Changes in the characterization of the human scalp due to the process of successive skin expansion

Djenane Cordeiro Pamplona, Claudio R. Carvalho
Civil Engineering Department, Catholic University, PUC-Rio, Rio de Janeiro – Brazil
Henrique Radwasnki, Ivo Pitanguy
38th Enfermaria da Santa Casa da Misericórdia, Rio de Janeiro – Brazil

Abstract

This research investigates the large deformations of the extended human skin of the scalp due to the surgical process of skin expansion. A detailed in vivo analysis is carried out involving two different patients. For each patient the data of at least four expansions were monitored obtaining no less than five measurements relating the volume inserted and pressure inside the skin expander for each expansion. To obtain a constitutive equation that could describe the human scalp, several well known constitutive relations were analyzed and Delfino's constitutive equation was selected. To obtain the parameters for the several steps of the expansion a numerical procedure was carried out. The skin of the scalp was considered for numerical purpose as a isotropic, homogeneous, incompressible and hiperelastic membrane. The comparison between the in vivo and numerical results for the membrane under expansion is used to identify the material elastic parameters of the model. The numerical analysis of the membrane was done using finite element by the software ABAQUS and the Newton Raphson Method by means of MATLAB. To our knowledge this is a pioneer work in this field and the results obtained in this research we can improve considerably the understanding of the human skin and the skin under successive expansions.

Keywords: human skin, skin expanders, finite elements.

1 Introduction

Skin expansion is a physiological process, defined as the ability of human skin to increase its superficial area responding to stress or a given deformation. Since the skin presents creep or relaxation, after a certain time of the imposed deformation the resulting stress decreases. The physiology of the skin expansion is not stretching the skin only, but using the relaxation process, to obtain an extra flap of the skin with the characteristics needed. Skin expansions are used to reconstruct burned areas, hiding scars, breasts after mastectomy, among many others. Skin expansion done near the places were

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the skin is needed provides skin of the same color, texture, sensibility and structure of the one to be removed, in cases of scars, burns and etc.

To model numerically reconstructive plastic surgeries and achieve a better understanding of them, it is crucial to determine the mechanical properties of the skin in vivo. Lately, several studies have been performed with this goal. Overviews were given by Piërard and co-workers and Rodrigues. The most frequently used techniques are tensile, indentation, torsion and suction experiments on the skin. Diridollou already mentioned that the data obtained is mainly descriptive. Occasionally, a model exhibiting (linear) Hookean material behavior is applied to obtain a Young's modulus. However, the value of the Young's modulus obtained is affected by various factors such as the amount of deformation (due to the non-linear stress-strain behavior), hydration, and length scale of the experiment (for example, indenter diameter or aperture size). It also varies considerably for different experimental techniques. Bader and Bowker, obtained for the Young's Modulus, E = 1.1-2.0 kPa measuring indentation using a 20 mm indenter. Agache obtained E = 0.42-0.85 MPa from torsion experiments using a disc of 25 mm diameter and guard ring of 35 mm diameter. Manschot in his work obtained E = 4.6-20 MPa for tensile tests using load pads of 10 $\times$ 10mm. Suction tests performed by Barel resulted in E = 0.13-0.26 MPa. Suction experiments performed by Diridollou using 100 mbar suction and an aperture size of 6 mm resulted in E = 153 kPa. In the above mentioned papers different techniques and models were used. What all these papers have in common is the use of simplified geometric models and boundary conditions, because all authors wanted to use closed form solutions for the numerical analysis. This might explain the different outcome of different types of experiments. In fact this means that the models only describe successfully the mechanical behavior of the skin for the particular loading case used in that experiment. In the literature, only few studies investigated the biomechanics of the tissue expansion. Socci L. and co-workers [1], studied the stresses and strains of the skin due to the inflation of an expander, only considering an axially-symmetric configuration, in which a flat circular flap of a thin membrane (i.e. the skin) is expanded by a spherical balloon. A phenomenological approach was adopted for the modeling of the growth after expander implantation. The following tasks were carried out developing a finite element model able to simulate the skin expansion procedure and validate this model using an experimental setup. It was implement an analytical growth law and a time-stepping algorithm in order to determine the skin growth within a discrete framework simulating a clinical skin expansion.

Our aim, in the present research is to develop a method to characterize the non-linear mechanical skin behavior for the skin under expansion using a numerical-*in vivo* technique. A consistent constitutive equation for the skin will allow the understanding of the skin under expansion permitting a better plan of the surgery, number and size of expanders, as well as in the numerical analysis of sutures, scars and a wide range of surgeries.

The present study is pioneer in its goal to model the human skin in successive skin expansions, obtaining different parameters to characterize the skin as the expansions go on. A detailed *in vivo* analysis is carried out. For each patient the data of at least four expansions were monitored obtaining at least five measurements relating the volume inserted and pressure inside the skin expander for each expansion. To obtain a constitutive equation that could describe the human skin, several well known constitutive relations were analyzed and Delfino's constitutive equation was chosen.

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Skin expanders are silicone bags with several shapes and volumes. The first step to expand the skin is the surgery to implant the skin expander under the skin. The surgeon draws on the skin, with ink, the shape and size of the skin expander. The choice for expanders is the biggest for that region and also it has to be big enough to provide pressures that can make the skin expand. Through an incision done on one side of the drawing, the surgeon separates the skin of the muscles, obeying the drawing, and in this way it is delimited the flap of skin to be expanded. Also through this incision the surgeon inserts the skin expander under the skin. The valve that is connected to the expander is also implanted under the skin. After the incision closed a saline solution, that should be equivalent to 10% of the nominal volume of the skin expander, is inserted inside the skin expander using a needle in the implanted valve. Only 15 days after the surgery, the process of expansion begins, in this way the process of cicatrisation is guaranteed. During the skin expansion procedure, weekly a certain volume of saline solution is inserted inside the expander. The volume depends on the size of the expander and mostly on the discomfort of the patient. As the solution is inserted the skin expands due to the increase of pressure inside of the expander producing pain in the patient. Due to the visco-elastic properties of the skin, after some time the skin relaxes diminishing the pressure inside the expander. After a week there is no measurable pressure inside the expander. The major disadvantage of the process is the need of two surgeries, one to implant the expander, the other to remove the expander and repair the problem.

2 *In vivo* analisys

To identify the behavior of the scalp due to successive skin expansions it is necessary to measure the pressure inside the skin expander previously, during and after the infiltration of the saline solution inside the expander. For this purpose an apparatus was developed, providing a pressure sensor coupled to a needle, Fig. 1.

2.1 Results

Two patients were analyzed, patient 1: with light dark skin; female, 33 years old, brunette, weighing 530 N and 1.60 m height, with a rectangular expander (400 ml) and patient 2: with white skin, female, 12 years old, weighing 350 N and 1.50 m height, with a semi-lunar croissant expander (300 ml). To measure the pressure inside the expander in each step, figure 2, the apparatus described in Figure 1 was coupled to a plastic Y tube. One upper side of the Y tube was attached to the syringe with the saline solution to be inserted, the other upper side of the tube was coupled to the apparatus developed to measure the pressure, and on the lower side of the Y tube was attached the needle used to insert the saline solution in the expander's valve. At each 5 or 10 ml of liquid inserted, after a small interval, the pressure inside of the expander was measured, providing a curve relating the volume inserted and the pressure measured at this volume, as seen in each curve. Figure 3 shows the results of the six weekly successive expansions done in patient 1. Six days after each expansion, due to the visco-elastic properties of the skin, the pressure inside of the expander reaches zero, Fig. 4.

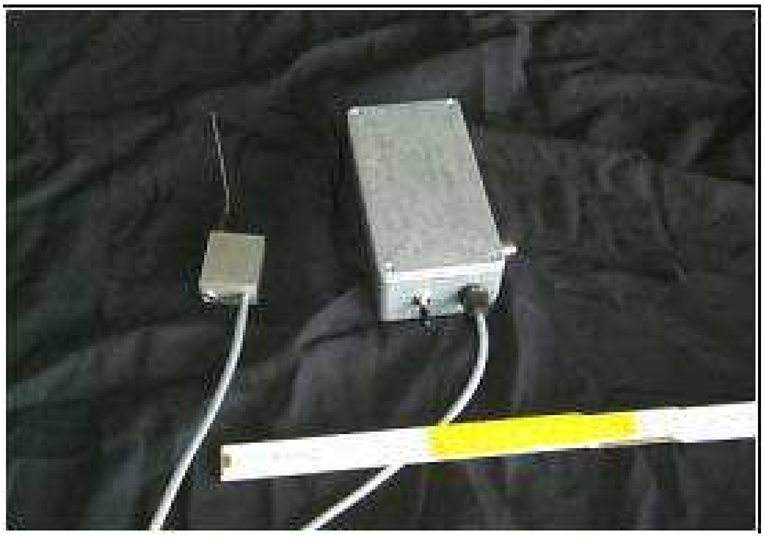

Figure 1: Apparatus to measure the pressure inside the skin expander.

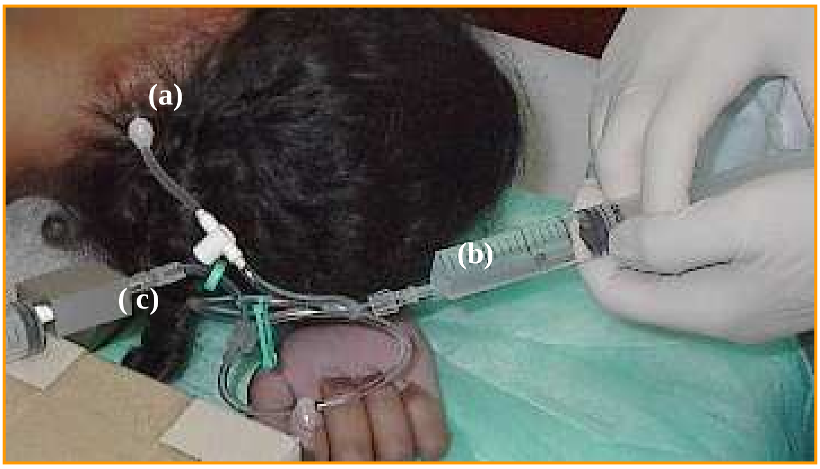

Figure 2: Measuring the skin expansion in patient 1, (a) needle, (b) syringe, (c) apparatus.

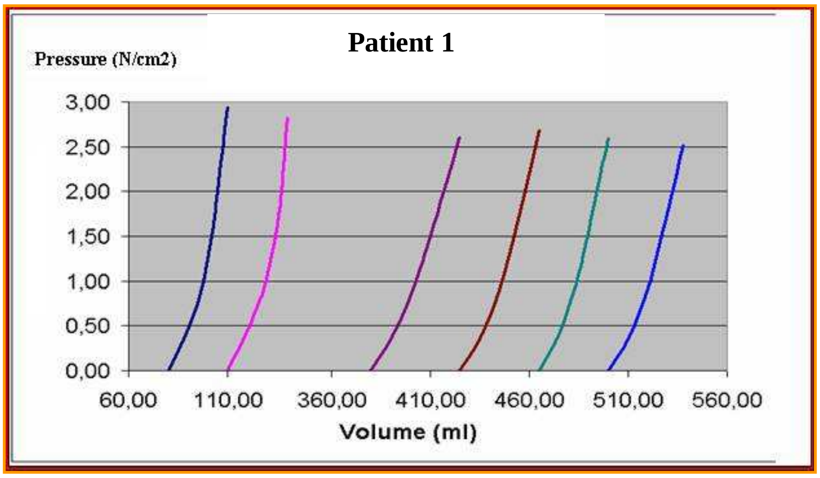

Figure 3: Measured pressures in six weekly successive expansions done in patient 1.

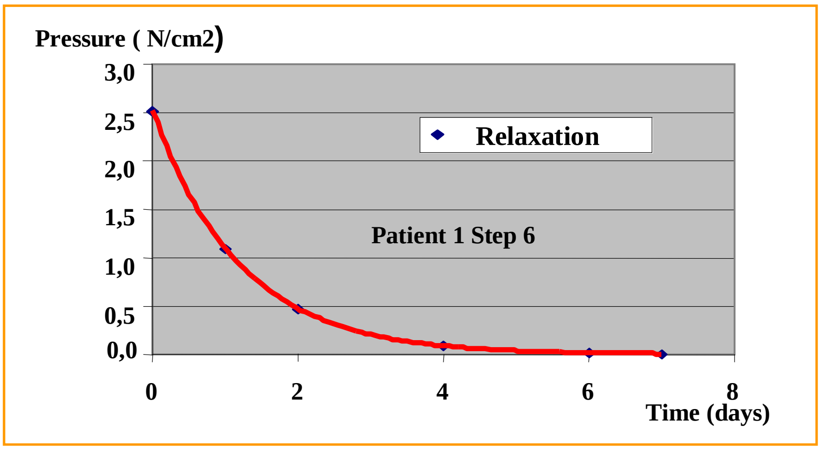

Figure 4: Relaxation of the skin measured in days after the sixth expansion of patient 1.

Tables 1 and 2 contain the results of maximum pressure reached in each weekly expansion, some expansions could not be measured for different reasons and they are pointed in the tables with empty rows. The letter A means the insertion of fluid done during the surgery.

Table 1: Patient 1 rectangular expander (Vexp=400ml), scalp; initial thickness 0.5 mm.

Step (i)	Initial Volume (V_{i-1} – ml)	Final Volume (V_{i-}- ml)	V_i-V_{i-1}(ml)	V*=V_i/Vexp	V**=$\frac{V_i-V_{i-1}}{V_{i-1}}$	Pressure (kPa)
A	00	80	80	x	x	x
1	80	110	30	0.28	0.38	29.50
2	110	140	30	0.35	0.27	28.20
3	140	380	240			
4	380	425	45	1.06	0.12	26.10
5	425	465	40	1.16	0.09	26.80
6	465	500	35	1.25	0.08	26.00
7	500	538	38	1.35	0.08	25.20

Table 2: Patient 2 croissant expander (Vexp=300ml), scalp; initial thickness 0.5 mm.

Step (i)	Initial Volume (V_{i-1} - ml)	Final Volume (V_{i-}- ml)	V_i-V_{i-1}(ml)	V*=V_i/Vexp	V**=$\frac{V_i-V_{i-1}}{V_{i-1}}$	Pressure (kPa)
A	00	214	214	x	x	xx
1	214	254	40	0.85	0.19	26.00
2	254	298	44	0.99	0.17	25.10
3	298	338	40	1.13	0.13	23.90
4	338	376	38	1.25	0.11	21.90

3 Numerical analisys

Although the number of patients studied is small, this works obtains one elastic constitutive equation that can characterize the skin of the scalp. To characterize the skin during expansion was necessary to model numerically the procedure and this was done using the finite elements method with the commercial program ABAQUS, coupled with the Newton Raphson method using the commercial program MATLAB.

3.1 Finite element formulation

Membrane structures are load adaptive, as they change their geometry to accommodate external loads with the minimum variation in stress levels. To do the numerical finite element analysis a mesh of linear hybrid membrane elements, (M3D4 e M3D3) was used, the thickness was provided by the surgeon. The choice for membrane elements was made after trying several type of elements even shell elements, since the deformation is very large, some elements could not be used. Given that the control of the volume inserted inside the skin expander was essential to model the medical procedure, it was made necessary to use fluid finite elements under the membrane. In those elements the pressure is applied on one unique node, called reference of cavity node; this pressure simulates the filling of the skin expander done with fluid. For both membrane and fluid elements the middle surface is the reference, the nodes in the boundary were considered simply supported, free to rotate. This boundary condition was chosen after criterions observation of the expanded skin, being sure that the skin in the boundaries to not presented peeling.

The skin was considered homogenous, hiperelastic, presenting visco-elastic behavior. The elastic behavior of this material is characterized through the Strain Energy Density, W, written as function of the strain invariants I_1, I_2 and I_3, For incompressible materials, as biological tissues, and consequently the skin, the third invariant $I_3=1$. There are several strain energies densities with those characteristics, and they are used to describe each material, the most known are Mooney-Rivlin, Neo-Hookean, Ogden, Polynomial, Fung's and Delfino's Exponential functions. After trying those equations to describe numerically the results of the performed expansions done in patients, Delfino's Exponential function was selected. Delfino [2] proposed it to describe the human artery under several loads; this function is represented by the following expression:

$$W = \frac{a}{b}\{\exp[\frac{b}{2}(I_1 - 3)] - 1\} \tag{1}$$

where W is the strain energy density; a e b are parameters of the material and I_1 is the first strain invariant defined by the principal stretches, λ_i .

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2. \tag{2}$$

The numerical model was done based on the *in vivo*, successive expansions, the final geometry of one expansion, is used as the initial geometry for the next expansion, with zero stress, since the pressure inside goes to zero in a week. Because the expansions are successive, at the end of every expansion done numerically the thickness of the modeled skin changes, but not uniformly. Since the final geometry of the previous expansion is used to begin the next expansion, to model different thickness for every membrane element was made impossible; thus the mean thickness of all elements obtained in the previous expansion was used in the successive one along with the previous geometry.

The ABAQUS code has a command to obtain the thickness of each finite element after deformed, in the end of each expansion. To identify the parameters that best describe the skin in each patient, as said before, the skin expansion in each step was modeled creating a inserted volume x pressure reached for each step of the successive expansions. To fit the numerical curve to the curves obtained during the expansions performed on the patients, and in this way finding the parameters for the skin in that specific expansion, the Newton Raphson method was used. To choose iteratively the parameter that would present smaller difference between the results obtained during the expansion *in vivo* and numerically, the Finite Element code was used with the MATLAB code.

3.2 Results

To obtain the elastic parameters of Delfino's constitutive equation for the scalp the following procedure was pursued. Since the skin expanders for the two patients had different total volumes, given by the factory, and shapes, the ratio, V*, between the total volume inside of the expander at the end of each expansion and the nominal volume of the expander given by the factory, is used as the variable to be related with the final pressure.

3.2.1 Patient 1

The dimensions of the rectangular skin expander of this patient are 13,6cm x 5,5cm x 5,6cm, and a mesh of 126 quadrilateral finite elements was used. Table 3 shows the results, for all the steps of this patient. For each expansion parameters a and b for Delfinos's function were obtained, showing that as the skin expands the parameters change. Parameter a changes from 0.213 MPa to 1.787 MPa, and parameter b changes from 31.5 to 120.5. The initial thickness of 0.5cm reaches a final thickness of 0.13cm, and as we said before, this value should be even smaller because we used the mean value for the thickness as the expansions went on. The maximum stretch, $\lambda\, max$, achieved is 3.65 and the maximum stress 67.96 N/cm^2. With the maximum stretch of the skin it is possible to know the amount of skin provided by the skin expansion. The maximum stress reached in each expansion is an important data, since this is what measures the discomfort or pain of the patient during the expansion.

3.2.2 Patient 2

The dimensions of the rectangular skin expander of this patient are 10.1cm x 5.6cm x 5.8cm, and a mesh of 161 triangular finite elements was used. Table 4 shows the results, for all the steps of this patient. For each expansion parameters a and b for Delfinos's function were obtained, showing that as the skin expands the parameters change. Parameter a changes from 0.636 MPa to 1.500 MPa, and parameter b changes from 42.65 to 65.6. The initial thickness of 0.5cm reaches a final thickness of 0.07cm, and as we said before, this value should be even smaller because we used the mean value for the thickness as the expansions went on. The maximum stretch, $\lambda\, max$, achieved is 4.72 and the maximum stress 106.1 N/cm^2. With the maximum stretch of the skin it is possible to know the amount of skin provided by the skin expansion. The maximum stress reached in each expansion is an important data, since this is what measures the discomfort or pain of the patient during the expansion.

Table 3: Results for Patient 1.

Step (i)	Initial Volume (V_i) ml	Final Volume V_f (ml)	$V_f - V_i$ (ml)	V_f/V_{mx} V *	Pressure (KPa)	λmáx (step)	λmáx (added)	σ máx(t) (N/cm^2)	Parameters	
									a (Mpa)	b
A	0	80	80	x	x	1,35	1,35	x	x	x
1	80	110	30	0,28	29,50	1,11	1,50	7,97	0,213	31,5
2	110	140	30	0,35	28,20	1,11	1,66	7,48	0,222	33,4
B	140	380	x	x	x	1,77	2,94	x	x	x
3	380	425	45	1,06	26,10	1,07	3,15	8,03	0,986	51,3
4	425	465	40	1,16	26,80	1,06	3,34	9,07	1,298	75,2
5	465	500	35	1,25	26,00	1,05	3,51	8,99	1,463	134,5
6	500	538	38	1,35	25,20	1,04	3,65	8,83	1,787	120,5

Table 4: Results for Patient 2.

Step (i)	Initial Volume (V_i) ml	Final Volume V_f (ml)	$V_f - V_i$ (ml)	V_f/V_{mx} V *	Pressure (KPa)	λmáx (step)	λmáx (added)	σ máx(t) (N/cm^2)	Parameters	
									a (Mpa)	b
A	0	214	x	x	x	3,60	3,60	x	x	x
1	214	254	40	x	26,00	1,09	3,92	11,65	0,636	42,6
2	254	298	44	0,85	25,10	1,08	4,24	11,22	0,491	48,2
3	298	338	40	0,99	23,90	1,06	4,49	8,60	1,007	49,8
4	338	376	38	1,13	21,90	1,05	4,72	7,43	1,500	65,6

3.2.3 Analysis of the results for the scalp

The goal is to obtain a curve that shows the change of the parameters as the skin is expanded. To obtain this change of the elastic parameters, a and b of Delfino's constitutive equation for the scalp the following procedure was pursued. The results obtained for the relation V* and the parameter a, from table 3 and 4, for each skin expansion were put together in Figure 5, permitting to obtain a mean curve to describe the behavior of the parameter a. Table 5 shows the variance and standard deviation representing the mean value and the obtained fitted values for parameters a.

The same practice was done for parameter b in Figure 6. Table 6 shows the variance and standard deviation representing the mean value and the obtained fitted values for parameters b.

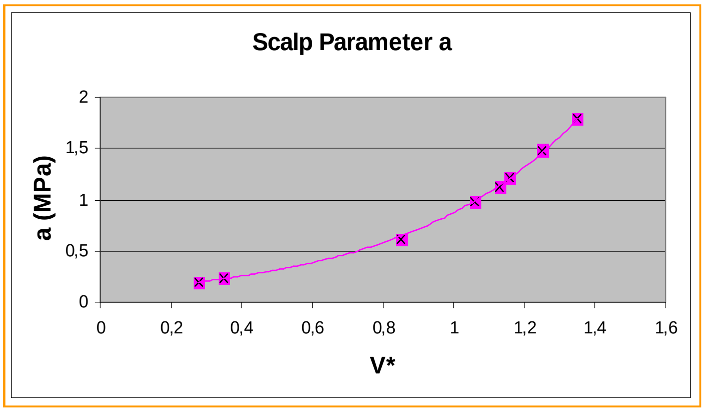

Figure 5: Curve describing the change in parameter a with the variable V^*.

Table 5: Results for the variance and standard deviation of the mean value and the obtained value for parameter a, the grey cells are the results of patient 2.

a MPa (ABAQUS)	V*	a MPa (curve)	Differences	Variance	Standard deviation
0,213	0,28	0,199	-0,0140	0,00005	0,010
0,222	0,35	0,241	0,0190	0,00009	0,013
0,636	0,85	0,616	-0,0200	0,00010	0,014
0,986	1,06	0,976	-0,0100	0,00002	0,007
1,007	1,13	1,123	0,1160	0,00338	0,082
1,298	1,16	1,215	-0,0830	0,00174	0,059
1,463	1,25	1,486	0,0230	0,00001	0,003
1,500	1,25	1,478	-0,0220	0,00012	0,015
1,787	1,35	1,796	0,0090	0,00002	0,006

The same practice was done for parameter b in Figure 6. Tables 5 and 6 shows the variance and standard deviation representing the mean value and the obtained fitted values for parameters a and b respectively.

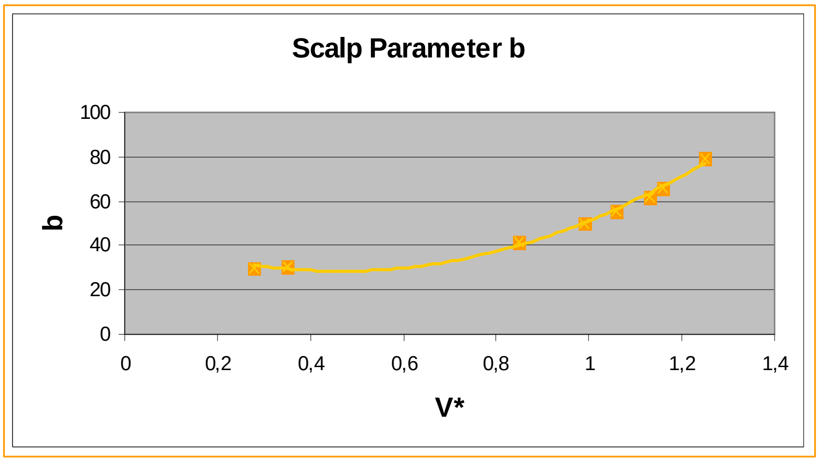

Figure 6: Curve describing the change in parameter b and the variable V^*.

Table 6: Results for the variance and standard deviation of the mean value and the obtained value for parameter b, the dashed cells are the results of patient 2.

b (ABAQUS)	V*	b (curve)	Differences	Variance	Standard deviation
31,5	0,28	30,09	-1,41	0,50	1,00
33,4	0,35	30,68	-2,72	1,84	1,92
42,6	0,85	41,72	-0,88	0,20	0,63
48,2	0,99	49,84	1,64	0,67	1,16
51,3	1,06	55,62	4,32	4,66	3,05
49,8	1,13	61,99	12,19	37,16	8,62
75,2	1,16	66,17	-9,03	20,39	6,39
65,6	1,25	79,20	13,60	46,23	9,62

4 Conclusions

The maximum difference between the curve obtained numerically using the fitted parameter a and b and the curve obtained *in vivo*, is of 1%, which is very encouraging. The pressures measured *in vivo* in the beginning of each expansion were very small and it was difficult and almost impossible to measure. We consider the results obtained for the parameters a and b quite reliable, taking in account the differences between the patients, age and race, although it is advisable to have more patients to obtain a more confinable result for the parameters to describe the scalp under expansion. The following is the curve that describes the behavior of constant a during expansion.

$$a = 1.187V^{*3} - 1.395V^{*2} + 1.075V^{*} - 0,015. \tag{3}$$

For parameter b the curve is in Equation 4,

$$b = 27.9 + 0.9e^{(V^{*}/0.31)}. \tag{4}$$

With the results obtained here we can have a better knowledge of the human skin under expansion. It is reasonable to understand that as the skin is extended, process done by the use of expanders, the collagen fibers are extended and in this way the resistance to expansion will increase, this can be seen by the increase of parameters a and b, of Delfinos's constitutive equation, as the expansion goes on. The present study is pioneer in its goal to model the human skin under successive expansions, obtaining different parameters to characterize the skin as the expansions go on.

The results, although the number of patients analyzed were small, only two, were quite encouraging, and we believe they can be used as an initial guess for the problem. Each patient had, between four and six expansion measured, obtaining at least five measurement for each expansion. The total data for this research contained more then 60 volumexpressure items. A further research can provide the type, number and volume of skin expanders necessary to obtain an extra amount of skin to repair a certain medical problem. Based in the results we can warn the surgeons against to expansion of the skin in regions over elastic foundation, as abdomen or over fatty tissue as on the upper leg.

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