—Report on Experiments and Clinical Cases—

Biomechanics and Computer Simulation of the Z-Plasty

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Abstract

Introduction: We compared the results of our computer simulation studies of Z-plasties of different design to those of earlier studies, such as laboratory studies in dogs.

Material and Methods: The contours of single Z-plasties of different designs on flat surfaces were transferred to finite element analytical software (ADINA version 8.7).

Results: The lengthening effect was almost proportional to the size of the Z-plasty, but was always less than what was predicted by geometric calculation. The percent gain in length decreased with the number of Z-plasties.

Conclusion: We used ADINA software analyze the lengthening effects of Z-plasties of different patterns. Our results support those of earlier experiments and should help increase our understanding of Z-plasties of various patterns.

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Key words: Z-plasty, computer simulation, finite element

Introduction

Z-plasty is a reliable technique for plastic or dermatologic surgeons to revise free-margin distortions. There are 3 main objectives when performing Z-plasty: to lengthen a contracted scar, to change the direction of a scar so that it is better aligned with the relaxed skin tension lines, and to interrupt and break a scar for better camouflage **(Fig. 1-a, b and c)**[1]. Although angles from 30° to 90° are possible, the 60° Z-plasty is the most common and is usually diagrammed as a symmetrical 60°-60° figure[2–4]. However, this can be altered, and surgeons can choose from many alternative designs[3]. At present, a plastic surgeon can only practice creating a Z-plasty on a live patient in an operating room, and the surgeon's decision usually rests on simple geometry and intuition. A surgical simulation system for postoperative skin suturing would reduce the labor required by plastic surgeons. Thus, a computer simulation, for practicing Z-plasty and predicting results, has long been our dream, but only a few tools are available for use in clinical practice[5].

In a preliminary study, we compared the results of our computer simulations of Z-plasties of different design to those of other studies of different Z-plasties, with the aim of applying computer simulation to clinical practice.

Material and Methods

Analysis was performed with a personal computer (2.0-GHz Intel Core i5 processor and 4 GB memory) and ADINA analytical software (version 8.7, ADINA R&D, Inc., Watertown, MA, USA). The contours of

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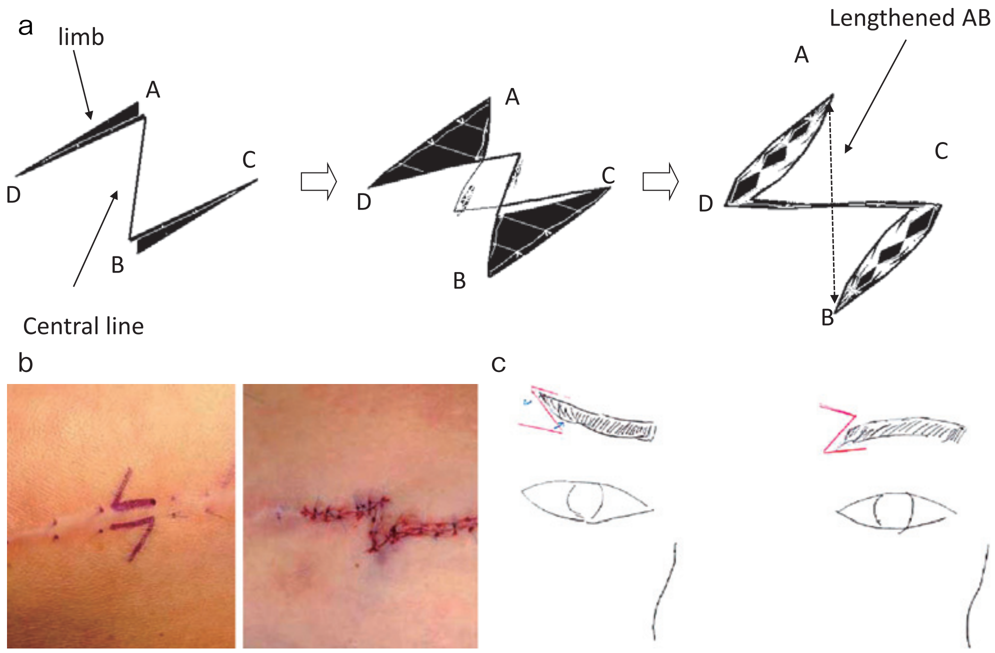

Fig. 1 **a**: Classic Z-plasty. Two triangular flaps of equal limb length and 60° angles are transposed.
b: Z-plasty with scar excision, interrupting and breaking a scar for better camouflage.
c: Changing a direction of scar.

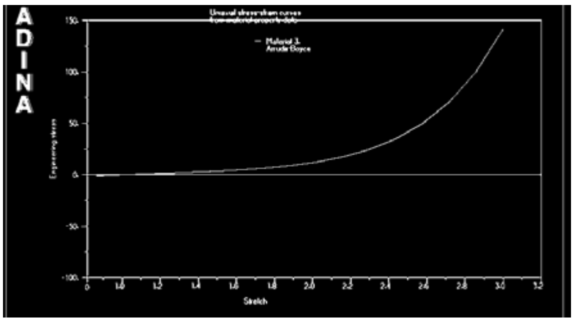

Fig. 2 Arruda and Boyce's 3-D hyperelastic solid model was used this time. It is based on a curve approximation algorithm that makes it possible to add characteristics very similar to those of actual skin.

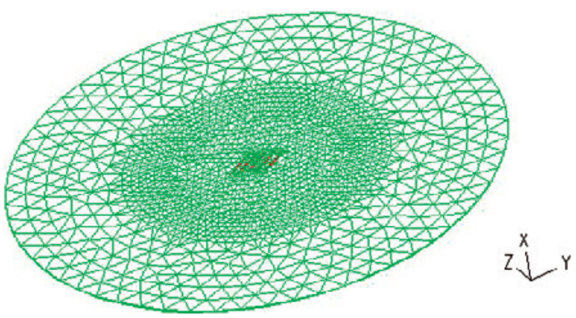

Fig. 3-1 The circular skin model with the Z-plasty model used in this study

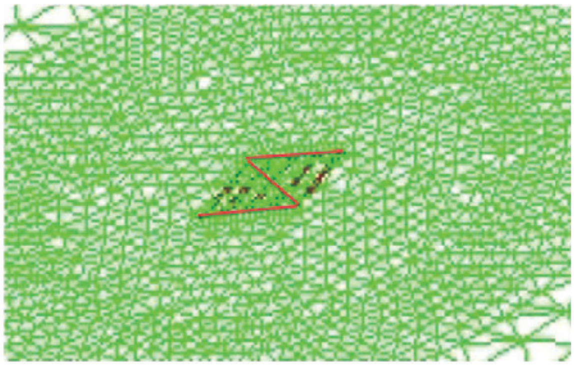

Fig. 3-2 Focus of the center of the Figure 3-1

different Z-plasties were transferred to a flat circular sheet, which exhibits characteristics based on an initially isotropic rubbery elastic constitutive law developed by Arruda and Boyce to model skin behavior **(Fig. 2, 3-1 and 4)**[6]. Measurements were made by simply transposing the flaps without estimating the pre-tension of the skin. The number of sutures was 10 per Z-plasty. With this model, the lengthening effects of the following stress patterns of Z-plasties on flat surfaces were compared.

I. Single 60° Z-plasties Differing in Size Only

Measurements of lengthening AB and shortening

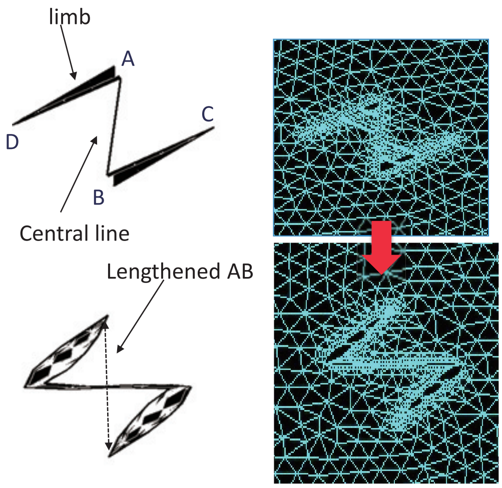

Fig. 4　Single 60° -60° Z-plasty

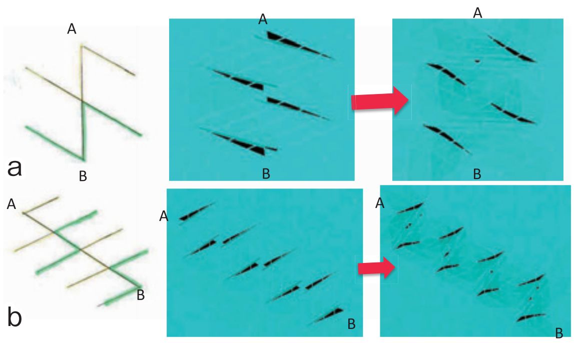

Fig. 5　Computational view of multiple z-plasties of the same total length of 8 cm.
(a: above) 2 z-plasties of 4 cm (b: below) 4 z-plasties of 2 cm.

CD of 60°-60° single Z-plasties **(Fig. 4)** with limbs of 1, 2, 4, 6, and 8 cm were made and compared by plotting x-, y-, and z-coordinates of points A to D before and after transposition. The distance of the coordinates for 2 points was calculated on the basis of the formula for a spatial vector.

II. Single and Serial Z-plasties of the Same Total Length But Differing in Individual Size and Number

The following models of 60°-60° Z-plasties were made: a single 8-cm Z-plasty, two 4-cm Z-plasties in series **(Fig. 5-a)**, and four 2-cm Z-plasties in series **(Fig. 5-b)**. The sum of the central limbs was 8 cm in each case. Measurements of lengthening AB and shortening CD were made with the same method as for the single Z-plasty experiment.

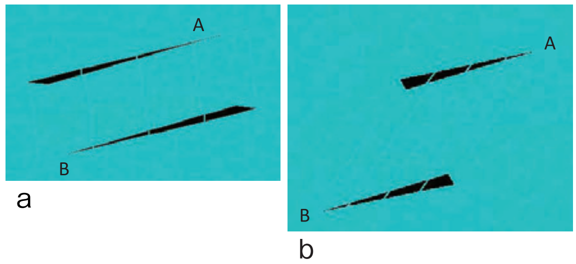

Fig. 6　Computational view of 8 cm z-plasties with different tip angles
(a: left) 30° -30° (b: right) 90° -90°

III. Symmetrical Z-plasties Differing in Tip Angles

A set of 8-cm Z-plasties with the following tip angles were plotted and transposed: 30°-30° **(Fig. 6-a)**, 45°-45°, 60°-60°, 75°-75°, and 90°-90° **(Fig. 6-b)**. The tension required to transpose these flaps was determined. The gains in length AB were recorded.

Results

I. Single 60° Z-plasties Differing Only in Size

Both the laboratory studies in dogs and computer simulation results showed that the lengthening effect increased with the size of the Z-plasty but was less than the 73% predicted with geometric calculations **(Fig. 7)**.

II. Single and Serial Z-plasties of the Same Total Length But Differing in Individual Size and Number

Although a 73% gain in length is predicted geometrically for each of the Z-plasties in this group, the results of both laboratory studies and computer simulation showed that the percent gain in length was less than that predicted mathematically. Other results were similar in both studies: the lengthening effect increased with the size of the Z-plasties in series or decreased with the number of Z-plasties in series, larger flaps with fewer Z-plasties yielded greater lengthening, and the percent gain in length increased with the size of the Z-plasties in series or decreased with the number of Z-plasties.

The decrease in the width at C'D' was roughly reciprocal to the lengthening at A'B' **(Fig. 8)**.

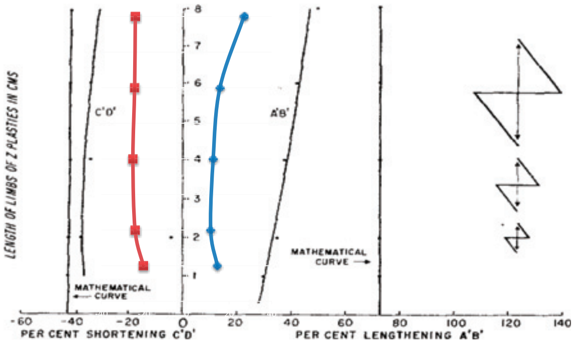

Fig. 7 The black line shows the results from Furnas and Fischer (1971); the present results are superimposed using thicker lines. Both the laboratory studies and our computer simulation studies show that the lengthening effect was less than the mathematical prediction, which is 73%. (Adapted from Fig. 6 in "Furnas DW, Fischer GW. The Z-plasty: Biomechanics and mathematics. Br. J Plast Surg. 1971; 24: 144")

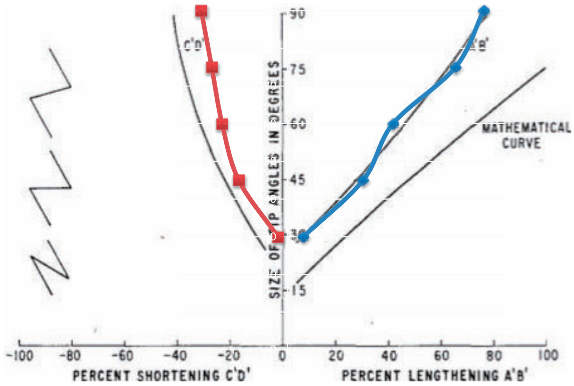

Fig. 9 The black line shows the result from Furnas and Fischer (1971); our results are superimposed using thicker lines.
The results were similar to those of earlier laboratory studies. Lengthening increased in proportion to the tip angle. (Adapted from Fig. 9 in "Furnas DW, Fischer GW. The Z-plasty: Biomechanics and mathematics. Br. J Plast Surg. 1971; 24: 144")

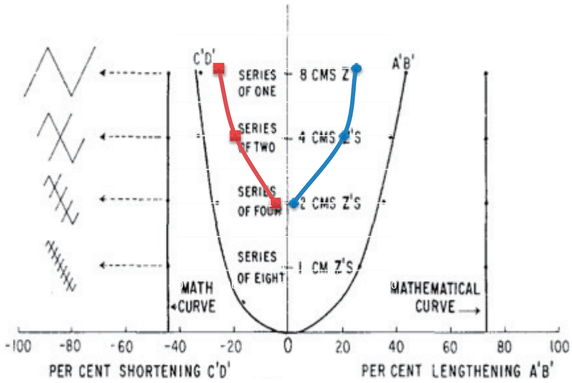

Fig. 8 The black line shows the results from Furnas and Fischer (1971); our results are superimposed using thicker lines. Our values were less than those of the laboratory studies, but larger flaps with fewer Z-plasties did yield greater lengthening, and the percent gain in length increased with the size of the Z-plasties in series or decreased with the number of Z-plasties. (Adapted from Fig. 7 in "Furnas DW, Fischer GW. The Z-plasty: Biomechanics and mathematics. Br. J Plast Surg. 1971; 24: 144")

III. Symmetrical Z-plasties Differing in Their Tip Angles

The results of both laboratory studies in dogs and computer simulation showed that the effective lengthening B'B' ranged from approximately 10% (30°-30° Z-plasty) to approximately 75% (90°-90° Z-plasty) and was always less than the mathematical prediction (24% for a 30°-30° Z-plasty and 124% for a 90°-90° Z-plasty); there was a direct linear relationship between the data in the 2 groups of figures (**Fig. 9**).

Discussion

In the present study, the surface of human skin was measured noninvasively with a device for rapidly measuring a 3-dimensional (3-D) surface, and then the skin suture was analyzed with the 3-D finite element method (FEM). By using the appropriate suturing method determined with the FEM, a clinical operation was performed and the clinical results were compared with the FEM results[7]. When Z-plasty is performed, the degree of lengthening is determined by the angles of the flap: the larger the angle, the greater the lengthening of the original scar; the smaller the angle, the less the lengthening of the original scar[2]. The geometric increase in scar length based on the angle between the limbs and the central incision of a Z-plasty is 73% for 60°-60° angles but is 25% for 30°-30° angles, 50% for 45°-45° angles, 100% for 75°-75° angles, and 125% for 90°-90° angles. However, Gibson and Kenedi measured Z-plasties in patients and discovered that the increase in scar length ranged from one-third less to two-thirds more than expected from their geometric calculations. They also showed that geometry alone is not a dependable guide[8]. Laboratory studies of Z-plasty were then performed with dog trunks by Furnas and Fischer to show some of these features[3]. Kawabata et al compared and supported their results by performing finite element analysis on pig skin[9]. Both Akimoto[9,10] and Dávila[12] measured the lengthening effects using computer simulation software. All of these studies have shown that the lengthening effects are less than those of predicted by geometric calculations.

The reasons for these results have not been examined in detail, but we suspect that the mechanical behavior of the human skin is a factor. The mechanical behavior of human skin is complex and shows a nonlinear stress-strain relationship[13–15], which can be attributed to the skin's collagen network[16]. Retel et al compared a nonlinear model with a plain linear elastic model using FEM and confirmed the practitioner's experimental know-how for the choice of the incision shape[17]. Yoshida et al performed a 3-D finite element analysis of a conventional spindle model and a modified S-shape model using nonlinear material and obtained results agreeing with clinical findings[7]. Therefore, we incorporated a nonlinear model with an initially isotropic rubbery elastic constitutive law developed by Arruda and Boyce[6] into our device to model skin behavior. This model, referred to as the 8-chain model, was developed to capture the large 3-D stress versus stretch behavior of rubbery elastic materials[6,15].

We analyzed some of these earlier studies, mainly the laboratory studies of Z-plasties performed with dog trunks by Furnas and Fischer[3], using computer simulation software and compared their results to our studies on Z-plasties of different designs. All of our computer simulation studies of the 3 stress patterns of Z-plasties show that the lengthening effects were less than those predicted with geometric calculations.

With single 60° Z-plasties differing in size, the lengthening was almost directly proportional to the size of the Z-plasty, a finding agreeing with those of Furnas and Fischer[3] and Kawabata et al[9], although our values seems less than the values of these previous studies, which were approximately 140%.

With single and serial Z-plasties of the same total length differing in individual size and number, our values also appeared to be less than those obtained in dog experiments, but fewer flaps in series and larger flaps led to a greater lengthening effect, which strongly support the results of dog experiments. In the third experiment, with symmetrical Z-plasties differing in their tip angles, the results of the lengthening effects strongly supported previous laboratory studies with dog trunks.

The results of our analysis agreed well with the laboratory results in dogs and suggest that our models simulate the behaviors of the Z-plasty. As for clinical guidance, it should be considered that the lengthening effects of the Z-plasty will be smaller than those predicted by geometric calculation.

The lower percentage length gain and the shorter length with the first 2 stress patterns may be due to the flaps being transpositioned without considering the extending effect of pre-tension of the skin. The modeling could be improved by investigating the settings and extending the effects of skin pre-tension.

Conclusion

We analyzed the lengthening effects of different patterns of Z-plasty on a nonlinear elastic skin model using ADINA software. The results of our analysis agreed well with laboratory results in dogs, support the results of earlier experiments, and suggest that our model simulates the behavior of Z-plasties. During actual surgery, we should consider that the lengthening effects of the Z-plasty are less than those predicted by geometric calculations.

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