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TWO-DIMENSIONAL MECHANICAL PROPERTIES OF RABBIT SKIN—I. EXPERIMENTAL SYSTEM*

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Abstract—An experimental system for two-dimensional tests of soft tissue was developed. It can perform *in vitro* two-dimensional tests at different rates (up to 6·0 mm/sec) as well as two-dimensional relaxation and creep tests. Effect of the temperature on two-dimensional stresses and strains can also be measured. Data reduction is greatly improved with the help of on-line PDP 8/e computer.

INTRODUCTION

Many investigations of the mechanical properties of tissues have been carried out in recent years. In the majority of the cases the experiments were limited to one-dimensional tests because of the difficulties in controlling simultaneously two or three-dimensional boundary conditions. Soft tissues are subject to large deformations for which one-dimensional data cannot be generalized to yield the three-dimensional constitutive equations. Very few investigators dealt with two-dimensional tests. Lee *et al.* (1967) controlled extension and inflation of several blood vessels. Similarly Doyle *et al.* (1971) investigated the carotid artery of the dog. Blatz *et al.* (1969) investigated fan-shaped segments of mesentery of cats and rabbits. Patel and Janicki (1970) investigated the *in vitro* static properties of both the left circumflex coronary artery and the common carotid artery of the dog.

It has been generally accepted in the literature that biological tissues are incompressible. In incompressible tissues one can obtain three-dimensional mechanical properties from two-dimensional tests.

In the present article we wish to describe an experimental system for the measurements of two-dimensional properties of tissues. It was developed and is successfully used for the skin.

GENERAL DESCRIPTION

Our objective is to establish the stress–strain-history relations of the tissue by measuring the force-length-time relations. The system is an optomechanical system designed to measure two-dimensional mechanical properties of thin specimens of rectangular planform. It consists of three independent units: a milieu measurement and control unit, a stretching and force measurement unit and an electronic dimensional analysis unit. In addition, this system contains an optional electronic feedback system which controls the stretching unit.

MILIEU MEASUREMENT AND CONTROL

The rectangular specimen floats in physiological saline solution contained in an open-to-atmosphere upper compartment of a double compartment tray. The lower compartment is a part of a thermoregulation system. Water of specified temperature is supplied by a temperature regulator (Lauda K-2/R, Brinkmann Instruments, W. Germany). The temperature of the saline is continuously monitored by means of electronic thermometer (TeleThermometer, Model 46 TUC, Yellow Springs Instruments Co., Inc.) which has reading resolution of 0·05°C. The room temperature is regulated and can be varied according to needs. The solution is slowly circulated, compensated for evaporation from time to time, and maintained at pH 7·4 by bicarbonate buffer.

It was found that after stabilization, the saline temperature is constant up to a variation of 0·05°C.

STRETCHING MECHANISM

The specimen is hooked along its four edges by means of small staples (up to 68 in number). Each hook is connected by means of a silk thread to a screw on one of the four force-distributing platforms (see Fig. 1). This set up allows individual adjustment of the tension of each thread. The force-distributing platforms are bridged over the edges of the saline tray in an identical manner for both directions (Fig. 2). One platform is rigidly mounted to the carriage of a sliding mechanism

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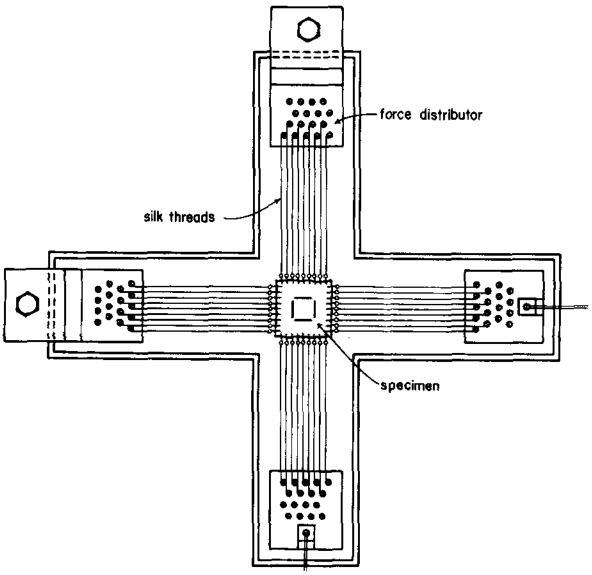

Fig. 1. Setup of specimen hooking and force distribution.

(Unislide, Model A-1500 by Velmex, Inc., New York) and the opposite platform is horizontally attached to a force transducer (Statham silver cell; force 0–60 g, max. displacement 0·12 mm) while at the same time hanging vertically from a cantilevered support. Both the support and transducer are rigidly connected to the carriage of another sliding unit. A pulley system on this carriage allows the force distributor to be pulled by a constant weight on top of the force exerted by the transducer. The carriages of the opposite sliding units are displaced by means of an interconnected threaded drive-shaft. The threads of the left and right sliding units are pulled by the drive shaft at equal rate in opposite directions so that the specimen can be stretched or contracted without changing its location.

This set up can perform two general types of stretching: a controlled stretching at a slow rate and a quick-stretching.

In the controlled slow-rate experiments the two drive-shafts are connected to a sprocket gear mechanism driven by electric motors (Model NSH 55 RH-Bodine Electric Company, U.S.A.). The motors are controlled by Minarik control boxes (Minarik Electric Co., U.S.A., Model W-36). The speed of stretch can be varied from 0·02 to 6·0 mm/sec.

In quick-stretching operations (associated with relaxation and creep experiments), the sliding carriages are disconnected from both the driving mechanism and from each other. A quick stretch is obtained by a direct application of force on the sliding carriages. Upon

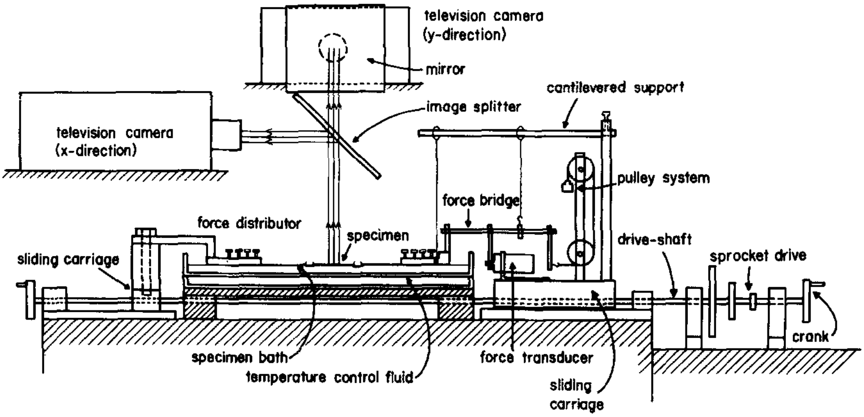

Fig. 2. Schematic view of stretching mechanism in one direction and optical system.

releasing the simple trigger mechanism which is made of a flexible cord and a clamp, the two sliding carriages move until they hit a preset brake. It was found that 'rise time' in this set up was always less than 0·5 sec for displacements up to 40 mm.

The loading strings are approximately parallel when the equipment is in operation. For a specimen varying in size from 3 × 3 to 6 × 6 cm the maximum deviation of the loading strings from the centerline is less than 0·05 rad. Thus at the very corners of the rectangular specimen a shear stress of the order of $\frac{1}{20}$th of the normal stress may exist at the maximum stretch. However, the distance between the 'bench marks' (the black rectangular marks) whose dimensional changes are measured is approximately half of the overall dimensions, therefore the maximum shear stress acting at the corners of the bench marks is expected to be no more than 2 or 3 per cent of the normal stress. These strings are 'tuned' (in the manner of piano tuning by turning a set of screws) at the beginning (during the preconditioning process) in such a way that the rectangular bench marks made on a relaxed specimen remain rectangular upon loading, without visible distortion. It was found that this can be achieved without undue difficulty after some practice.

The deformation of the strings is negligible compared with the stretch of the specimen in the physiological stress range examined in the present investigation (tensile stress of the order of 2 g/mm^2 or 3 lb/in^2). If higher stresses were considered, more rigid loading strings would have to be used. Note that the physiological stress range is far below the tearing strength or ultimate strength of the skin, which may be three orders of magnitude larger.

DIMENSIONAL ANALYSIS SYSTEM

The dimensions of the specimen are continuously measured and monitored by a Video-Dimension-Analyzer (VDA). This system consists of three units: a television camera, a video processor* and a television monitor. The video processor provides an analog signal proportional to the horizontal distance between independently selectable levels of optical density, in two independent areas (windows) in the televised scene. (Fig. 3).

The video processor operates directly with the composite video signal from the camera. It utilizes the vertical and horizontal synchronization pulses to define the X-Y coordinates of the windows as well as their height and width. When video signal is within the window it is continuously compared with a preselected voltage which corresponds to shade of grey of the edge being measured. When the raster voltage exceeds this reference, a counting circuit is started. The circuit is stopped by a similar process in the second window, and the count thus becomes a measure of the distance between the desired shades of grey. Each raster line within the windows is processed in the same fashion. The final count is averaged exactly and then presented to a sample and hold circuit which is updated in the next frame when the whole procedure is repeated. The frequency response of the video processor is 20 Hz. It is well within the capabilities of the commercial vidicon cameras, which due to tube persistence have responses of the order of 10 Hz. Details of VDA and other applications have been described by Intaglietta and Tompkins (1972), Tompkins and Intaglietta (1972) and Yin *et al.* (1972).

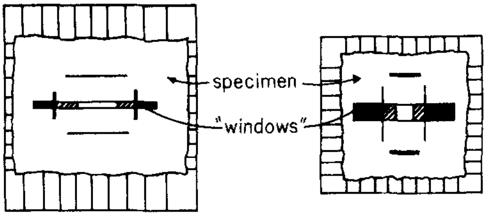

Fig. 3. Typical display of the specimen on the two VDA monitors.

In the present work the strain of the skin was measured in two perpendicular directions. Two pairs of parallel black lines were painted on the specimen. The distance between each pair of these lines was analyzed by an independent VDA. The specimen was observed by two television cameras (Cohu Electronics Model 2810 and RCA PK 20 camera) in two directions by an optical setup consisting of an image splitter (a partial mirror), a complete mirror and a cold light projector (microluminator, Circon Corporation, U.S.A.) see Fig. 2. A typical two-dimensional display of the skin specimen on the television monitors (Conrac Model RVC 17 and KN 89) is shown in Fig. 3. The dimensions were measured on a small middle portion of the specimen (about 10 per cent of the area) thus allowing for dissipation of any irregularities at the edges (e.g. force concentration around the hooks).

ACCURACY OF THE VDA SYSTEM

The accuracy of the dimensional measurements by the VDA is determined by two factors, the resolution of the system and its linearity. The resolution of the VDA is equal to the horizontal resolution of the television camera. In the present work the horizontal

* A commercial version of this processor is available through "Perspective Measurements", 6665 Convoy Court, San Diego, California 92111.

Table 1. Analog output of Y-direction VDA (Cohu camera) for a fixed object at 17 locations across a field

Location	Reading (mV)	Location	Reading (mV)	Location	Reading (mV)
0	398	6	400	12	405
1	394	7	404	13	405
2	394	8	404	14	406
3	395	9	408	15	407
4	396	10	409	16	407
5	398	11	407		

resolution of the RCA camera was 1/600 and that of the Cohu camera 1/900. The measured object occupied between 1/3 and 2/3 of the picture width. Hence the system's resolution was always better than 1/200 or 0·5 per cent.

The linearity of the VDA is again a function of the linearity of the television camera. The linearity of the two VDA systems was checked in two ways:

1. Fixed image at different locations—a fixed image was measured at 17 different locations of the field from extreme left to extreme right. The results for the VDA system with Cohu camera (Y-direction) are shown in Table 1.

The results of Table 1 give an average of 402·176 and S.D. of 5·306 or 1·31 per cent. In actual experiments, extreme right and left locations were never used. If we eliminate those readings we get an average of 402·133 and standard deviation of 5·410 or 1·34 per cent. The results for the VDA system with RCA camera (x-direction) are given in Table 2.

The results of Table 2 yield an average of 355·824 and S.D. of 2·505 or 0·70 per cent. Elimination of location 0, 16 yields average of 355·375 and S.D. of 1·746 or 0·49 per cent.

2. Linear regression line—the field was divided by 48 equally spaced vertical black lines. The distance between each symmetric pair was measured by the VDA and a best fit linear regression line was then constructed (in the least-squares sense). This test resembles closely the actual test conditions. The results for the Y-direction VDA system (Cohu camera) are given in Table 3.

The results of Table 3 yield a linear regression line ($y = bx + a$) with $b = 42{\cdot}1800$, $a = 2{\cdot}7633$, correlation coefficient $r = 0{\cdot}9999$ and S.E. $S_{y \cdot x} = 1{\cdot}8573$. Since the measured object in actual tests occupied more than $\frac{1}{3}$ of the field's width (corresponding to reading of 637 mV)—the S.E. is $\leq 0{\cdot}29$ per cent of the reading.

The results for the X-direction VDA system (RCA camera) are shown in Table 4.

The results of Table 4 yield a linear regression line ($y = bx + a$) with $b = 42{\cdot}3434$, $a = 4{\cdot}0749$, correlation coefficient $r = 0{\cdot}9999$ and S.E. $S_{x \cdot y} = 1{\cdot}8999$, which related to the reading of $\frac{1}{3}$ of the field's width (630) yields 0·30 per cent of the reading.

Overall accuracy—the linearity tests are inherently biased by resolution errors. Since the second linearity test resembles the actual test conditions, the maximum error in the dimensional analysis is the highest among either resolution error or second linearity test error, i.e. 0·50 per cent.

FEEDBACK CONTROL UNIT

The stretching mechanism described above can independently stretch the tissue in two directions according to a prescribed program. In several kinds of experiments, it is, however, necessary to stretch one direction in a manner which is dependent on the behavior of the tissue itself and cannot be arbitrarily chosen.

Table 2. Analog output of X-direction VDA (RCA camera) for a fixed object at 17 locations across the field

Location	Reading (mV)	Location	Reading (mV)	Location	Reading (mV)
0	363	6	354	12	357
1	360	7	354	13	356
2	358	8	354	14	355
3	356	9	354	15	354
4	354	10	355	16	355
5	354	11	356		

Table 3. Analog output of Y-direction VDA (Cohu camera) for various dimensions of centrally located objects

Units distance	Reading (mV)	Units distance	Reading (mV)
1	43	25	1061
3	128	27	1146
5	213	29	1228
7	297	31	1308
9	382	33	1395
11	467	35	1477
13	551	37	1564
15	637	39	1646
17	722	41	1729
19	806	43	1816
21	887	45	1902
23	972	47	1985

Table 4. Analog output of X-direction VDA (RCA camera) for various dimensions of centrally located objects

Units distance	Reading (mV)	Units distance	Reading (mV)
1	43	25	1055
3	125	27	1138
5	209	29	1221
7	292	31	1307
9	377	33	1394
11	461	35	1476
13	545	37	1562
15	630	39	1646
17	714	41	1732
19	800	43	1819
21	884	45	1904
23	968	47	1990

Two examples are (1) Stretching in one direction (X) while keeping the transverse one (Y) constant in length. (2) Creep test—the stretching force is kept constant. In the first case a dimension is controlled. In the second case a force is controlled. Figure 4 shows the scheme of a feedback control unit which performs the above tasks. The setup described in Fig. 4 is for the displacement mode: the transverse direction is 'seen' by the cameras. The output of the analyzer is set to zero; any change in the dimension measured is converted to positive or negative output from the analyzer. This output is amplified by two voltage amplifiers (Cohu, Kintel Division Model 112A) and a power amplifier (Hewlett Packard Power Supply—Amplifier Model 6824A) and supplies the rotor of the driving motor of the transverse direction. The field is supplied constantly with 60 V. The circuit contains a clipper which prevents overloading of the amplifiers. A 50Ω resistor was used to keep a minimum load on the power amplifier.

The quality of the feedback control unit is measured by its ability to keep the transverse direction constant. It was measured in the following way: The output of the transverse VDA analyzer was observed by a Digital Voltmeter (Hewlett Packard Model 3440 with 3444A Multi-function Unit) and compared to the signal corresponding to the equilibrium dimension. It was found that the output never exceeded 2·0 mV in the constant rate of stretch experiments (with rate of stretch up to 2·0 mm/sec). The output corresponding to equilibrium dimension was always above 800 mV. Hence the deviation was less than 0·25 per cent.

CAPABILITY OF THE EXPERIMENTAL SYSTEM

The system described here is capable of performing various types of two dimensional experiments of thin tissues:

1. Slow rate experiments in which the specimen is stretched and then contracted in one direction at rates between 0·02 and 6·0 mm/sec while the other dimension of the specimen is kept constant. The measured quantities are: the forces in the main and transverse direction vs. the extension ratio.

2. Slow rate experiments in which the two transversed dimensions of the specimen are independently changed according to prescribed program. The two transversed forces and two transversed extension ratios can be measured.

3. Relaxation experiments in which the specimen is quickly stretched in one direction while the other is kept constant. Decay of the two transversed forces with time is measured as well as the constant extension ratio.

4. Creep experiments in which the specimen is stretched in one direction at a constant load while the

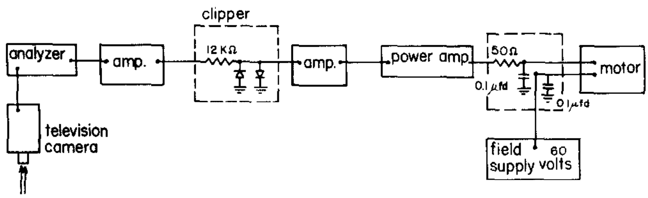

Fig. 4. Scheme of the feedback control unit.

dimension of the other direction is kept constant. The changes of the stretched dimension and transverse load with time is continuously measured.

5. The effect of temperature on the stress–strain relationship, dimensions of the specimen at equilibrium, extension forces at constant dimensions, and extension ratio under constant load. Forces, dimensions, temperature and time are continuously measured and monitored.

Table 5. Input and output readings of log module in the case of reference voltage = 0·100 VDC and slope = 1 VDC/decade

E_{in} (V)	E_{out} (V)
0·100	0·000
0·0100	+0·9950
0·0010	+1·9910
1·000	−1·003
10·00	−2·000

RECORDING FACILITIES

The recording unit is an independent system and need not be mentioned. However, it was found that suitable recording facilities enhance data collection and data reduction of two dimensional test to a great extent. The recorders used were two *X-Y* recorders (Hewlett Packard Model 7005B and F. L. Moseley Co., California Model 2D-2A). They are supplied by direct signals either from the force-transducers amplifiers or by the VDA units. In relaxation experiments the time axis was driven by a time base unit (Hewlett Packard 17108 AM Time Base). It was found advantageous to record force decay in relaxation experiments vs logarithm of time. Figure 5 shows a scheme of the log time base unit which consisted of a linear time base unit mentioned above, a log module (Teledyne Philbrick 4350 Unit) and dual power supply (Hewlett Packard 6205B Dual DC Power Supply). The results of a test of the performance of the log module are shown in Table 5.

The log time unit was found to be linear with the logarithm of time in the interval 0·01–17·5 min (the upper value due to upper limit of output of the linear time base unit).

In the process of data-reduction it was found that manual-data-reduction of two dimensional tests of skin is both inaccurate and laborious. Subsequently, a small computer was incorporated to the recording system. The computer (Digital Equipment Co., U.S.A., Model PDP 8/e with programmable clock, extended arithmetic element, 8K memory, 64 channel A-D, 3 Schmitt triggers, 4 channels D-A) was fed with all the data on line (while the experiments were running) and punched the data on a paper tape.

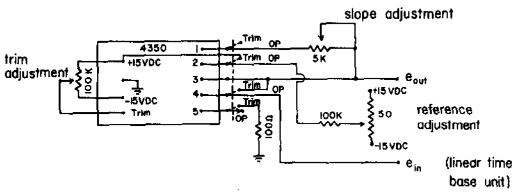

Fig. 5. Scheme of the log time base module.

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