Quantitative difference of acute intraoperative expansion in various body regions

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Abstract. – OBJECTIVE: To investigate the efficacy of intraoperative sustained limited expansion (ISLE) by examining the ex vivo biomechanical properties of acutely expanded skin flaps.

MATERIALS AND METHODS: Fourteen fresh male cadavers were tested. On both sides of each cadaver, a 4 × 10 cm, the laterally based flap was raised at the external auditory canal of the scalp and a 15 × 8 cm, the proximately based flap was raised at the lateral arm, anterior thorax, and lateral thigh. For each body region, a flap on one side was subject to acute intermittent expansion, while the corresponding contralateral flap served as the control. Both control and acutely expanded flaps underwent stepwise loading to assess their biomechanical properties.

RESULTS: No dimensional changes were observed in the acutely expanded flaps when compared to the controls. Mean stiffness and strain values were not significantly different from control values for flaps raised on the scalp, but statistically significant changes were found for those on the lateral arm, anterior thorax and lateral thigh ($p < 0.05$).

CONCLUSIONS: ISLE produced statistically significant biomechanical improvements when applied to the flaps raised on the arm, thorax and thigh, leading to a significant gain in compliance. We suggest that the ineffectiveness of ISLE, when applied to scalp flaps, was due to the inelasticity of the galea aponeurotica. Our findings confirm the general effectiveness of acute skin expansion as means of reducing wound-closure tension after large skin excisions; at least in regions other than the scalp.

Key Words:
Tissue expansion, Biomechanical phenomena, Wound closure technique, Reconstructive surgery.

Introduction

Background

The method of intraoperative sustained limited expansion (ISLE) was first introduced by Sasaki in 1987[1]. He reported that acute intermittent expansion could stretch the skin beyond its natural limit, reducing the closure tension of surgical wounds and allowing immediate reconstruction. The technique can be performed under either local or general anesthesia. First, an adequate-sized pocket is created, and a tissue expander is implanted. This is then positioned and held in place by a temporary suture with its tube exiting from one end. Finally, a cycle consisting of a 3-minute expansion followed by a 3-minute rest is repeated three times. Each time, the expander is filled as much as possible according to the tissue tolerance as revealed by capillary refilling and the firmness of the implanted expander. After each load cycle, the fill volume is increased, demonstrating the occurrence of tissue recruitment.

Although a number of decades have passed since Sasaki's initial report, a consensus on the true efficacy of ISLE is yet to be reached. For example, Abramo et al[2] reported successful cleft-palate repair for large defects using a 5-mm Foley catheter, and Mackay et al[3] performed ISLE in a pig model, reporting that undermining the wound edges resulted in decreased closure tension and that this goal could not be achieved via ISLE. However, Bartell and Mustoe[4] showed that the biomechanical properties of pig skin are significantly different from those of human skin, thereby diminishing the relevance of Mackay et al[3] and other work[5,6] since it was performed using animal models. Hochman et al[6] demonstrated that ISLE could effectively reduce wound closure tension, but when the degree of undermining achieved by the implant was matched surgically, no difference between the techniques was observed. It is reported that ILSE is capable of inducing viscoelastic behavior in the affected skin, even though the reduction in wound-closure tension mainly derives from the undermining necessary for insertion of the implant[7].

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With this paper, we set out to assess the efficacy of ISLE by examining the *ex vivo* biomechanical properties of acutely expanded skin flaps on the scalp the lateral arm, anterior thorax and lateral thigh[8,9].

Materials and Methods

For this study, 14 fresh male cadavers (mean age at death, 64 years; ranging from 38 to 81 years) were tested. The bodies were not subject to embalming or other preservation processes.

Design of Scalp Flaps

For all cadavers, a 4 × 10 cm, the laterally based flap was raised from the external auditory canal on each side of the scalp. This was followed by 4 × 10 cm subgaleal undermining of both flaps to create pockets for the tissue expander. The expander (elliptical implant, 10 × 6 cm, 75 cc; Mentor, Santa Barbara, CA, USA) was randomly inserted into one of the bilateral pockets and the other pocket served as the control. Temporary wound closure was achieved using a continuous 1/0 silk suture. The stress cycle was performed as previously described by Sasaki[1]. The flap started from the superior border of the ear lobe to reduce the risk of further undermining due to implant expansion. At the end of the acute expansion, the flaps were immediately measured to quantify any change in their size. Control and expanded flaps were then raised with the underlying galea aponeurotica. A rigid metal ruler was positioned at the base of each flap and fixed to the pericranium with a 4/0 nylon suture. Then a 1/0 Maxon (Davis & Geck, Gosport, UK) suture was passed full-thickness through each flap, 0.5 cm lateral to the tip and 1 cm anterior and posterior to the midpoint of the tip.

Design of Flaps on the Lateral Arm, the Anterior Thorax and the Lateral Thigh

A 15 × 8 cm, the proximately based flap was raised on the lateral arm, anterior thorax and lateral thigh on both sides of each cadaver. Under each flap, a subcutaneous pocket was created starting from the 8-cm tip incisions. As above, the expander (rectangular implant, 15 × 8 cm × 6.5 cm, 680 cc; CUI Corporation, Santa Barbara, CA, USA) was randomly inserted into the pocket of one side only, while the contralateral pocket served as the control. A continuous 1/0 silk suture was used to achieve temporary wound closure and the stress cycle was again performed according to the method of Sasaki[1]. The acute expansion was carried out while the researcher's hand pressed on the base of each flap, thus preventing excessive undermining of the tissue, which could alter the results of the study. After acute expansion, the flaps were immediately measured to quantify any change in their size. Control and expanded flaps were then raised from the underlying fascia and a rigid metal ruler was positioned at the base of each flap and fixed to the muscular fascial plane with a 4/0 nylon suture. Then a 1/0 Maxon suture was passed full-thickness through each flap, 0.5 cm lateral to the tip and 2.5 cm from the midpoint of the tip on both sides.

Assessment of Acutely Expanded Flaps and Data Collection

Stepwise loading was performed by means of a dynamometer (FD111; Borletti, Florence, Italy) and a force transducer (D2000; Maywood Instruments Ltd., Hampshire, UK) connected to the Maxon suture[10-15]. A 5-N increase in loading stress was applied for each step (range: 0 to 50 N). The force was applied as fast as possible to reduce the bias that can result from the viscous components of the flaps[16]. Flaps were not under tension between the loading steps. For the flaps of the scalp, each measurement took approximately 2 seconds. For flaps at the other body regions, the measurement took approximately 4 seconds. Raposio and Nordström[10,11], Raposio et al[12-14], Raposio[15] previously demonstrated that this time interval was capable of eliciting viscoelastic behavior of the skin; while the loading stress applied did not result in a permanent change in the flap length.

During each loading step, the force applied and the elongation obtained were recorded to create a load-elongation curve from which the stress/strain relationship and the mean stiffness could be obtained. The biomechanical properties of the cutaneous tissue can be described in terms of *stress* (force per unit of original cross section) and *strain* (change in length divided by the original length)[17], with the stress/strain curve showing the relationship between the force (stress) and the resulting elongation (strain) for a given cross-sectional area[15]. The slope of the stress-strain curve represents the stiffness of the cutaneous tissue and is given by the ratio of the applied force to the displacement of the flap[8,9]. Thus, the compliance of the flap is indirectly described by the mean stiffness: the greater the mean stiffness, the lower the compliance.

Statistical Analysis

The mean, standard deviation and standard error were calculated for all outcomes. A two-tailed paired *t*-test was used to compare control and treatment values. Differences were considered statistically significant if p was less than 0.05.

Results

Data were successfully obtained from all flaps. No statistically significant dimensional changes were found in the acutely expanded flaps.

The load-elongation curves were obtained for both control and acutely expanded flaps. The tissue's stress response to displacement (expansion) was visualized in both acutely expanded and control flaps as a three-phase characteristic. Cutaneous tissue compliance was initially linear (load range: 0 to 5 N) but it gradually reduced (load range: 5 to 15 N) until the stress-strain relationship became exponential due to the rapidly increasing stiffness (load range: 15 to 50 N). Mean stiffness values for all flaps are given in Figure 1.

Our previous work[10] demonstrated that 15 N is the optimal closing-tension load at a suture when advancing a cutaneous flap; therefore, we graphed and compared the mean strain values of the flaps when a 15-N stress was applied (Figure 2).

Acutely Expanded Scalp Flaps

The difference between the stiffness values of acutely expanded (mean, 153.74 gr/mm; SD = ±15.4) and control (mean, 154.05 gr/mm; SD = ±15.7) flaps was not statistically significant (p < 0.05). The mean strain of the acutely expanded (mean, 10.893 mm; SD = ±2.478) and control

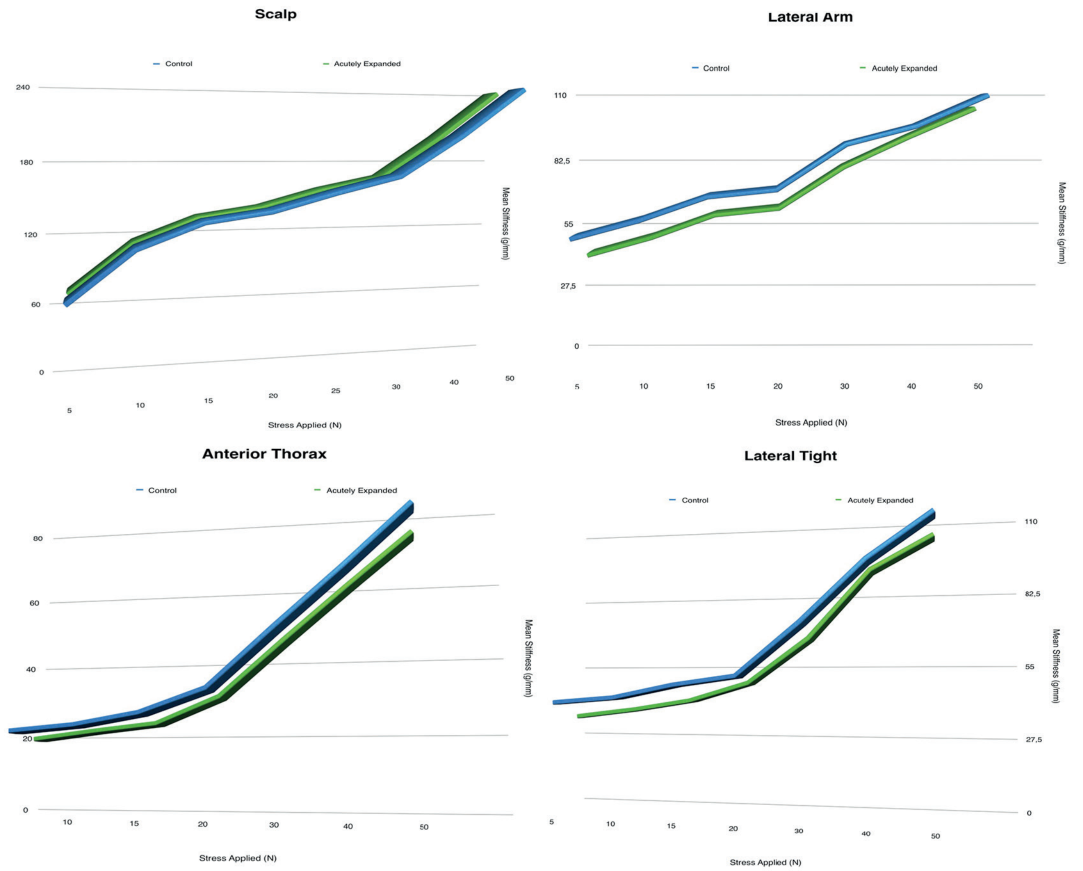

Figure 1. Mean stiffness of acutely expanded and control flaps under progressively increasing stress. The difference between expanded and control flaps was not statistically significant for those raised on the scalp ($p > 0.05$). In contrast, a statistically significant decrease was found for flaps raised on the lateral arm, anterior thorax and lateral thigh ($p < 0.05$).

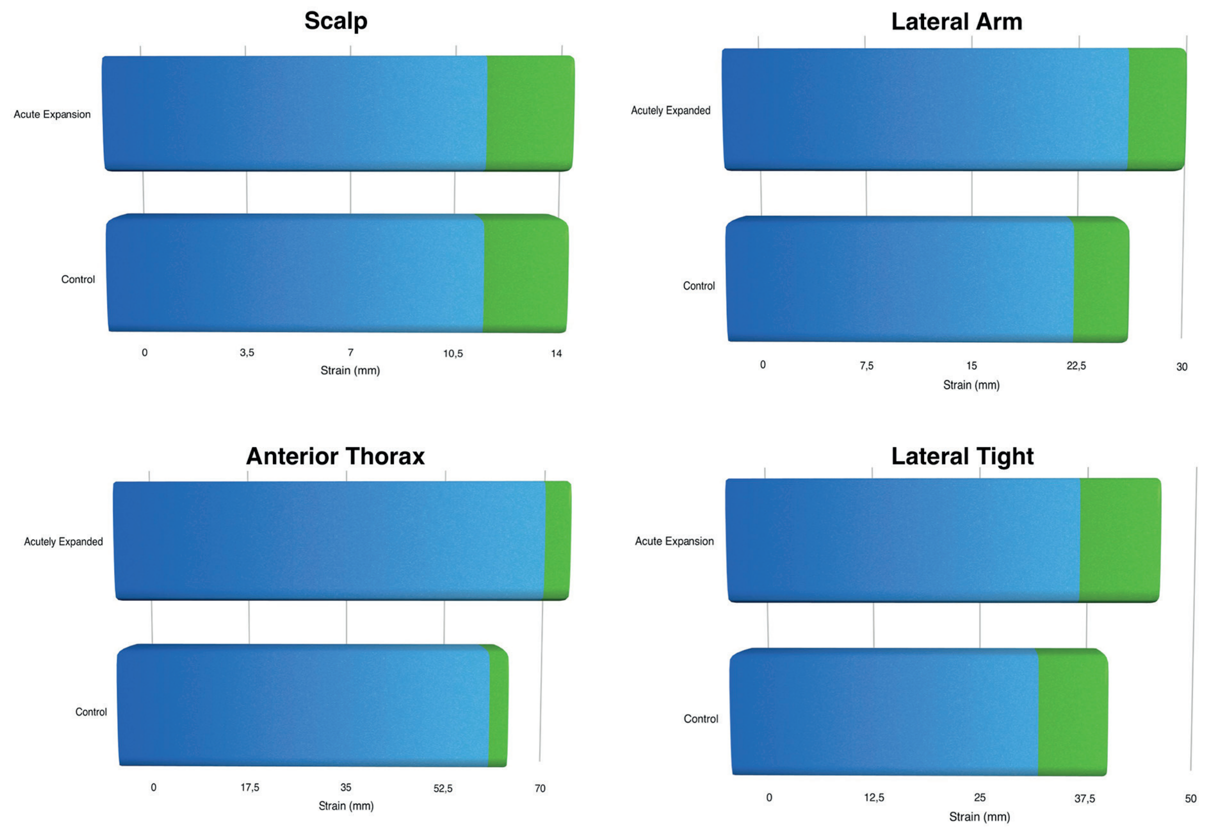

Figure 2. Mean strains of acutely expanded and control flaps calculated when a 15-N load was applied. The difference between expanded and control flaps was not statistically significant for flaps raised on the scalp ($p > 0.05$). A statistically significant difference was found for flaps raised at the lateral arm, anterior thorax and lateral thigh ($p < 0.05$).

(mean, 10.869 mm; SD = ±2.431) scalp flaps under a 15-N stress also did not show any statistically significant difference ($p < 0.05$).

Acutely Expanded Flaps on the Lateral Arm, Anterior Thorax and Lateral Thigh

The difference between the stiffness values of acutely expanded and control flaps raised at the same body region (contralaterally) was statistically significant ($p < 0.05$). The same was true of the mean strain values for flaps in these regions ($p < 0.05$; applied stress, 15 N).

Discussion

Unlike many engineering materials, cutaneous tissue is a living heterogeneous substance, composed of different biological materials and capable of responding to physical stimuli. Indeed, non-linearity, anisotropy and viscoelasticity are all characteristic of the skin's mechanical behavior[17]. Therefore, the stress cycles were performed using a force that was applied homogenously to the skin flap and parallel to the surrounding skin surface in order to minimize the influence of anisotropy. Conversely, the viscoelasticity of skin is essential to the efficacy of ISLE in reconstructive surgery. Cutaneous tissue shows both viscous and elastic properties. When low stress is applied, skin acts as an elastic material; it demonstrates immediate strain but it returns to its original state as soon as the force is removed. However, under higher stress, it behaves like a viscous material and strain becomes a function of both stress and time. This leads to the time-dependent phenomena of creep and stress relaxation that are routinely exploited in the acute intermittent expansion. Mechanical creep refers to the increase in the length of the skin when it is placed under a constant stress. When the stress applied is sufficiently high, slight creep can occur shortly afterward as a consequence of collagen-fiber straightening and displacement of interstitial fluid. Stress relaxation is the reduction of the force required when the skin is kept under constant tension by a given strain. Serial excision of large lesions relies on this stress-relaxation response of the skin.

In our work, the biomechanical properties of acutely expanded (ISLE) and control flaps were determined using an *ex vivo* model. No statistically significant dimensional changes were observed in the acutely expanded flaps, but significant changes in their tensiometric properties were found. Under a 15-N stress, the mean stiffness of acutely expanded flaps on the lateral arm, lateral thigh and anterior thorax was significantly decreased versus that of corresponding contralateral control flaps, which were subcutaneously undermined but not subjected to expansion. This corresponded to respective compliance gains of 15.48%, 8.48% and 14.44% for flaps on the lateral arm, anterior thorax and lateral thigh. According to our results, acute skin expansion appears to be an effective means of reducing wound-closure tension. The gains obtained were similar to those reported by Chretien-Marquet[18] (10.5%) but considerably smaller than those reported by Auletta et al[19] (36%).

In contrast, acute expansion of scalp flaps did not induce any compliance gain over the simple subgaleal undermining of the controls; mean stiffness, tissue compliance and flap lengths were not statistically different between the two groups. Our data was acquired from cadaveric rather than living tissue; therefore, one could argue that ISLE relies on biological properties of the skin that are lost postmortem. However, acute expansion of flaps in regions of the body other than the scalp did produce significant biomechanical improvements; hence we regard our model as effective and this has been demonstrated by other clinical studies[18,19]. A more consistent explanation for our scalp results might be that flaps raised here differ from those elsewhere in the body, owing to the presence of the galea aponeurotica. The galea aponeurotica is an inelastic membrane between the subcutaneous connective tissue and the loose connective tissue of the pericranium. Its inelasticity might prevent the acute intermittent expansion from inducing mechanical creep in the overlying skin. To the best of our knowledge, no study has yet been carried out to examine this hypothesis.

Conclusions

Our findings confirm the effectiveness of acute intermittent skin expansion for reducing wound-closure tension after a large skin excision. The technique produced significant gains in skin-flap compliance (8.5-15.5%) in all tested body regions, with the notable exception of the scalp. We suggest that the absence of an effect at the scalp was due to the inelasticity of the galea aponeurotica, but further researches will be required to test this hypothesis.

Authors' declaration of personal interests:
Edoardo Raposio has not served as a speaker, consultant or advisory-board member for any organization. He is not an employee of any organization and does not own stocks or shares in any organization. Nicolò Bertozzi has not served as a speaker, consultant or advisory-board member for any organization. He is not an employee of any organization and does not own stocks or shares in any organization. The authors, Nicolò Bertozzi and Edoardo Raposio, declare that they have no conflicts of interest.

Declaration of funding interests:
This study, including the preparation of this manuscript, did not receive any funding. Initial data analysis was performed by the authors.

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