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Biomechanical comparison between conventional and rapid expansion of skin

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Summary This study was designed to investigate the effects of different surgical expansion regimens on the biomechanical features of expanded skin. Two hundred and forty millilitres expanders were implanted on the backs of six adult dogs. Six flaps were designed on the dorsum of each dog. After serial expansion, the expander was left beneath the skin for a certain period of time, which is called the maintaining period. Rapid expansion and conventional expansion with various maintaining periods were compared. The experimental result shows that the area gain of expanded skin surface had no significant difference between the rapid and conventional expansion. Both the tension in vivo and the instant stretch-back ratio increased during the expansion, but fell almost to control values after four weeks' maintaining period. Biomechanical properties in vitro, such as tensile strength, stress-strain, stress-relaxation, and creep were tested by INSTRON material testing machine. Results show that the biomechanical properties of expanded specimens differ significantly from those of their controls immediately after expansion. However, the difference reduces with prolongation of maintaining time. With the same maintaining period, the biomechanical properties of rapidly expanded skin are similar to conventionally expanded skin. We conclude that rapid skin expansion did not demonstrate any deleterious effect when compared with the conventional expansion. Extension of the maintaining period can improve the biomechanical properties of expanded skin and effectively reduce the stretch-back ratio. Therefore, rapid expansion with an extended maintaining period is acceptable in clinical practice.

Skin expansion has become a widely used technique in plastic surgery. By means of a subcutaneous implanted balloon that is subsequently inflated, the skin overlying the balloon is mechanically expanded in order to increase its surface area and so to gain tissue for reconstructive purposes. Recent experimental and clinical experience suggests that expansion for 1–2 weeks is just as effective as the

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longer delayed expansion of 6–8 weeks.[1–5] The clinical experience suggests that if the expander is left beneath the skin for a period of time after expansion, the stretch-back ratio of the expanded skin can be reduced significantly, and the maximum amount of expansion can be achieved. However, these observations have not been studied scientifically. This study used a dog model whose skin possesses biomechanical properties similar to that of human skin.[7–9] Expanded skin from different expansion regimens, sham-operated sites (expander inserted but not inflated) and nonoperated control sites were compared biomechanically, both in vivo and in vitro.

Material and methods

Six adult Beagle dogs of undertint skin and hair (female or male) were selected for experiments. The dogs were provided by the Animal Laboratory of Chinese PLA General Hospital. The weight of each dog was about 20 kg. Six 5×8 cm^2 areas were marked with an electric tattoo instrument on each animal bilaterally over the rib cage. The specimens were divided into four groups: A. Rapid expansion regimen (E2): expanded every day for two weeks. B. Conventional expansion regimen (E6): expanded weekly for six week. C. Sham-operated: the balloons were inserted but not inflated. D. Nonoperated control. A and B groups were subdivided into smaller groups according to the maintaining time after expansion: maintained for one week (m1), maintained for two weeks (m2), maintained for four weeks (m4). Anaesthesia was achieved by intramuscular injection of ketamine and the dosage was 0.05 ml/kg to maintain for 2 h. After 2 h, the dosage was maintained by 0.02 ml/kg, injected once an hour. All dogs undergoing general anaesthesia were monitored to ensure an adequate level of anaesthesia for the procedure being performed, and to minimise perioperative mortality and morbidity. Factors monitored included depth of anaesthesia respiratory function and body temperature. Strict aseptic technique was employed. The investigator and animal care staff were all essential members of the perioperative care team and careful communication between these team members minimised dog distress and created an environment in which a perioperative care program could be effectively managed.

Under anaesthesia and aseptic conditions, 240 ml rectangular expanders were surgically inserted beneath the skin and panniculus carnosus of the marked regions. At each expansion, saline was injected to generate an intraluminal balloon pressure of 60 mmHg. When the expansion period and maintaining period were completed, under anaesthesia, the dog skin underwent a second operation for a series of biomechanical skin properties measurements, both in vivo and in vitro.

Measurement in vivo

Measurement of expanded skin area

A thin wire was used to conform to the base periphery of the expanded skin; this thin wire contour was then traced on a sheet of white paper. The outlined region was the base area, marked A_0. The base and the tattooed center of expanded skin were re-marked with methylene blue. Two layers of lens paper were then affixed to the surface of the expander projection by painting it with natural liquid emulsified rubber. A paper pattern was formed within 10–15 min with hair dryer, and a special rubber-paper membrane representing the overlying ballooned skin surface was recreated (irregular hemisphere). Stelliform snips at intervals of about 10 mm were made along the edge, so that the velamen could be spread flat. This flat rubber-paper velamen was then placed on a large sheet of black paper, and its image was input into a computer through a fixed CCD camera. The area was then measured by computing its total pixel number. The center area of expanded skin was remarked with a special ink before the paper mold was made, so that it could be imprinted on the membrane. The underlying base area could also be measured with the method stated above.

Measurement of tension in vivo and stretch-back ratio

The measurement equipment was made by ourselves. A rectangle skin flap 4×7 cm^2 was marked with a template on the center of the expanded skin. The long side of the flap is parallel to the spinal column of the dog. A 'U' incision down to the capsule was made along the two long sides and the short side of the flap, and the base of the flap, which was on the cephalic side, was left untouched. With three precision force transducers, which were laid on the cross-shaped rack (Fig. 1), the following parameters were measured.

The tension in vivo: when the skin is cut, it retracts immediately. The tensions that are required to return it back to its original in vivo dimensions, both in length and in width are called the longitudinal and transverse tension in vivo.

The instant stretch-back ratio: $K = (S_0 - S)/S_0$, where S is the present area, S_0 is the primary area.

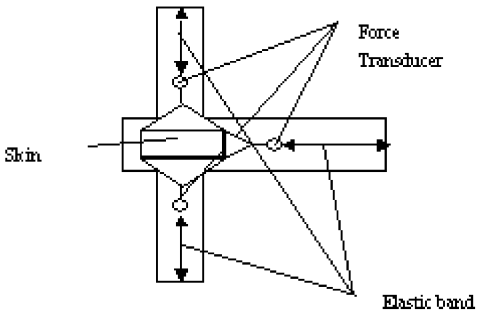

Fig. 1 The schematic diagram for measuring tension in vivo.

The stretch-back ratios under no tension and under normal tension (by using tension of nonoperated control skin) were measured.

The experiment follows these steps: first, the stretch-back ratio and tension in vivo of nonoperated control were measured. Second, the following parameters of the expanded and sham-operated skin with capsule were measured: stretch-back ratio under no tension, stretch-back ratio under normal tension, and tension in vivo. Third, removing the capsule, the above parameters were measured again.

Biomechanical properties in vitro

Four identical strips were cut from the skin overlying the expanders with a special cutting device consisting of five parallel surgical knives. The stress relaxation, stress-strain relationship, creep characteristics and tensile strength of the specimens were tested on an INSTRON material machine (made in UK). The experiment is performed under normal temperature; an ultrasound moistener is used to keep the specimen moist. The computer automatically collected data.

Stress-strain relationship

The specimens are loaded and unloaded under a constant rate of 20 mm/min for three cycles. It was seen that the hysteresis loop decreased between successive cycles and eventually disappears. After three cycles, the specimens are regarded as preconditioned. All specimens were preconditioned in the stress-strain relationship, stress relaxation and creep tests.

Stress relaxation

If the tissue is rapidly loaded to a finite strain and then its length held constant, the stress decreases with time, which exhibits the phenomenon of stress relaxation. In this study, elongation speed is 125 mm/min, and the stretched length was maintained for 20 min while the absolute tension on samples was monitored with time.

Creep

If a certain load is suddenly given to the tissue and the stress is maintained constant afterwards, the tissue continues to deform and this phenomenon is called creep. In this test, a constant load of 20 N is applied over 20 min.

Tensile strength

For this test, a dumb-bell shaped skin specimen is cut. This is to produce rupture at the center of the specimen. A load is applied to the specimen at a constant strain rate of 20 mm/min until failure. Lagragian stress is used as the tensile strength, i.e. stress as calculated from original unstrained cross sectional area of the specimen. The data are listed as means with standard errors in all tables. Statistical analysis was performed on the test data of various groups stated above using analysis of variance followed by the Student-Newman-Keuls multiple-range test for control of experiment-wise error.

Result

Measurement in vivo

Expanded skin area

The change in the center of expanded skin was evaluated by the increased ratio of the marked region in the expanding center. The surface area gain is calculated as follows: $(A\text{-}A_0)/A_0$. The results are shown in Table 1, no significant difference was seen both in the change of center area and surface area gain among these two expansion regimens. After maintaining for four weeks the average central area increase was 100% and the average surface area increase was 90%.

Stretch-back ratio and tension in vivo

The result of stretch-back ratio is listed in Table 2.

Table 1 Increased ratio of area

	Increased ratio of whole area (%)	Increased ratio of central part (%)
E2m1	0.6402 ± 0.0946	0.7673 ± 0.1521
E2m2	0.7420 ± 0.1658	0.906 ± 0.1356
E2m4	0.855 ± 0.1433	0.986 ± 0.1291
E6m1	0.670 ± 0.1463	0.796 ± 0.1464
E6m2	0.884 ± 0.2629	0.936 ± 0.1867
E6m4	0.903 ± 0.1431	1.012 ± 0.1181

Table 2 Instant strech-back (under normal tension or no tension)

Groups	No tension[a]	No tension[b]	Normal tension[a]	Normal tension[b]
Control	0.2233 ± 0.0333	0.2233 ± 0.0333		
Sham-operated	0.2303 ± 0.0527	0.0947 ± 0.0750	0.1084 ± 0.0170	0.0019 ± .0017
E2m4	0.2951 ± .0589	0.2544 ± 0.0424	0.1338 ± 0.01914	0.0806 ± 0.0139
E2m2	0.3430 ± 0.0751	0.2834 ± 0.0771	0.1717 ± 0.03681	0.1364 ± 0.0290
E2m1	0.4236 ± 0.0176	0.3207 ± 0.0142	0.3394 ± 0.0242	0.2234 ± 0.0374
E6m4	0.2338 ± 0.0264	0.2208 ± 0.0663	0.1414 ± 0.03505	0.0913 ± 0.0214
E6m2	0.3047 ± 0.0409	0.2923 ± 0.0552	0.1553 ± 0.01904	0.1169 ± 0.0182
E6m1	0.4069 ± 0.0267	0.3383 ± 0.0341	0.3069 ± 0.03175	0.1881 ± 0.0581

[a] With capsule.
[b] Without capsule.

It can be seen that with capsule and under no tension, the average instant stretch-back ratio of skin samples from expanded groups was greater than that of control and sham-operated groups. Under normal tension (tension of nonoperated skin), there is still some stretch-back in the expanded skin. Significant difference could be seen between groups that were maintained for one week and other groups. The stretch-back ratio decreased with increase in maintaining period. Under the same maintaining period, there is no significant difference between skin from the rapid regimen and conventional regimen. The stretch-back ratio could be dramatically reduced if the capsule was removed.

The result of tension in vivo is shown in Table 3. For different maintaining period a similar varied pattern to the stretch-back was seen. This suggests that probably due to tissue accommodation, prolonging the maintaining period will get to values of normal tension in vivo and stretch-back ratio.

Biomechanical properties in vitro

Stress-strain relationship

The stress-strain curves of rapid and conventional expansion regimen with different maintaining periods are shown in Fig. 2(A) and (B). In Fig. 2, the ordinate is the Eulerian stress σ (which is referred to the cross-section of the deformed specimen A) is λ times Lagrangian stress T (which is load P divided by the reference area A_{ref}); the abscissa is Greenian strain ε, for an incompressible material, the cross-sectional area of a cylindrical specimen is reduced by a factor $1/\lambda$ when the length of the specimen is increased by a factor λ and the Greenian strain ϵ is $\frac{1}{2}(\lambda^2 - 1)$. The figures show that the stress-strain curve slope (elastic modulus) of the expanded specimen deviates from that of its control most with one week's maintaining period, but the deviation reduces with the increase of maintaining period. From the Fig. 2, differences in elastic modulus between specimens would indicate the effect of the integrity. The elastic modulus of each specimen was calculated at a stress of 2.0 MPa. We found that the slope of conventional expanded specimen (E2m4) is 17.2 and the slope value of rapid expanded specimen (E6m4) is 17.7. They are very close.

Stress relaxation

The generalised relaxation curves $G(t)$ of specimens with various maintaining period are shown in Fig. 3(A) and (B). From the experimental data, the generalised relaxation $G(t)$ curve is essentially a linear function of $\ln t$ (t is the time) within the experimental time.

Table 3 Tension in vivo (with capsule or without capsule)

Groups	Longitudinal tension[a]	Transverse tension[a]	Longitudinal tension[b]	Transverse tension[b]
Control	64.20 ± 14.83	63.86 ± 18.87	64.20 ± 14.83	63.86 ± 18.87
Sham-operated	101.35 ± 12.93	81.86 ± 11.33	67.96 ± 13.75	78.52 ± 10.90
E2m4	141.17 ± 11.07	160.66 ± 18.95	84.22 ± 14.23	77.84 ± 16.27
E2m2	196.38 ± 22.58	185.81 ± 19.74	114.58 ± 18.45	107.98 ± 19.03
E2m1	259.23 ± 22.22	218.95 ± 34.29	189.97 ± 26.12	151.97 ± 33.30
E6m4	133.89 ± 18.56	122.23 ± 28.32	69.22 ± 08.19	73.54 ± 06.44
E6m2	147.82 ± 25.96	191.99 ± 25.10	86.74 ± 18.54	80.85 ± 11.32
E6m1	261.87 ± 57.65	217.95 ± 46.02	176.25 ± 38.10	133.56 ± 27.36

[a] With capsule.
[b] Without capsule.

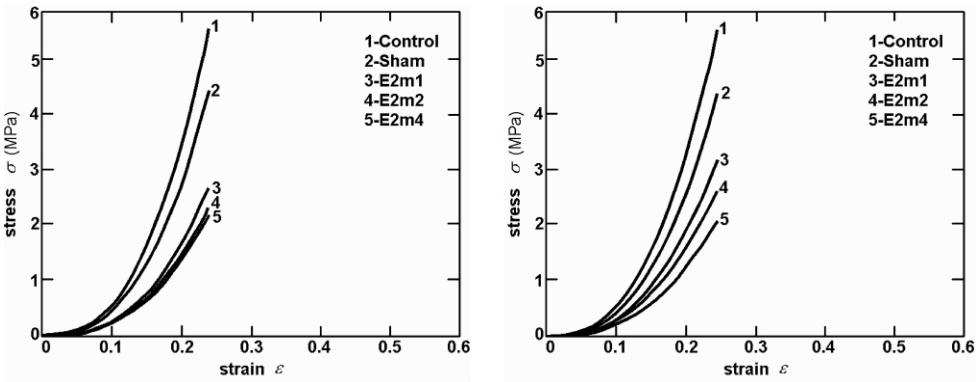

Fig. 2 Stress–strain curves: (A) rapid expansion; (B) conventional expansion.

The following two parameters can be used to reflect the relaxation degree of a specimen. K_r is the slope of fitted $G(t) - \ln t$. G_e is the value of $G(t)$ at the end of the stress-relaxation test (1200 seconds in this test). K and G_e reflect the speed of relaxation. The slopes of the stress relaxation curves were also evaluated to compare the integrity of the mucopolysaccharide matrix. A rapid relaxation of the material indicates that the fibers realign or migrate in response to the applied stress. This is possible only if the watery ground substance or matrix is intact. Slow relaxation indicates that the material behaves more like an elastic solid, suggesting that the fiber have become immobilised. The two parameters of expanded and control specimens are listed in Table 4. The great contribution that the maintaining period made to the relaxation degree can be seen. Significant difference was seen in the groups within a week maintaining period, the longer maintaining period the lesser the difference. With the same longer maintaining period (4 weeks) for conventional expansion (E2m4) the K_r is 0.04863 and the G_e is 0.5786, for rapid expansion (E6m4) the K_r is 0.04713 and the G_e is 0.5886, so no significant difference can be seen between the two expansion regimens.

Creep

The reduced relaxation function $J(t)$ is used to normalise relaxation under various stretch conditions. The generalised relaxation curves $J(t)$ of specimens of rapid and conventional expansion regimen with various maintaining period are shown in Fig. 4(A) and (B). It can be seen from the figures that the $J(t)$ curves of expanded specimens are higher than the curves of their controls and sham controls. The curves of the expanded skin deviated greatly from its control after expansion; but with an increase of the maintaining time, the expanded curve approached with its controls.

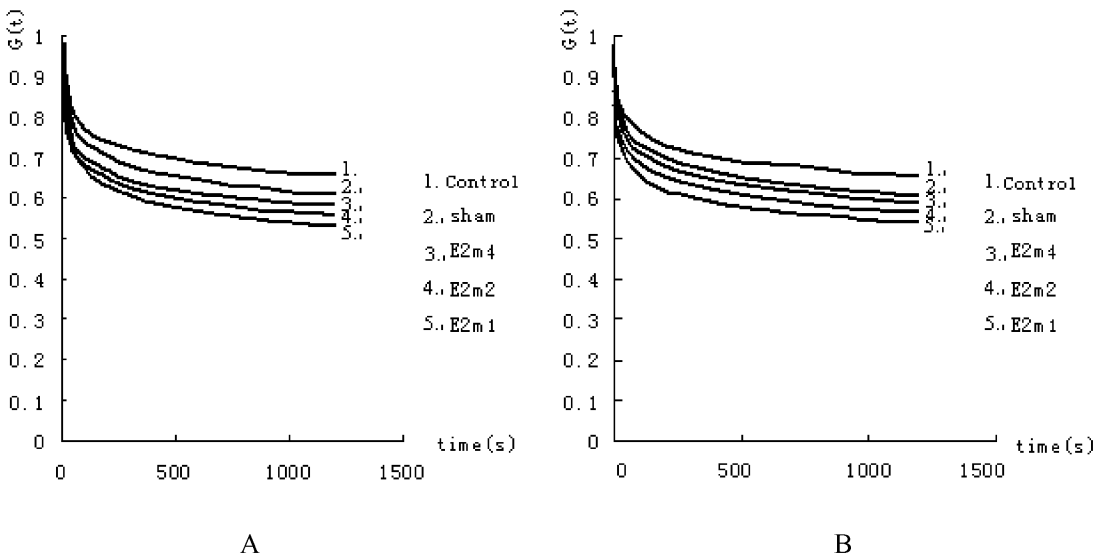

Fig. 3 Reduced stress relaxation curves: (A) rapid expansion; (B) conventional expansion.

Table 4 Parameters of stress relaxation

Groups	K_r	G_e
control	0.04275 ± 0.00461 B	0.6520 ± 0.0341 B
Sham-operate	0.04485 ± 0.00269 B	0.6034 ± 0.0857 B
E2m4	0.04863 ± 0.00296 B	0.5786 ± 0.0358 B
E2m2	0.04895 ± 0.00201 B	0.5603 ± 0.0148 B
E2m1	0.05283 ± 0.00188 A	0.5265 ± 0.0104 A
E6m4	0.04713 ± 0.00541 B	0.5886 ± 0.0347 B
E6m2	0.04880 ± 0.00355 B	0.5618 ± 0.0210 B
E6m1	0.05323 ± 0.00275 A	0.5371 ± 0.0196 A

Means with the same letter are not significantly different at the 0.05 confidence level.

Table 5 Parameters of creep

Groups	K_c	J_e
Control	0.00035 ± 0.00067 B	1.01443 ± 0.00217 B
Sham-operated	0.00036 ± 0.00043 B	1.01576 ± 0.00216 B
E2m4	0.00465 ± 0.00033 B	1.01811 ± 0.00064 B
E2m2	0.00490 ± 0.00443 B	1.01953 ± 0.00169 B
E2m1	0.00528 ± 0.00188 A	1.02206 ± 0.00067 A
E6m4	0.00398 ± 0.00061 B	1.01576 ± 0.00111 B
E6m2	0.00437 ± 0.00053 B	1.01797 ± 0.00237 B
E6m1	0.00505 ± 0.00024 A	1.02232 ± 0.00124 A

With same letter means there is not significantly different at the 0.05 confidence level.

The creep and the stress relaxation are inherent mechanical properties of soft tissue. But they have different characteristics.

The following two parameters can be used to reflect the creep degree of a specimen. K_c is the slope of fitted $J(t) - \ln t$. J_e is the value of $J(t)$ at the end of the creep test. K_c and J_c reflect the speed of creep. The parameters of creep listed in Table 5.

This result shows that creep levels rely on the maintaining time. After the longer maintaining time (4 weeks), the parameters are very close to that of the sham control. For conventional expansion (E2m4) the K_c is 0.00465 and the J_c is 1.0181, for rapid expansion (E6m4) the K_c is 0.00398 and the J_e is 1.01576 so they have no significant differences parameters were found between the rapid and conventional expansion.

Tensile strength

Tensile stresses were evaluated and the results are listed in Table 6. Results show that the tensile strength of the control group is statistically greater than other groups. No significant difference can be seen among the expanded regimens.

Table 6 Tensile strength

Groups	n	Tensile strength (MPa)
Control	6	9.67 ± 0.99 A
Sham-operated	4	8.38 ± 0.03 B
E2m4	4	8.47 ± 0.58 B
E2m2	4	8.89 ± 0.39 B
E2m1	4	8.36 ± 0.83 B
E6m4	4	8.21 ± 0.47 B
E6m2	4	7.86 ± 0.82 B
E6m1	4	7.73 ± 0.55 B

Means with the same letter are not significantly different at the 0.05 confidence level.

Discussion

Rapid expansion and conventional expansion have a similar effect on the area gained in the expanded skin at the time of harvest.

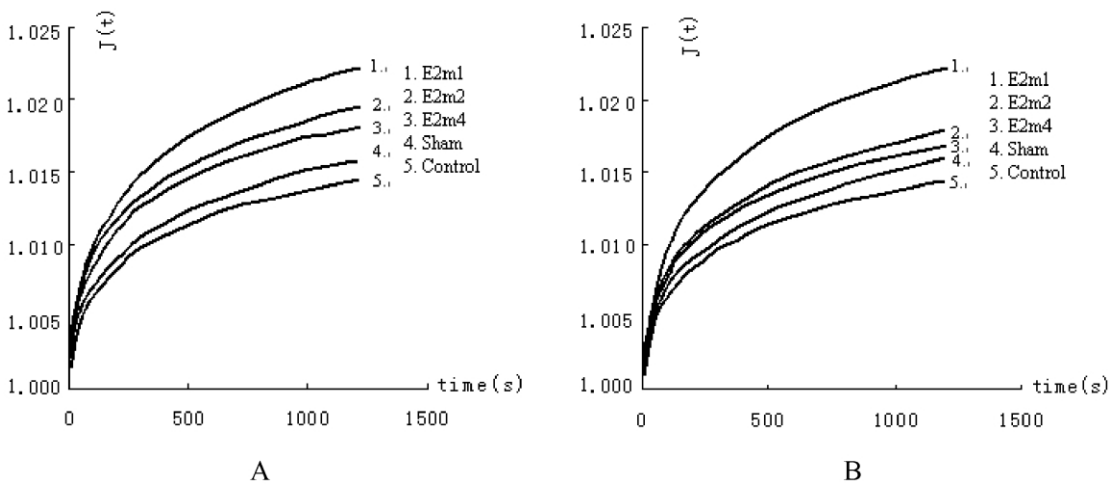

Fig. 4 Reduced creep curves: (A) rapid expansion; (B) conventional expansion.

There is a considerable increase in the stretch-back ratio and tension in vivo in the expanded skin. However, the increase could be reduced by extension of maintaining period. On the other hand, with the same maintaining period, skin properties in vivo are similar under the two expansion regimens.

It should also be emphasised that both conventional and rapid expansion, show similar varied biomechanical properties in vitro, as in vivo, which demonstrates that maintaining period is the important factor in rehabilitation of the properties of expanded skin.

Our conclusion is that rapid expansion does not show any deleterious effects when compared with the conventional regimen. Extension of the maintaining period will be very beneficial for the expanded skin to regain its biomechanical properties, reduce the instant stretch-back ratio and to maximise the surface area gain as well. These tests, either conventional or rapid show that expanded skin demonstrates very similar characteristics to the controls after a four-week maintaining period. Thus from a biomechanical view point, rapid expansion with extension of maintaining period as well as conventional expansion is acceptable in clinical practice.

Acknowledgements

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