J. Biomechanics, 1974, Vol. 7, pp. 171-182. Pergamon Press. Printed in Great Britain

TWO-DIMENSIONAL MECHANICAL PROPERTIES OF RABBIT SKIN—II. EXPERIMENTAL RESULTS*

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Abstract—*In vitro* biaxial mechanical properties of rabbit skin were investigated with experimental system reported previously (Lanir and Fung, 1973). The basic mechanical properties of rabbit skin are presented. Their investigation requires appropriate test procedures to ensure reliability of the results. The main features of biaxial stress–strain-history relations in relaxation tests and constant-rate-of stretch tests as well as their dependence on temperature are presented and discussed.

INTRODUCTION

The mechanical properties of skin are important indicators of pathological situations (edema, Ehlers–Danlos syndrome, wound healing etc.). Precise knowledge of the mechanical properties of the skin will be of great value to plastic surgeons in designing the size, shape and orientation of skin grafts.

Mechanical tests of skin reported so far were mainly associated with specific test conditions with an attempt either to standardize them for clinical use or to construct a rheological model based on the data obtained. Papers in the literature show that indentation tests (Kirk and Kvorning, 1949; Sokoloff, 1966) are repeatable, nontraumatic and relatively easy to perform in clinical conditions. The same applies to *in vivo* torsional tests (Finlay, 1970; Vasblom, 1967; Duggan, 1967) and *in vivo* uniaxial stretching tests (Kenedi *et al.*, 1964). On the other hand, skin-fold and viscous-compressibility tests (Tregear, 1966; Clegg and Kent, 1967; Hickmann *et al.*, 1966), as well as tests involving inflation or suction of a circular membrane (Grahame and Holt, 1969) are associated with both the elasticity of the skin and the fluid permeability through it; such tests are difficult to interpret. The simplest *in vitro* tests are uniaxial tension tests (Ridge and Wright, 1964; 1966) in which the effect of the surrounding tissues is completely eliminated.

These *in vivo* and *in vitro* tests can yield some information on the mechanical properties of the skin, but they do not yield a complete three-dimensional stress–strain-history relationship and are therefore insufficient for any detailed exploration of the mechanics of the skin in surgery and physiology. The effects of the surrounding tissues are unknown in the *in vivo* tests. The uniaxial tests are limited in scope. Attempts to compare the results of different tests (Tregear, 1966; White *et al.*, 1971) have not met with great success mainly because it is difficult to extrapolate from several partial tests to gain a whole picture. A comprehensive three-dimensional model of the skin can be constructed only on the basis of three-dimensional tests. Fortunately, the skin may be regarded as an incompressible material (for which the bulk modulus is many orders of magnitude larger than the shear modulus and Young's modulus).‡ For an incompressible material any change in the third dimension can be calculated from the changes in the other two dimensions. Therefore a complete three-dimensional model can be derived from a complete two-dimensional test. For the skin, a complete two-dimensional test has not been reported so far because of obvious difficulties in controlling load and stretching on several boundaries at the same time. In a previous article (Lanir and Fung, 1973) the authors report details of a two-dimensional experimental system that was developed at UCSD and used for testing rabbit skin. In the present work the results of those tests are reported.

* *Received* 15 *April* 1973.

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‡ This is believed to be true in the physiological stress range considered in the present paper. Hard data for the skin are lacking. In the case of arteries, Carew *et al.* (1968) have shown that the bulk modulus is about 1000 times the Young's modulus when the mean pressure in the artery is 100 mm Hg, corresponding to a Poisson's ratio of 0·4998 in a linear incremental relation between stress and strain. The compressibility is often attributed to the movement of water in or out of the tissue. The permeability of the skin is comparable with that of the artery; hence incompressibility in the physiological stress range may be assumed. If a much higher stress level was considered, for example, in studying tearing or breaking of the skin, this assumption is not valid.

PREPARATION OF THE SPECIMEN

Specimens from 47 albino male rabbits, weighing between 2·2 and 2·8 kg were tested. The rabbits were sacrificed by injection of sodium pentobarbital and thoroughly shaved in the belly area. A rectangular specimen from an area exterior to the nipple line was separated from the fatty layer and removed. Prior to this its dimensions *in situ* while the rabbit was lying on its side with legs in normal angle to the body were measured. The specimen was allowed to relax for 15 min on a lucite plate moistened with normal saline solution. The relaxed dimensions were measured for evaluation of the *in vivo* extension ratios. A rectangular specimen of 35 × 35 mm was cut out in such a manner that two boundaries were parallel to the body length direction and two boundaries were normal to it. The volume of the specimen was calculated from the weight of the specimen in air and in normal saline. The volume was used to evaluate the thickness of the specimen (Ellis, 1969). The specimen was then stapled on its edges by 36 equally spaced small staples (TOT 50 Swingline), which were connected by silk threads to 4 force distributors (Lanir and Fung, 1973) inside a specially designed temperature controlled bath tray. Sudan black dissolved in alcohol was used to paint two pairs of straight black lines on the top (epidermis) side of the skin. The open compartment of the bath tray was filled with normal saline, the lower, closed compartment was connected to the thermoregulator, preset at a selected temperature. The specimen was allowed to relax for another 15 min while floating in the solution. Its relaxed dimensions were then measured both manually and by the electro–optical video dimensional analyzer (Lanir and Fung, 1973). Any further measurements of the specimen's dimensions were done by the video dimensional analyzer.

METHOD

Several kinds of tests were carried out:

1. Biaxial slow-rate-of-stretching tests in which the rectangular specimen is stretched in one direction at a constant rate (0·02, 0·2 and 2·0 mm/sec) while the dimension in the other direction is kept constant.
2. Uniaxial slow-rate-of-stretching tests in which the specimen is stretched in one direction at the constant rates named above, while no load is applied on the edges in the other direction.
3. Biaxial relaxation tests in which the specimen is quickly stretched (at a speed of about 80 cm/sec) in one direction while the dimension in the other direction is kept constant. At the end of stretching the dimensions are kept constant while the stress relaxes.
4. Uniaxial relaxation tests in which the specimen is quickly stretched in one direction while the other edges are left free. At the end of stretching the length of specimen is kept constant.
5. Effect of temperature on biaxial relaxation rests.
6. Effect of temperature on relaxed stresses when the specimen is kept in constant dimensions.

These experiments yield information on the constitutive equation of the skin and the effect of temperature on it. In addition, experiments were performed to check the uniqueness of the unstressed configuration, repeatability of data, preconditioning procedures, effect of swelling, degradation of the material with time, and the orthotropy of the material.

RESULTS

In the following we present findings relating to some basic mechanical properties of rabbit skin:

1. *Repeatability of results*

In a living skin metabolic activity is always present. How does metabolism in the skin affect its mechanical behavior? This question will be examined from several points of view.

a. *Preconditioning.* It is known (e.g. Fung, 1971) that successive cyclic uniaxial tests of tissue yield unequal results which converge as the number of cycle increases. Hence, one way to ensure repeatability of results is to precondition the tissue by carrying out a test procedure several times until the results converge. It was found in the present work that biaxial tests require biaxial preconditioning; i.e. by repeating the biaxial procedure a number of times, rather than by performing successive uniaxial procedures in different directions.

b. *Dispersion of results.* Results of identical mechanical tests vary about a mean. Relaxation curves can be defined in the statistical sense of ensemble averages after preconditioning (see Fig. 1).

c. *Uniqueness of unstressed configuration.* The question of the existence of a unique unstressed configuration of a skin specimen is of great importance. Not all viscoelastic materials have unique unstressed configurations: elastic materials, Voigt materials, and Kelvin materials do; Maxwell materials do not. If it exists, then all deformations may be referred to the unique unstressed configuration, and we can speak of well-defined strain components. If it exists, then a unification of different kinds of tests is possible.

Our tests on rabbit skin indicate that if a specimen is allowed to relax for a sufficiently long time after any biaxial testing, the dimensions of the specimen will return to those of the initial unstressed configuration provided that at no point during the testing history

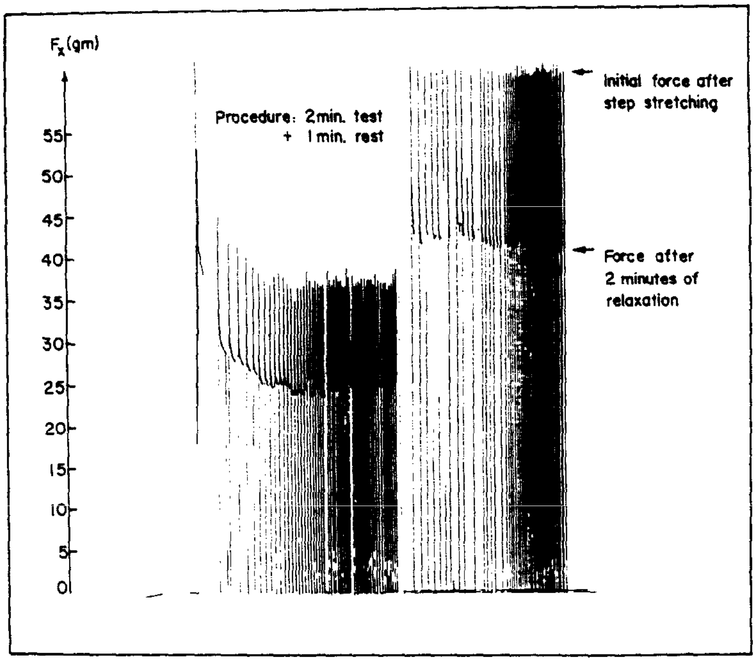

Fig. 1. Display of results of two sets of successive identical relaxation tests performed on two specimens. Vertical axis shows force. Horizontal axis indicates time (approximately in log scale). Each test lasted 2 min and was followed by 1 min rest. Note preconditioning pattern on the first few cycles of the first specimen, and regular patterns after preconditioning.

was any surface dimension allowed to decrease below its value in the initial unstressed configuration. The condition of the absence of negative strain seems to be quite imperative with regard to the uniqueness of unstressed configuration. Note that this condition is not met in an uniaxial tension test, in which the lateral dimensions are allowed to shrink. It is not surprising, then, that a specimen often fails to return to the unstressed state after uniaxial tension tests.

In practical experiments, however, it is impractical to wait a very long time between successive tests. The approach adopted in this work was to observe that each kind of test has a unique equilibrium configuration of its own to which all results of this kind of tests are related. All these equilibrium configurations are related in turn to the initial unstressed configurations.

d. *Degradation of the specimen with time.* This question was checked in special tests in which specimens were mounted, preconditioned, tested, allowed to relax in cold ($\sim 10^\circ$C) normal saline for 24 hr and then preconditioned and tested again in an identical manner. The results showed no degradation. Repetition at room temperature again showed no degradation. For additional confidence—in most of the regular tests (excluding the tests in which the tissue was irreversibly altered by fast changes of temperature)—the first test of a series was repeated in the end. No significant degradation was observed in any of the specimens.

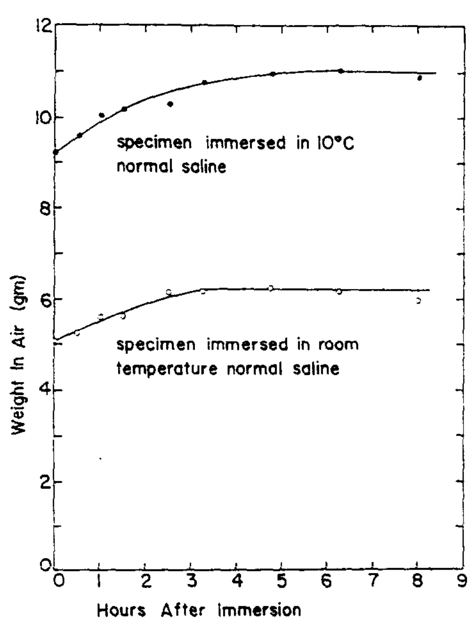

Fig. 2. Time course of swelling of two fresh specimens immersed in normal saline solution at different temperatures. Swelling is expressed as weight in air.

2. *Effect of swelling*

The skin specimens swell in the saline bath. As a result their volume increased. Figure 2 shows the time course of swelling of two fresh rabbit skin specimens. One feature seen from Fig. 2 is that most of the swelling takes place within 3–4 hr after immersion. In order to eliminate the possibility of different effects of swell-

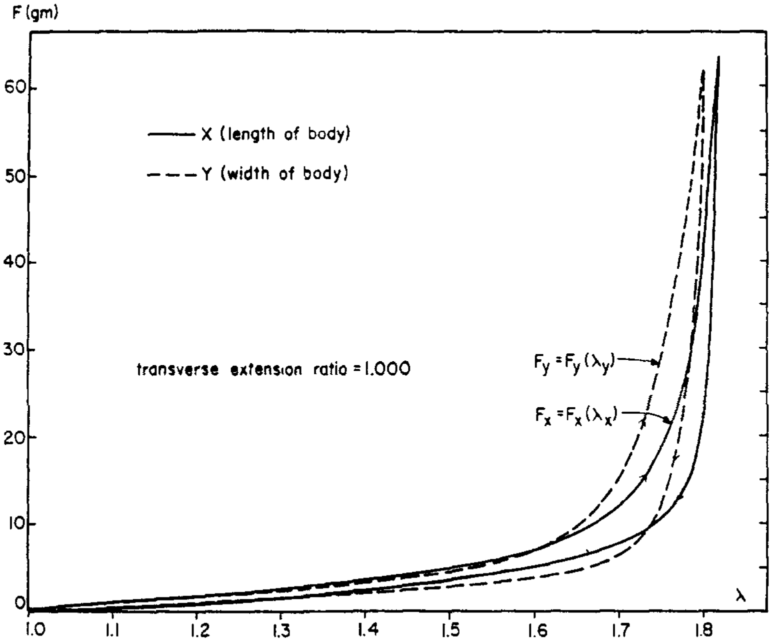

Fig. 3(a)

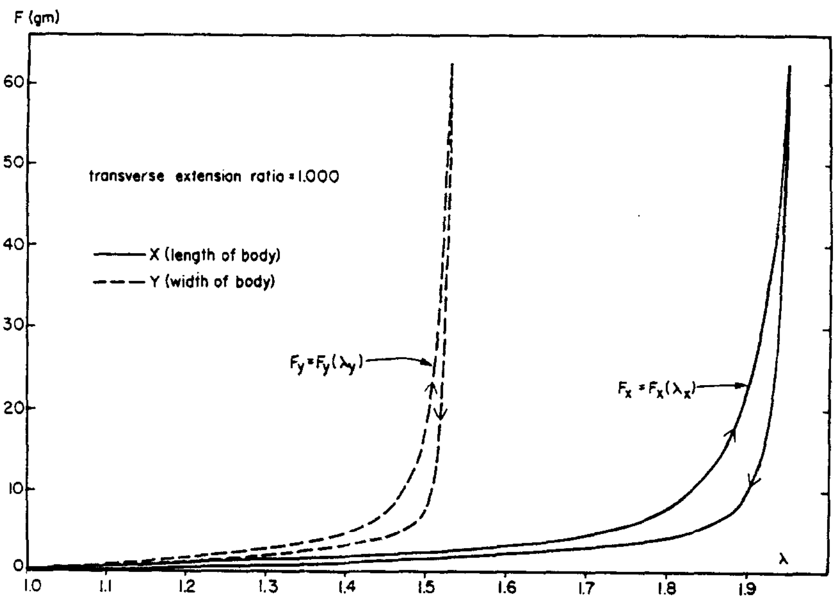

Fig. 3(b)

Fig. 3. Variation of anisotropy in different specimens. (a) A specimen with similar responses in two normal directions. The solid curve refers to a biaxial stretch in the direction along the length of the body while the transverse direction is kept at the relaxed dimension. The dotted curve refers to stretching in the direction of the width of the body. Tension in the direction of stretching is shown. (b) A specimen with different responses in two normal directions.

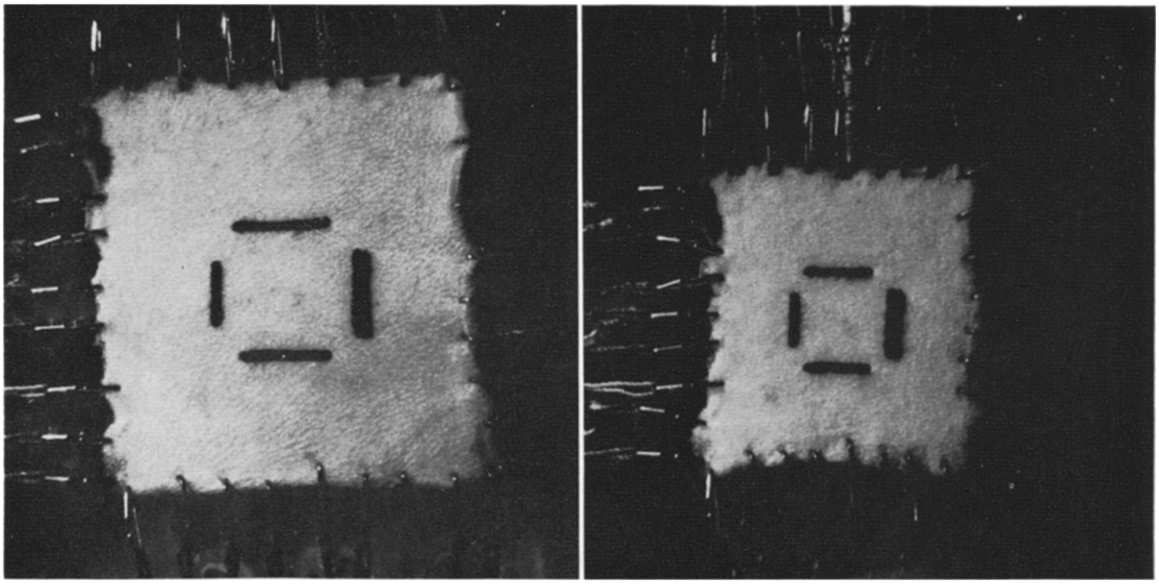

Fig. 4. Photograph of a specimen before and after stretching. The x-direction is along the length of the body. Note the stretching of the black lines marked on the skin. These lines did not rotate.

(*Facing p.* 174)

ing on the results, all specimens were allowed to swell for 4 hr before data was collected.

The effect of swelling on the mechanical behavior of rabbit skin was checked as follows. Uniaxial tension tests of vertically mounted fresh specimens were performed in an Instron machine with the specimens exposed to air. The results were compared with those of an identical test performed on the same specimens after immersion in normal saline solution for 4 hr. The comparison showed that the swelling affects the mechanical behavior considerably: it decreases the stress for equal strain. This result raises the question of the relevance of the *in vitro* tests to the *in vivo* condition. More precise tests of the effect of swelling are needed in order to arrive at a correct interpretation of the results of *in vitro* tests.

3. *Isotropy*

It is generally accepted in the literature that skin *in vivo* is anisotropic (Langer, 1861; Finlay, 1969; Gibson *et al.*, 1969). Relaxed skin *in vitro* is anisotropic as well (Ridge and Wright, 1966; Kenedi *et al.*, 1964). The anisotropy of rabbit skin can be easily demonstrated in a biaxial test by comparing results of two identical tests performed in two normal directions. In the present work it was found that the surface anisotropy (anisotropy of quantities measured in the surface of the skin) of comparable specimens from different animals vary greatly. Compare Figs. 3a and b. The rabbit skin, although anisotropic, seems to exhibit a symmetry with respect to two normal planes, i.e.—it is orthotropic. Those planes are associated with the preferred orientation of the collagen fibers in the skin. A strong indication of the orthotropy is the fact that upon homogeneous stretching in the directions of the length and width of the body the stained black lines on the specimen (parallel to the direction of stretching—see Lanir and Fung, 1973) do not rotate (see Fig. 4). This suggests the absence of shear strain in the xy-direction.

Anisotropy of the rabbit skin in the direction normal to its surface is demonstrated in Fig. 5. A specimen was stretched in the longitudinal direction while the transverse direction was stress free. The dimensions in both x- and y-directions were measured simultaneously. The thickness was calculated from the condition of incompressibility. It is seen that the two stretch ratios λ_y and λ_z in the directions perpendicular to the longitudinal axis change in different manner. If the material were isotropic we must have $\lambda_y = \lambda_z$ in this case.

4. *Stress–strain relations*

Stress–strain relations of rabbit skin are time dependent and therefore not unique. Fung (1971) suggested that for soft tissues in a wide range of strain rates the stress–strain relationship is insensitive to the strain rate in a constant strain-rate test, but is different in loading and unloading. Consequently he felt that if a stretching is imposed instantaneously (as a step function), the instantaneous stress obtained will be a unique function of the strain. He calls this instantaneous response the 'elastic response'. This point will be discussed later in view of the present results. On the other hand, Patel and Janicki (1970) stretched canine arteries biaxially in a sequence of inflation/deflation and extension/contraction steps and found (a) no significant hysteresis if stresses are measured every time after a relax-

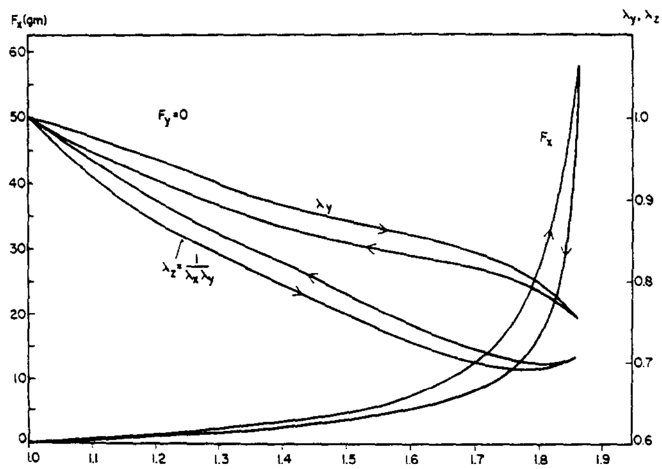

Fig. 5. Response of rabbit skin in a uniaxial tension test. Stretching in x-direction (length of body) at a constant rate. F_x = load in stretched direction; λ_y = stretch ratio in the direction of body width; λ_z = stretch ratio in the direction perpendicular to the skin calculated under the assumption of incompressibility of the skin.

ation of 1 min, (b) the final stress corresponding to the same strain was equal in any different sequences of steps.

This result suggests that in a dog's arteries the relaxed stress is uniquely related to the strain. The validity of this result in other kinds of tissues is an open question which need to be tested experimentally.

The preliminary results obtained so far point to some difficulties in the exact interpretation of the results of biaxial tests of rabbit skin. Experimental data must be cautiously examined before any conclusions can be reached. With this in mind we proceed to present the results of our tests:

1. Biaxial slow-rate-of-stretch tests yielded results represented in Fig. 6. Several features are noticeable: (a) Stress–strain relations are nonlinear—the stiffness of the tissue increases with increasing strain. (b) Considerable hysteresis exists in all strain rates. (c) The stress–strain relations are only slightly dependent on the strain-rate: Higher strain-rate increases the stress. (d) The descending curve does not terminate in the origin. A preconditioned specimen will return to the original dimensions only after a long period of relaxation.

Results of biaxial stretch test at constant rates of stretch performed on the same specimen in two different directions—first stretched in the x-direction, then stretched in the y-direction, with the transverse stretch ratio kept at 1—are shown by solid curves in Fig. 7. Results of uniaxial tension tests of the same specimen with no load on the transverse edges are also shown in this figure by the dotted curves.

In biaxial stretch tests we control the transverse dimension to keep it constant. Different values of the constant transverse stretch ratio (λ_y) will yield different stress–strain relations, see Fig. 8.

2. A typical result of a uniaxial tension test of rabbit skin is given in Fig. 5. The features of the stress–strain relationship in the stretched direction are similar to those of the biaxial stretch tests. The transverse dimension changes continuously during the test. Calculation of the thickness changes indicate the existence of a minimum thickness which is attributed to buckling of the skin in the transverse direction. Comparison of a uniaxial tension and a biaxial stretch test of the same specimen (Fig. 7) shows that at a given stretch ratio in the loading direction the stress in the uniaxial test is considerably lower than that in the biaxial stretch condition.

3. Relaxation of the force in the main direction in a biaxial relaxation test followed patterns shown in Fig. 9. The transverse force relaxes in a similar fashion. One immediate feature noticeable is that the relaxation curve depends on the strain or initial stress, i.e. the curves do not normalize to a single curve independent of strain or initial stress. Hence the rabbit skin is not linear with respect to time dependency. Another feature is that in low stretch ratios the loads relaxed up to a certain value within the observation period (10 min) and stayed in those values thereafter.

The concept of 'elastic response' suggested by Fung (1971) seems to be valid in the case of rabbit skin. Figure 10 shows a comparison between the forces reached immediately after the step stretches in the biaxial relaxation tests (filled circles) and those arrived

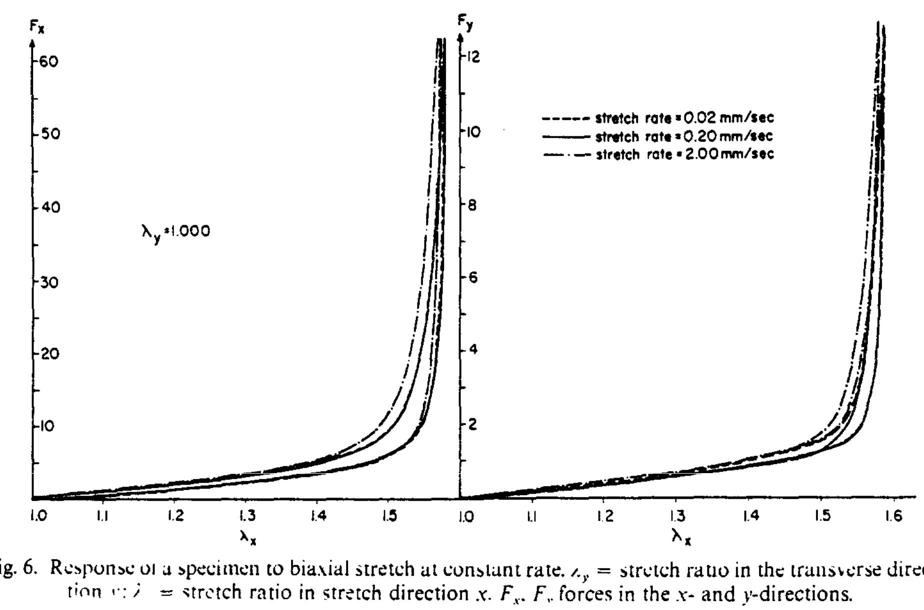

Fig. 6. Response of a specimen to biaxial stretch at constant rate. λ_y = stretch ratio in the transverse direction y; λ = stretch ratio in stretch direction x. F_x, F_y forces in the x- and y-directions.

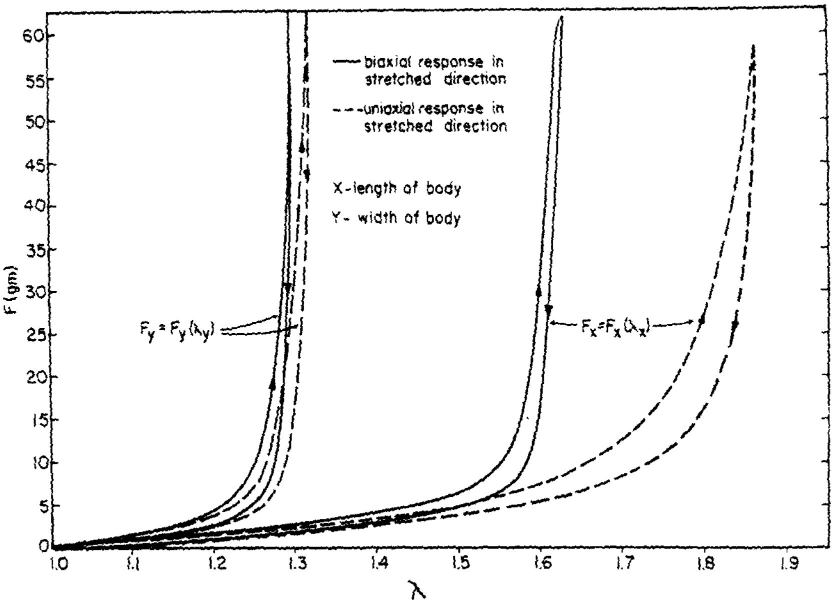

Fig. 7. Response of a specimen to stretch tests in two normal directions. Solid lines—responses in biaxial tests. Broken line—responses in uniaxial tension tests. See test.

by a slow, constant-rate-of-stretch test (solid curves) on the same specimen. The strain-rate of the step loading (corresponding to the dots) was about 800 mm/sec; that of the slow stretch test (solid curves) was about 0·02 mm/sec, a difference of 40,000-fold. The dispersion of the dots around the curves is due to transient problems in the stretching mechanism. The general agreement between the dots and the curves indicates again the low sensitivity of the stress–strain relations to strain-rate.

The difference in the relaxation functions in the stretched direction (x) and transverse direction (y) is shown in Fig. 11. This refers to a single biaxial relaxation test. It is evident that the relaxation functions in the two directions cannot be normalized to a single curve. This suggests that the relaxation phenomenon is

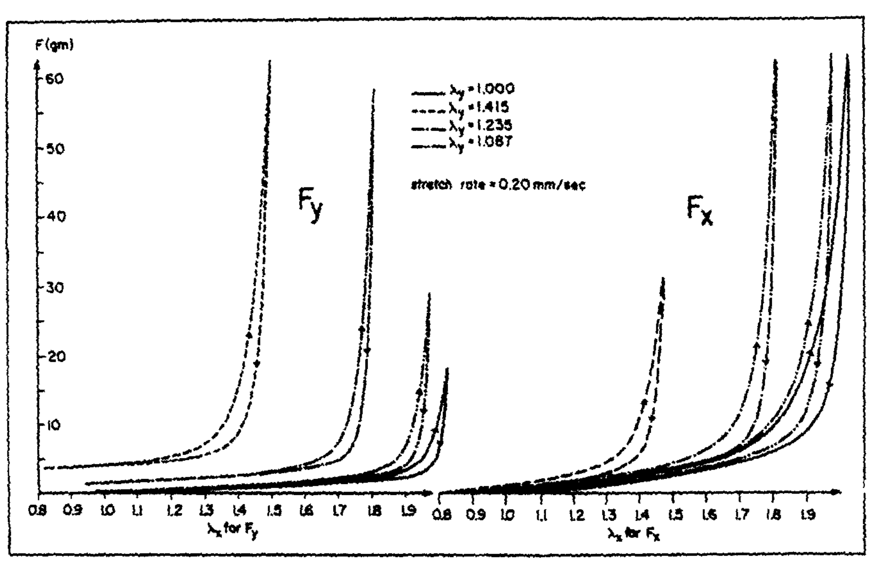

Fig. 8. Variation of the response to biaxial stretch with various values of the transverse stretch ratio (λ_y).

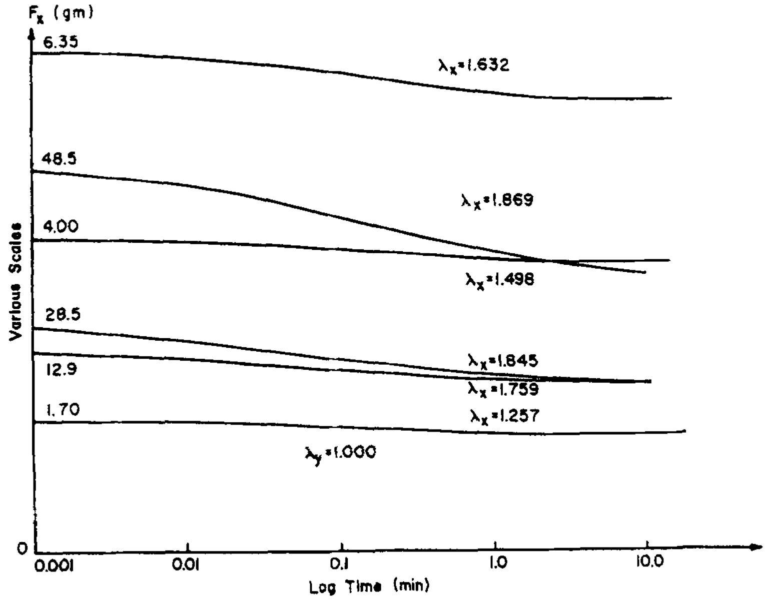

Fig. 9. Relaxation of load in the x-direction after a step stretch to λ_x in the x-direction while the stretch ratio in the transverse direction, λ_y, is kept at 1. The various curves have different scales for load.

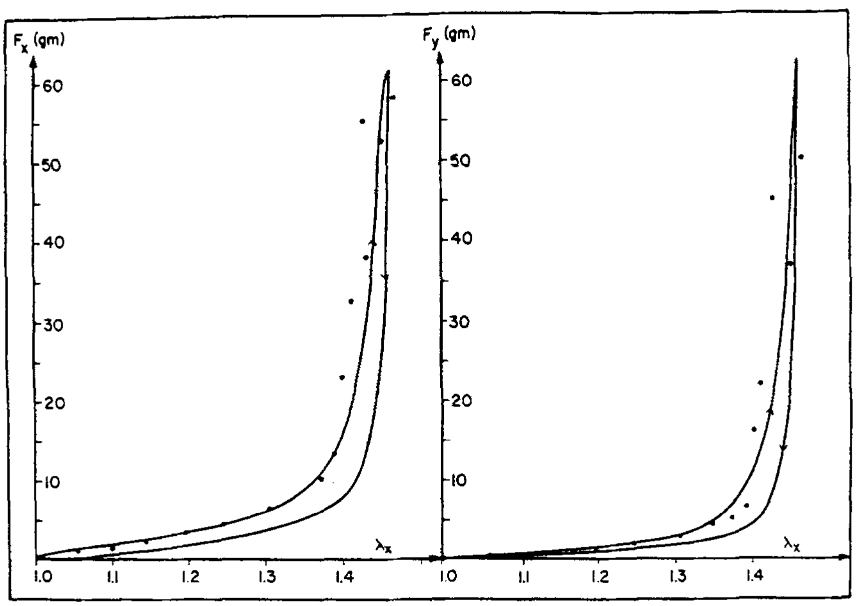

Fig. 10. Comparison between the forces reached immediately after the step stretches in the relaxation tests (filled circles) and those arrived by a slow, constant-rate-of-stretch test (solid curves) on the same specimen.

a complicated one—it probably involves internal changes of oriented fibers in the tissue.

4. Relaxation after a step uniaxial stretch while the transverse edges were free and without loading yielded results shown in Fig. 12. The force in the stretched direction relaxes in a manner similar to that in biaxial stretch tests. The transverse dimension, however, is not constant, but changes continuously during the relaxa-

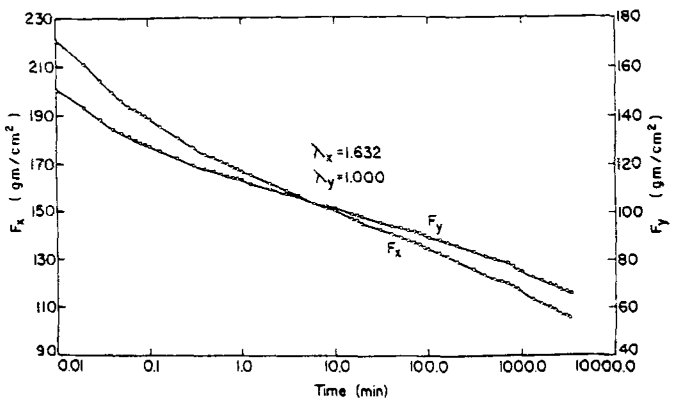

Fig. 11. Comparison between relaxation of load in the main direction (F_x) to that of the load in the transverse direction (F_y) following a step stretching in the x-direction while the dimension in the y-direction was kept constant.

tion process. The extent of that change in transverse dimension is about 5 per cent in 10 min. It seems that a uniaxial relaxation test is not a true relaxation test in the sense that all dimensions are not constant. This result again points to the adaptation of the tissue to stretching, by reorientation of the collagen fibers to decrease both the transverse dimension and the stress in the stretched direction.

5. Temperature affects the mechanical properties of rabbit skin in a variety of manners, of which only a few have been tested in the present work.

Figure 13 shows the results of a test in which the

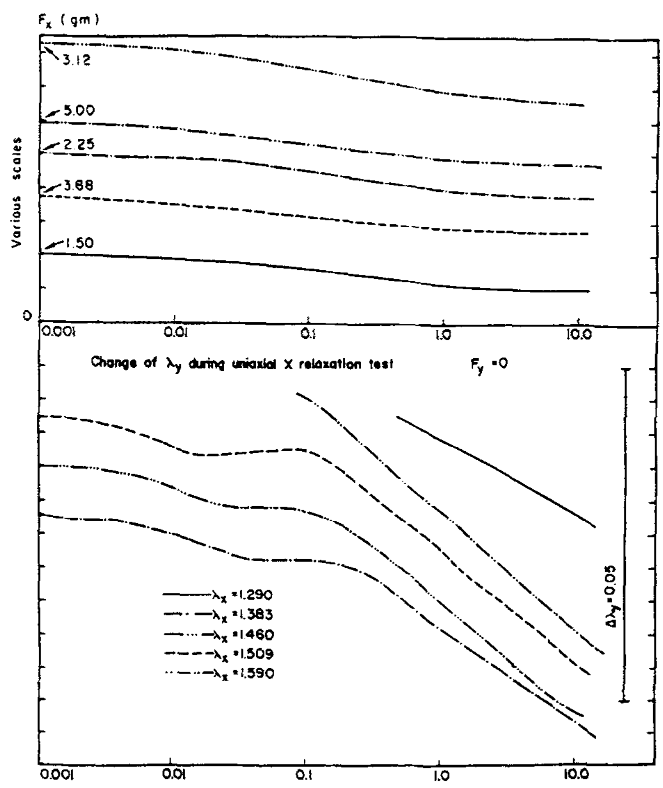

Fig. 12. Response of specimen to uniaxial step stretch. The transverse edges were free. Upper part: relaxation of load with time (the various curves have different scales). Lower part: change of transverse dimension during relaxation process.

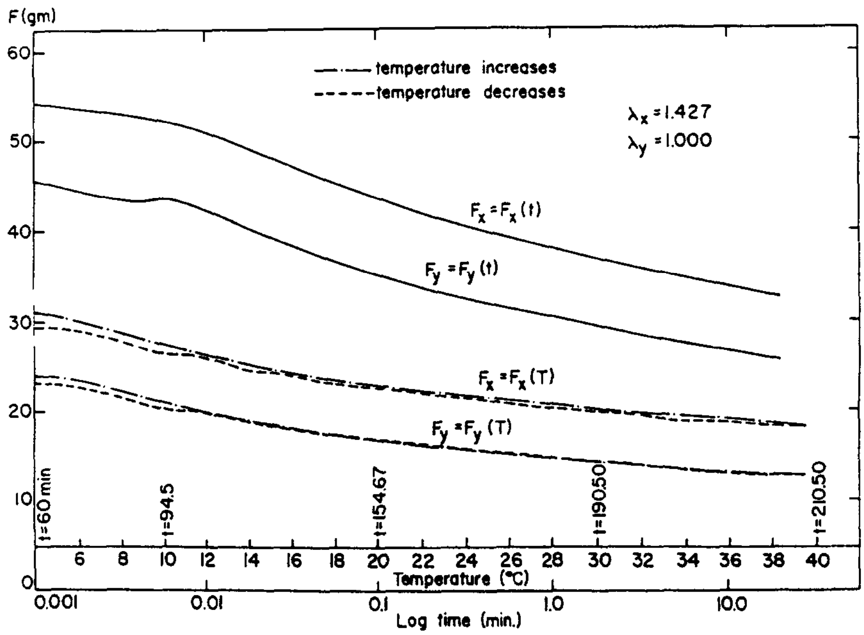

Fig. 13. Biaxial relaxation and variation of relaxed stresses with temperature. *Upper solid curves*: Stress relaxation after a biaxial stretch. Forces F_x, F_y are plotted against time t. *Lower curves*: At the end of 1 hr, temperature was first increased and then decreased. Rate of change of temperature $\cong$ 0·23°C min. Note similarity of curves of increasing and decreasing temperature.

specimen was biaxially stretched and then allowed to relax under constant dimensions for one hour. Its temperature was then increased very slowly (~0·23°C per minute) up to 40°C and decreased back to about 4°C. The curves of increasing and decreasing temperature are similar and the whole cycle was repeatable. When this cycle was carried out faster the ascending and descending curves became dissimilar. Those curves

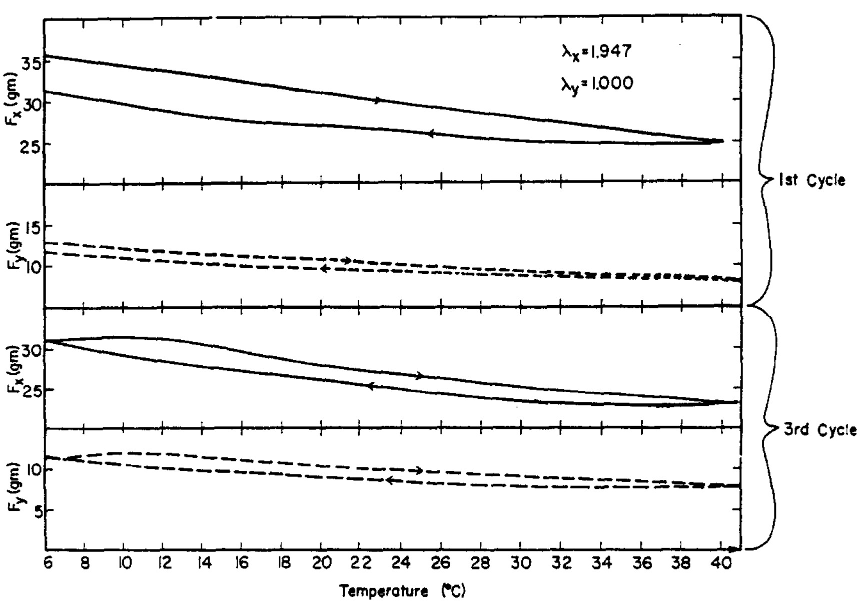

Fig. 14. Variation of relaxed biaxial stresses under rapidly changing temperature (2·7°C/min). Upper two curves—first cycle; Lower curves—third cycle.

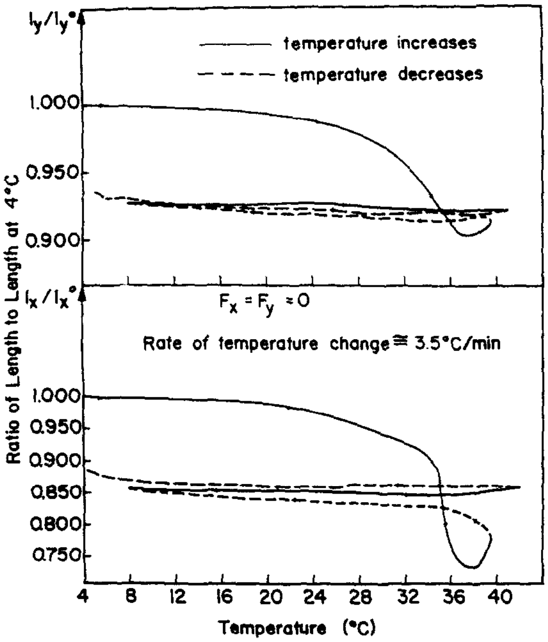

Fig. 15. Variation of equilibrium dimensions (in two normal directions) under subsequent cycles of rapidly changing temperature.

became repeatable only after two more similar cycles, see Fig. 14. It seems that in cases of rapidly changing temperature the tissue requires 'temperature preconditioning' in order to obtain repeatable results.

A similar phenomenon was observed when the dimensions under zero forces were measured under rapidly changing temperature, see Fig. 15. The first cycle was not repeatable and the dimensions changed considerably. In the subsequent cycles the changes of the dimensions with temperature were much smaller.

The effect of temperature on the relaxed forces at constant dimensions depends on the stretch ratios of the specimen, see Fig. 16. In low stretch ratios increasing temperature will increase the forces. In higher stretch ratios the loads will decrease with increasing temperature. This behavior is similar to that of rubber and is the basis of the attempt to deal with skin as a rubbery material with respect to its mechanical properties (King and Lawton, 1950; Saunders, 1964).

CONCLUSION

Biaxial mechanical tests are an important tool for the investigation of tissues. It was found, however, that

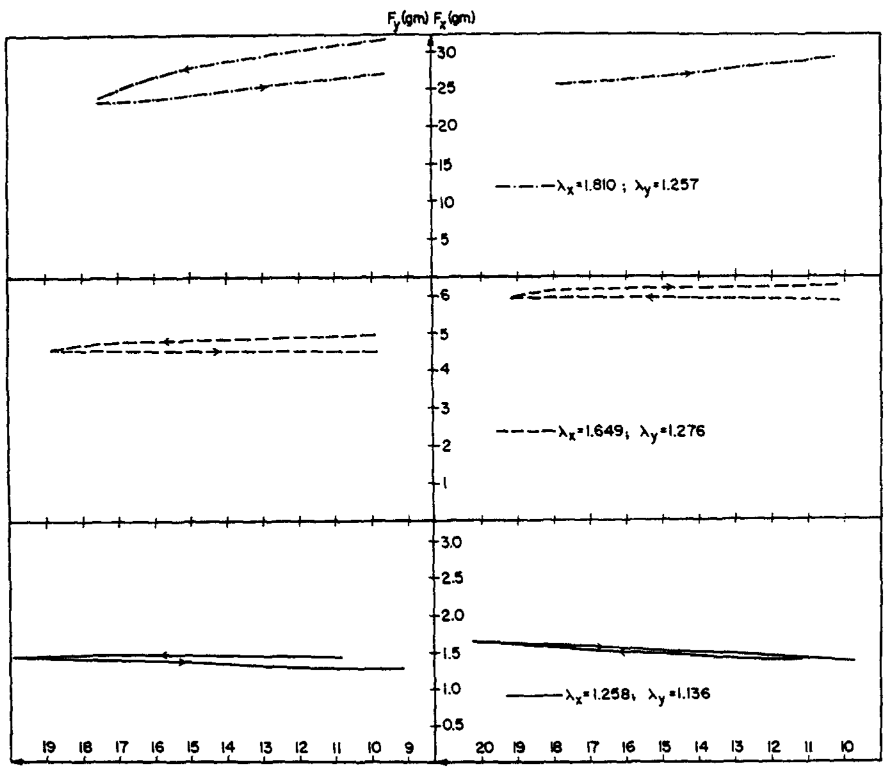

Fig. 16. Variation of relaxed stresses under rapidly changing temperature for different values of stretch ratios.

in the case of skin the results of mechanical tests must be interpreted cautiously, and that the tests must be performed carefully due to special properties of the tissue: Results are not repeatable under certain conditions and are always dispersed; a preconditioning process is necessary; the equilibrium configuration is hardly obtainable during the test procedure and can only be related to the fully relaxed configuration indirectly. The tissue swells considerably in normal saline during the first 3–4 hr but is quite stable afterwards (for at least 24 hr). The skin is anisotropic in its mechanical properties, but probably possesses orthotropic symmetry.

The mechanical tests showed that strain is uniquely related to the initial stress after a step increase in the strain, thus confirming Fung's (1971) hypothesis ('elastic response'). Biaxial stress–strain relations in constant-rate-of-strain tests are nonlinear, and only slightly dependent on the strain-rate. They exhibit considerable hysteresis. Similar uniaxial tension tests (with no load on the transverse edges) result in lower stresses. Biaxial relaxation tests yield results which do not normalize to a single curve, thus pointing to nonlinearity of time dependence and invalidity of Boltzman hypothesis for rabbit skin. Loads in specimens subjected to low stretch ratios relax comparatively fast to a stable value. The initial stresses of biaxial relaxation tests agree well with the stress–strain relations in constant-rate-of-strain tests (ascending part) which confirms the concept of 'elastic response'. Uniaxial relaxation tests were found to be not true relaxation tests due to considerable changes in the transversed dimensions during the relaxation process.

The temperature effect on the mechanical properties depends both on the rate of temperature change and on the strains and stresses in the tissue. Fast changes of the temperature yield unrepeatable results in the first few cycles. In low stretch ratios, increasing temperature will increase the loads but in high stretch ratios the effect is reversed—a behavior similar to that of rubber.

Acknowledgements—Support of this work by USPHS-NIH National Heart and Lung Institute through Grant HL 12494 and NIH fellowship 1-F03-GM-54, 379-01 and by National Science Foundation Grant GK 32072X is gratefully acknowledged.

REFERENCES

Carew, T. E., Vaishnav, R. N. and Patel, D. J. (1968) Compressibility of the arterial wall. *Circ. Res.* **23**, 61–68.

Clegg, E. J. and Kent, C. (1967) Skinfold compressibility in young adults. *Hum. Biol.* **39**, 418–429.

Dugan, T. C. (1967) Dynamic mechanical testing of living tissues. *Dig. 7th Intl. Conf. on Med. Biol. Eng. Fed. Med. Biol. Eng. Stockholm*, p. 368.

Ellis, D. G. (1969) Cross-sectional area measurements for tendon specimens: a comparison of several methods. *J. Biomechanics* 2, 175–186.

Finlay, B. (1969) Scanning electron microscopy of the human dermis under uniaxial strain. *Bio. Med. Engng* **4** (7), 322–327.

Finlay, B. (1970) Dynamic mechanical testing of human skin *in vivo*. *J. Biomechanics* **3**, 557–568.

Fung, Y. C. (1971) *Biomechanics—Its Foundation and Objectives* (Edited by Fung, Y. C., Perrone, N. and Anliker, M.), p. 181. Prentice-Hall, New Jersey.

Gibson, T., Stark, H. and Evans, J. H. (1969) Directional variation in extensibility of human skin *in vitro*. *J. Biomechanics* **2**, 201–204.

Grahame, R. and Holt, P. J. L. (1969) The influence of aging on the *in vivo* elasticity of human skin. *Gerontologia* **15**, 121–139.

Hickmann, K. E., Lindan, O., Reswick, J. F. and Scanlan, R. H. (1966) Deformation and Flow in Compressed Skin Tissues. *Biomedical Fluid Mechanics Symposium ASME, N.Y.*, pp. 127–147.

Kenedi, R. M., Gibson, T. and Daly, C. H. (1964) *Biomechanics and Related Bio-Engineering Topics* (Edited by Kenedi, R. M.), pp. 147–158. Pergamon Press, Oxford.

King, A. L. and Lawton, R. W. (1950) *Medical Physics* (Edited by Glasser, O.), Vol. II, pp. 303–316. Year Book Pub. Inc., Chicago.

Kirk, E. and Kvorning, S. A. (1949) Quantitative measurements of the elastic properties of the skin and subcutaneous tissue in young adults and old individuals. *J. Gerontol.* **4**, 273–284.

Langer, K. (1861) Zur Anatomie und Physiologie der Haut—I. Uber die spaltbarkeit der Cutis. *S. B. Akad. Wiss. Wien* **44**, 19.

Lanir, Y. and Fung, Y. C. (1974) Two-dimensional mechanical properties of rabbit skin—I. Experimental system. *J. Biomechanics* **7**, 29–34.

Patel, D. J. and Janicki, J. S. (1970) Static elastic properties of the left coronary circumflex artery and the common carotid artery in dogs. *Circ. Res.* **27**, 149–158.

Ridge, M. D. and Wright, V. (1964) *Biomechanics and Related Bioengineering Topics* (Edited by Kenedi, R. M.), pp. 165–175. Pergamon Press, Oxford.

Ridge, M. D. and Wright, V. (1966) The directional effect of skin—a Bioengineering study of skin with particular reference to Langer's lines. *J. Invest. Dermatol.* **46** (4), 341–346.

Saunders, D. W. (1964) *Biomechanics and Related Bioengineering Topics* (Edited by Kenedi, R. M.), pp. 301–319. Pergamon Press, Oxford.

Sokoloff, L. (1966) Elasticity of aging cartilage. *Fed. Proc.* **25** (3), 1089–1095.

Tregear, R. T. (1966) *Physical Function of Skin*. Academic Press, New York.

Vlasblom, D. C. (1967) Skin elasticity. *In vivo* measurements of small deformation. *Dig. 7th Int. Conf. Med. Biol. Eng.*, p. 369. Stockholm.

White, W. L., Brody, G. S., Glaser, A. A., Marangoni, R. D., Beckwith, T. G., Must, J. D. and Lehman, J. A. (1971) Tensiometric studies of unwounded and wounded skin: Results using a standardized testing method. *Ann. Surg.* **173** (1), 19–25.