required characteristics. For example, skin expansions are used to reconstruct burned areas and breasts after mastectomy as well as to hide scars and defects. Several papers have been published on the behavior of the skin due to expansion. Beauchene et al. (1989) presented an animal experiment performed on 24 animals that expanded the skin of the peritoneal cavity for 32 days. The authors concluded that the skin tension increased dramatically

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at the time of inflation but fell to almost the control values at the end of 32 days and the skin thickness, which initially decreased, returned to normal by the end of the experiment. Silver et al. (2003), in an overview on the mechanobiology underlying skin growth, affirm that the tension in the skin affects the skin biology and is responsible for the growth of the skin because tensile stresses applied to skin appear to stimulate cellular growth. Buganza Tepole et al. (2011) established a new computational model for stretch-induced skin growth during tissue expansion. To model skin growth, the authors adopted the multiplicative decomposition of the deformation gradient into an elastic and a growth portion. The growth was characterized as an irreversible, stretch-driven, transversely isotropic process parameterized in terms of a single scalar-valued growth multiplier, the in-plane area growth. The analysis was performed by numerically simulating the process of gradual tissue expander inflation. In particular, they compared the spatiotemporal evolution of the area growth, elastic strains, and residual stresses for four commonly available tissue expander geometries. Zollner et al. (2012) presented a continuum model for skin growth that summarizes the underlying mechanotransduction pathways collectively in a single phenomenological variable, the strain-driven area growth. To simulate the process of tissue expansion in an anatomically exact geometry, they created a finite element mesh from three-dimensional computer tomography images of a child. They only modeled the tissue expander implicitly by controlling the expander pressure. However, the interplay between the mechanics and the biology during tissue expansion remains unquantified. The authors maintain that, during expansion, the epidermis (0.06 to 1 mm) undergoes significant thickening and the dermis (1 to 4 mm) and subcutaneous tissue becomes significantly thinner. Although there is some tension transfer to the epidermis, the maximum tension occurs in the dermis, which explains why there is a significant thinning of the skin in some models, including Pamplona and Carvalho (2012). The highlighted studies indicate that skin growth and its thickness during the expansion process are controversial issues that require more research to clarify the process. In this research, the measured pressure inside the skin expander dropped dramatically in the first days and even in the first hours of expansion, due to the viscoelastic properties of the skin. This discontinuity in the stresses levels during the studied expansion process is the principal reason for not considering the growth of the skin in this model. We attributed this skin behavior to relaxation due to viscoelastic properties and not due to structural or molecular changes. In real tissue expansion, the external control parameter is the expander volume, not the internal pressure. Some simulations display creep under constant loading, but clinical tissue expansion may display relaxation under constant deformation instead; therefore, these models do not account for the fact that the tensile stress varies due to relaxation. In practice, it can be seen that if an expansion is frustrated in the initial steps, it stops before the expected number of expansions, and after the skin expander is removed, there is no extra flap of skin. The skin returns to its original size. When the skin expansion is completed, at the moment of the surgery, the skin immediately recovers part of the expanded surface area, given that, it is necessary to consider the need of 20–30% of extra tissue due to the dog ear, and mechanical recovery of the skin (Padam, 2009; Bhandari, 2009). It appears that only one to two months after the reconstruction, the skin gains its original thickness. The site of the expansion can be very important for attaining the extra flap of skin (Pamplona and Mota, 2012). The present article suggests the type, number and volume of skin expanders necessary to obtain the extra amount of skin to repair a certain medical problem and also proposes a constitutive equation to describe and predict the behavior of the expanded skin. We also show the importance of the site chosen for the expansion to assure that the whole procedure can be successfully accomplished.

2. Planning the skin expansion

Skin expansions are usually performed near the places where the skin is required to provide skin of the same color, texture, sensibility and structure as the skin to be removed, such as in the cases of scars, burns and so on. The question that is constantly raised during expansion is whether it will create enough skin; in other words, whether the achieved expansion is adequate to resurface the defect (Padam, 2009). These questions can be answered if one knows how much new tissue is required for the reconstruction in a given condition and if this required tissue (surface area) can be calculated in relation to the volume injected under of the expanded tissue. Additionally, the site of expansion can be very important to attain the extra flap of skin (Pamplona and Mota, 2012). Skin expanders are silicone bags of several shapes (circular, square, oval, croissant and rectangular) and internal volumes that are implanted under the subcutaneous tissue in different parts of the body. Through an incision, the surgeon inserts the skin expander and its valve under the skin. After the incision is closed, a saline solution, which should be equivalent to 10% of the nominal volume of the skin expander (Radwanski, 2012), V_n, is injected into the skin expander using a needle in the implanted valve. Some days after the surgery, the process of expansion begins, and in this way the process of cicatrization is guaranteed. During the skin expansion procedure, a certain volume of saline solution is injected into the expander every week. As the solution is injected, the skin expands due to the increase of pressure inside the expander producing stresses in the skin and, consequently pain in the patient. Because of the viscoelastic properties of the skin, the skin relaxes after some time, diminishing the pressure inside the expander and, the pain of the patient. After a week, there is no measurable pressure inside the expander. Fig. 1 shows a complete expansion in the stomach with a croissant skin expander.

Fig. 1 – Expansion in the stomach.

2.1. The methodology to choose the number and sizes of skin expanders

The first step is to measure the amount of superficial area, S_d, of skin required to resurface the defect. To cover the defect surface, it is necessary to obtain 20% to 30% more tissue by expansion due to dog ear and skin retraction that occurs after the removal of the skin expander. The excess tissue also takes care of the retraction of the skin itself. Therefore, the surface area to be obtained by expansion is represented by S_d^*. This superficial area has to be equal or smaller than the size of the flap of skin obtained by expansion using the formulas and tables that are developed in this research. Note that the extra flap of skin, S_f, is the superficial area of the expanded skin minus the base of the expander because this region must be covered again with skin

$$S_f \geq S_d^* = 1.3 \times S_d \tag{1}$$

The superficial area of the extra flap obviously depends on the amount of injected liquid, which has an internal volume of V_i.

A rectangular skin expander is a parallelepiped of base $a \times b$ and height c. The extra flap of skin, S_f, is related to the internal volume, V_i, by the following mathematical formula

$$S_f = \frac{2 \times (a+b)}{a \times b} V_i \tag{2}$$

A round skin expander has a radius a and height h. Unlike the rectangular skin expander, the relationship between S_f and V_i is nonlinear for round expanders because the value of h changes nonlinearly depending on the infiltrated volume. The extra flap of skin, S_f, is related to the internal volume, V_i, by the following formula obtained by Gerolamo Cardomo in his book Ars Magna (1545)

$$S_f = \pi \times a^2 \times \beta^2;$$
$$\beta = \frac{(4 \times C + 4 \times \sqrt{4 + C^2})^{3/2} - 4}{2 \times (4 \times C + 4 \times \sqrt{4 + C^2})^{1/3}}$$
$$C = -\frac{6 \times V_i}{\pi \times a^3} \tag{3}$$

The formulas for the extra flap of skin were obtained mathematically; therefore, it is necessary to verify if the results obtained are compatible with reality. To do so, an experimental apparatus was developed with a rigid acrylic base where two skin expanders were attached. One expander was round (V_n of 200 ml), with radius a=4.8 cm, and height h=4.1 cm, and the other was rectangular (V_n of 240 ml), with base a=9.6 cm, b=5.9 cm, and height c=5.0 cm (see Fig. 2). A latex membrane covered the skin expanders to simulate the skin.

The superficial surface was obtained and measured with a 3D scanner for every 50 ml of injected liquid. Using the software Rhinoceros 4, the internal volume and superficial area were obtained. The scanned surfaces can be seen in Figs. 3 and 4.

Fig. 2 – Experimental apparatus.

2.2. Results for choosing the number and sizes of the skin expanders

The experimentally obtained extra flap of skin, S_f^*, is the measured surface minus the area of the basis of the skin expander because this surface has to be recovered with skin. The following results enable us to realize the differences between the results obtained by a mathematical formula and those obtained in a more realistic way with a 3D scanner. Tables 1 and 2 show the comparison between the extra flap measured with the scanner (S_f^*) and the extra flap calculated from the formula (S_f) for each injected volume (V_i). The value measured by the scanner when there is no liquid inside the expander is due to the existing wrinkles on the flat membrane, as seen on the left in Figs. 3 and 4 (for V_i of 0 ml). In reality, the extra flap that can be used for the reconstruction is only 2/3 of the obtained area because, as mentioned above, the skin retracts after the removal of the skin expander and flap itself also retracts.

It can be seen that the behavior of the expander when filled freely is different from when it is confined under the membrane or skin and over a rigid base. For the round expander, the difference in size between the measured and the calculated extra flap is approximately 10%, where the calculated value is larger. The difference in the results can be more clearly observed for the rectangular expander because the corners of its shape when confined becomes rounded and not sharp as in a parallelepiped, resulting in a smaller superficial area.

3. The skin behavior and parameters

Skin expansion is usually performed near the site to be reconstructed and sometimes over fatty tissue. During a number of weeks, the surgeon injects a certain volume of saline solution, V_i, into the skin expander, creating an internal pressure. After a week, the internal pressure is reduced to zero and a new injection is possible. When monitoring the internal pressure and the injected volume during several skin expansions, we observed discrepancies depending on the site of the expansion (Pamplona and Mota, 2012), which is the focus of this portion of the present work.

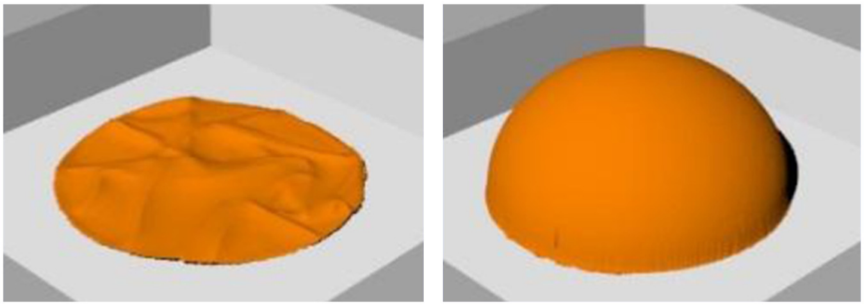

Fig. 3 – Scanned surface of the circular expander for the internal volumes of 0 ml (left) and 200 ml (right).

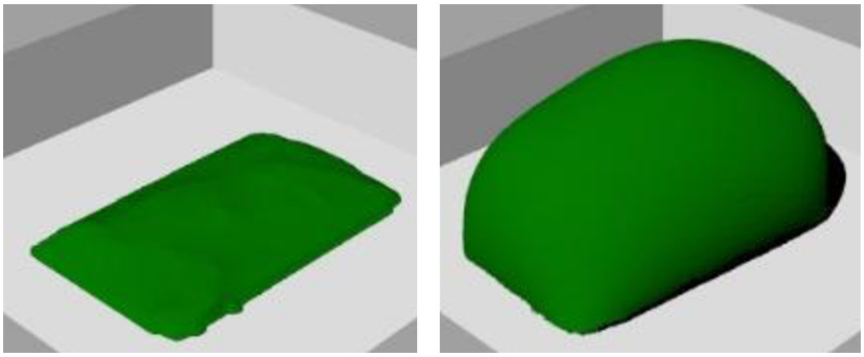

Fig. 4 – Scanned surface of the rectangular expander for the internal volumes of 0 ml (left) and 240 ml (right).

Table 1 – Results for the circular skin expander, relating the injected volume (V_i) to the measured extra flap (S_f^*) and the calculated extra flap (S_f).

V_i	S_f (cm^2)	S_f^* (cm^2)	$2/3S_f^*$ (cm^2)
0	0.00	0.00	0.00
50	8.44	5.69	5.63
100	18.76	20.09	12.51
150	44.20	38.83	29.47
200	67.07	59.23	44.71

Table 2 – Results for the rectangular skin expander, relating the injected volume (V_i) to the measured extra flap (S_f^*) and the calculated extra flap (S_f).

V_i	S_f^* (cm^2)	S_f (cm^2)	$2/3S_f^*$ (cm^2)
0	0.00	0.00	0.00
50	22.26	27.36	14.84
100	41.47	54.73	27.48
150	71.21	82.10	47.48
200	94.52	109.46	63.01
240	105.09	131.35	70.06

3.1. *Experimental methodology to measure the skin behavior*

To monitor the skin expansion and check and identify the behavior of the skin from successive skin expansions, it was necessary to measure the pressure inside the skin expander before, during, and after the injection of saline solution for each expansion. For this purpose, an apparatus with a pressure sensor coupled to the syringe used to perform the injection of the liquid was developed, as seen in Fig. 5.

The results that follow are for three expansions in the same patient, a female 20 years of age. One expansion was in the upper part of the thorax (V_n of 200 ml), and the other two were over the rib cage (V_n of 400 ml). The volume related in the results is V^* because the nominal volumes of the skin expanders were different, although all three expanders were rectangular

$$V^* = \frac{V_i}{V_n}. \tag{4}$$

3.2. *In vivo results*

Fig. 6 shows that the skin expansion behaved very similarly in the three sites. However, during the fourth expansion, seen in Fig. 7, the behavior of the first rib cage expander began to diverge from the other two. It is noted that the patient felt uncomfortable after this point, and due to the pain, this expansion did not succeed. The curves in both figures were obtained through polynomial fitting.

Fig. 7 shows the differences in the behavior of the procedure depending on the implantation site for the skin expander. This result was expected, and the expansion over an elastic foundation is discussed in our previous article (Pamplona and Mota, 2012).

Fig. 5 – Apparatus developed to measure the pressure inside the skin expander.

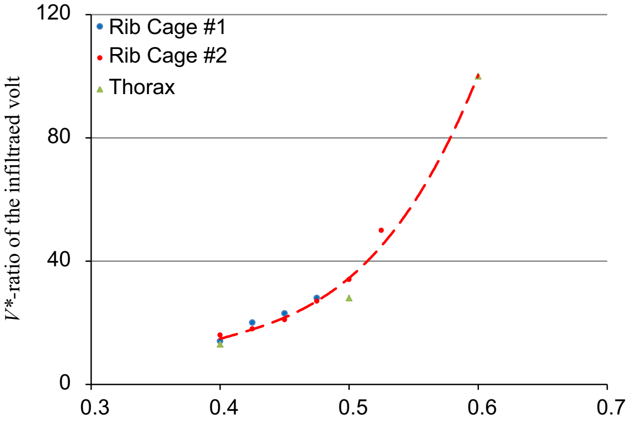

Fig. 6 – Results from the third skin expansion for all three expanders, the line is a polynomial fitting for the three expansions.

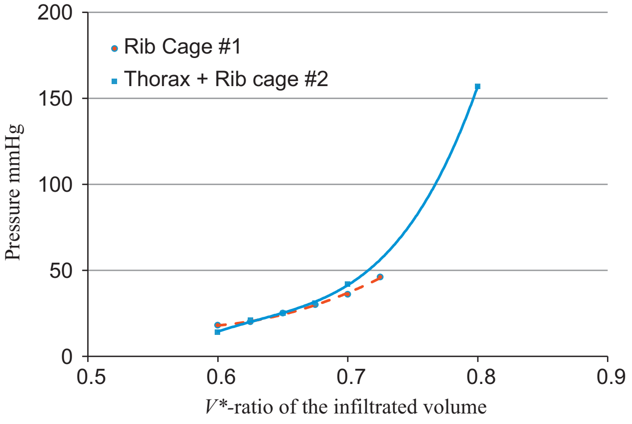

Fig. 7 – Results from the fourth skin expansion for the three expanders with polynomial fitting.

3.3. *Numerical methodology to characterize the skin behavior parameters*

To characterize the skin during expansion, it is necessary to model the procedure numerically, which can be accomplished using the commercial finite elements software program ABAQUS v 6.11. The goal was to identify the parameters for Delfino's elastic constitutive equation and characterize the skin of the thorax for this patient. The parameters of the constitutive equation for each expansion are not the same because the collagen fibers of the stretched skin offer more resistance to expansion over the course of the expansion, as observed by Lim et al. (2008).

To perform the numerical analysis, the finite element mesh used was the linear hybrid membrane quadrilateral (M3D4). The control of the volume injected into the skin expander was essential for modeling this medical procedure, which could only be performed in ABAQUS by using fluid finite elements (F3D4). In the fluid elements, the pressure was applied to one unique node, which is called the reference of cavity node. This pressure simulated the injection of the fluid into the skin expander. The middle surface was the reference point for both the membrane and the fluid elements. In the numerical analysis, the final geometry of one expansion was used as the initial geometry for the next expansion, where the stress and pressure were equal to zero because the internal pressure dropped to zero within a week due to the relaxation of the skin. Because the expansions were successive, the thickness of the modeled skin changed at the end of each expansion, but not uniformly, and those values and the geometry were exported for the new expansion. The results are presented in the following figures and tables. The boundary was considered to be simply connected and free to rotate. This boundary condition was chosen after the careful observation of the expanded skin to ensure that the skin at the boundary did not exhibit peeling. The contact between the skin and the expander was not considered in the numerical model. Skin is considered to be homogenous and hyperelastic, although it possesses properties that are much more complex. This type of material is characterized through the Strain Energy Density, W, which is a function of the strain invariants I_1, I_2, and I_3. Delfino's exponential function was chosen because it provided the best fit for these type of data (Pamplona and Carvalho, 2012). This equation was initially proposed to describe a human artery under several loads and is represented by the expression in

$$W = \frac{c}{d}\left\{e^{[(d(I_1-3)/2)-1]}\right\} \tag{5}$$

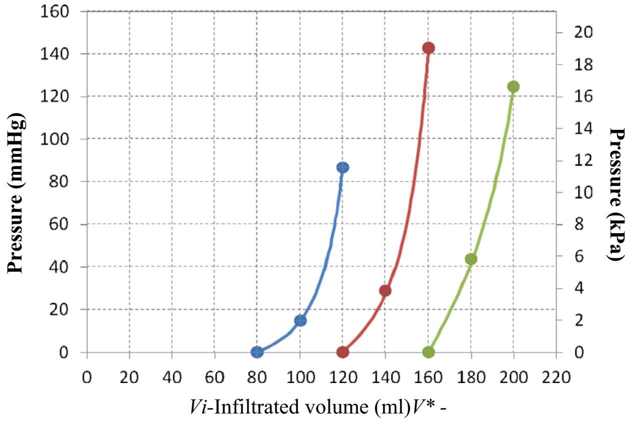

Fig. 8 – Results for the best fit from the fourth to sixth skin expansions, the dots are the measured pressures.

here, c and d are the parameters of the material and I_1 is the first strain invariant. Although Delfino's material model do not consider nonlinear stiffening originating from fiber undulation, as the model proposed by Gasser et al. (2006), it was chosen for its simplicity of implementation in ABAQUS. To take the stiffing into account varying material parameters upon expansion were considered. The initial thickness of the skin, $H=8$ mm, was determined by the surgeon performing the surgery. For incompressible materials, such as biological tissues, $I_3=1$ is used for the third invariant, providing the ratio between the initial thickness, H, and the final thickness, t.

3.4. *The numerical results to characterize the skin behavior parameters*

To numerically model the expansions over the thorax, parameters c and d for Delfino's constitutive equation, seen

Table 3 – Parameters for characterizing the skin of the thorax, obtained by Fig. 8.

Expansion	Initial volume (ml)	Final volume (ml)	Final measured pressure (mmHg)	Final thickness (mm)	c (MPa)	d
4	80	120	90	3.96	0.0125	19.75
5	120	160	147	3.24	0.0380	27.00
6	160	200	154	2.76	0.1100	20.00

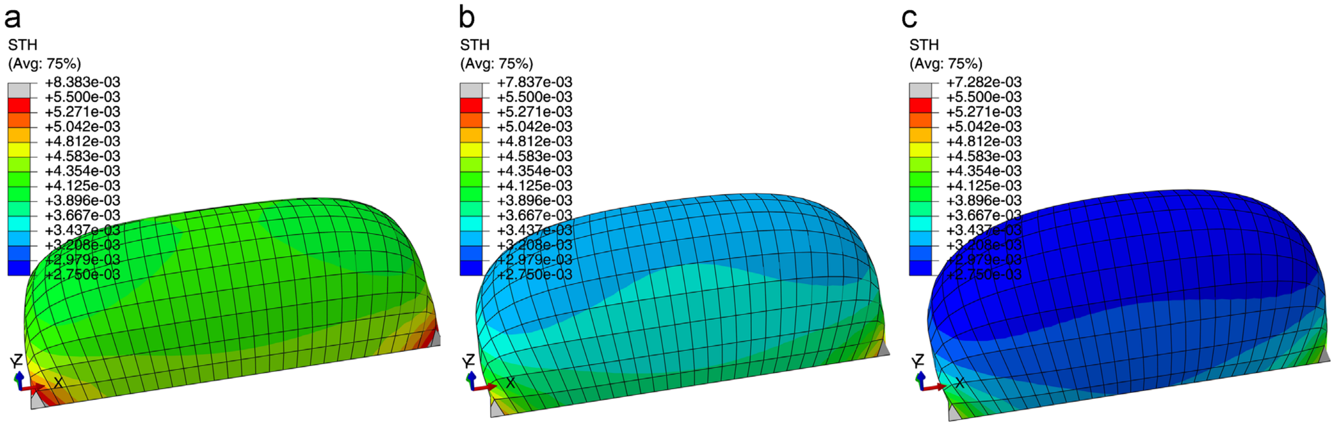

Fig. 9 – Finite elements results for the thicknesses (a) 80–120 ml, (b) 120–160 ml, and (c) 160–200 ml.

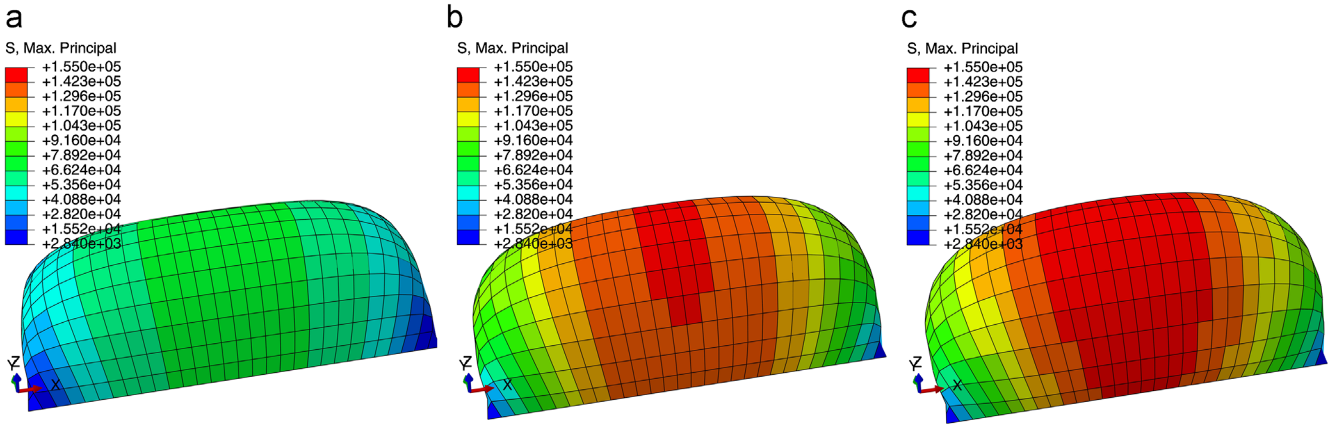

Fig. 10 – Finite elements results for the principal stresses (a) 80–120 ml, (b) 120–160 ml, and (c) 160–200 ml.

in Eq. (5), of the thorax were obtained and are shown in Table 3.

Fig. 8 shows the numerically generated curves from the best-fit parameters *c* and *d* for each expansion (shown in Table 3) and the *in vivo* measured points for the three expansions. The fitting was performed minimizing, using the least square method, the differences between the results *in vivo* and the ones obtained by the finite elements simulation.

Fig. 9 shows the thinning of this skin as the expansions proceeded and Fig. 10 shows the stresses that the skin underwent at the end of each expansion in the thorax.

4. Discussion and conclusions

This work shows that the behavior of the expander when filled freely is different from when it is confined under a membrane or the skin. For the round expander, the calculated value of the extra flap was approximately 10% greater than the measured value. The difference was more clearly observed in the rectangular expander because the corners of its shape became rounded when confined and were not as sharp as in a parallelepiped, resulting in a different superficial area. The difference for this case was approximately 30%. The differences for small amounts of injected liquid were not considered because there were wrinkles and an uneven deformation. It is very important to note that for the same volume inserted, for example, 200 ml, the usable extra flap of skin obtained with the rectangular skin expander (63.01 cm^2) is one-third greater than that obtained with the round skin expander (44.71 cm^2), suggesting that the use of the rectangular expander is recommended. To obtain the same amount of extra flap with the round skin expander, it would be necessary to inject more liquid and increase the number times for the patient to be subjected to the procedure, increasing the patient's discomfort and pain.

This research indicated that the site chosen for the skin expansion is of great importance. An expansion performed over an elastic foundation can be frustrated because the liquid will not expand the skin as expected but will rather compress the elastic foundation. When this occurs, the measured pressure inside the skin expander can be small although there is a considerable amount of liquid being injected. The finite element portion of this research modeled the skin expansion of the thorax and characterized the skin with the parameters of Delfino's constitutive equation, using the same methodology of our previous article (Pamplona and Carvalho, 2012). The *in vivo* measurements showed that the skin relaxed after each expansion because all of the pressure measurements inside the expanders were reduced within one week after the procedure. Although there are recent proposals supporting that tensile stress or the control of the expander's internal pressure stimulates cellular growth, in reality, the external control parameter is the injected volume. As a result of the viscoelastic property of the skin, the pressure inside the expander drops dramatically in the first days and even in the first hours after expansion due to relaxation. This is the principal reason why skin growth was not considered here, and why relaxation due to viscoelastic properties and not due to structural or molecular changes was used to model the change in the geometry of the skin. It is important to note that as the skin is extended, such as with expanders or in other procedures that thin the skin, the collagen fibers are also extended and cause stiffening in the skin, which results in it being more and more resistant to expansion or further stretching. We observed this phenomenon as an increase in parameter *c* of Delfino's constitutive equation with subsequent expansions. The results presented in this study are very promising in this field and extend our understanding of the expansion of skin and other biological tissues. Additional research will provide the optimal type, number, and volume of skin expanders for the several shapes of skin expanders, as well as the frequency of expansions on several anatomic sites, which are factors necessary to obtain a specified amount of skin for the repair of particular medical problems. The thickness of the skin can be measured using ultrasound techniques at the beginning and end of each expansion, giving promising clues to understand the process.

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