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ERRATA - January 1965

The following corrections apply to Technical Documentary Report No. AMRL-TDR-64-23, Young's Modulus and Breaking Strength of Body Tissues.

Page iii

Change the last sentence of the ABSTRACT to read:

> The breaking index ranged from 0.18 for the longitudinal direction of the mid-esophagus to 0.69 for the transverse direction in the same organ.

Page 10

Change the first sentence of the last paragraph to read:

> Finally, the value of the breaking index ranges from 0.18 for the longitudinal direction of the middle section of the esophagus to 0.69 for the transverse direction of the upper section of the esophagus.

BIOPHYSICS LABORATORY
AEROSPACE MEDICAL RESEARCH LABORATORIES
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FOREWORD

The information presented in this report was obtained by The Chicago Medical School, Chicago, Illinois, under Contract No. AF 33(616)- 7053 for the 6570th Aerospace Medical Research Laboratories, Aerospace Medical Division, under authority of Project No. 7231, "Biomechanics of Aerospace Operations," Task No. 723101, "Effects of Vibration and Impact." The responsible investigator in this research at The Chicago Medical School was Dr. John L. Nickerson. In this work he had the active assistance of Anna Paradijeff, M. D. , Milana Drazic, M. Sc. , Gary Nemhauser, M. D. , Mrs. Benita Satzman, Mr. Charles Gannon, B. S. , Mr. Leslie Hallock, B. S. , Mr. Leo Drennan, Mr. Jerry Eder, B. S. The research contained in this report was accomplished during the period from March 1960 to December 31, 1962. Major Neville P. Clarke, of the Vibration and Impact Branch, Biodynamics and Bionics Division, Biophysics Laboratory, served as contract monitor.

The experiments reported herein were conducted according to the "Principles of Laboratory Animal Care" established by the National Society for Medical Research.

ABSTRACT

The research described in this report concerns the measurement of Young's modulus, the breaking strength and the breaking index in the stretching of tissues of the dog and of humans. The breaking index is defined as the ratio of breaking strength to Young's modulus. These measurements were made by static determinations of the stress-strain relationship. Some twenty-three different tissues or segments of tissue were used in these tests. The results reported have an accuracy of the order of 25%. The values reported on the few samples of human tissue studied are different only to a small degree from the values found for the tissues of the dog. The values for Young's modulus ranged from 5.7 x 10^6 dynes per square centimeter for the transverse direction around the aortic arch to 110 x 10^6 dynes per square centimeter for the skin of the abdomen. The values for the breaking strength ranged from 3.3 to 44.4 kilograms per square centimeter for the same tissues. The breaking index ranged from 0.18 for the longitudinal direction of the mid-esophagus to 0.~~[illegible]~~ .64 for the ~~longitudinal~~ transverse direction in the same organ.

PUBLICATION REVIEW

This technical documentary report is approved.

J. W. HEIM
Technical Director
Biophysics Laboratory

OBJECTIVE

In the development of high-speed transportation of living creatures, it has become necessary, for their protection from mechanical damage, to know some of the physical characteristics of various portions of their anatomy. The present research was performed as part of the effort to determine these physical characteristics. In particular, the purpose of this research was to determine the value of Young's modulus of stretch and of the breaking tension under stretch of numerous body tissues. The method used was the conventional static loading with measurement of load and stretch.

METHOD

This research was performed in considerable detail on the tissues of the dog in vitro. In a few cases, tissues of the human were also used in the same type of experiment.

For these static measurements, the procedure was as follows (see also Figure 1):

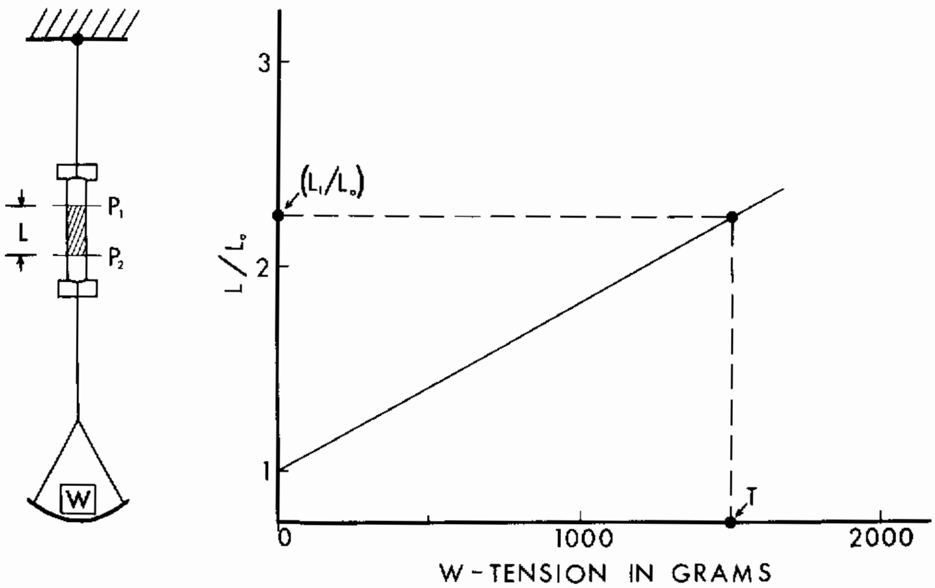

Figure 1. Tissue Stretch and Length Tension Diagram.

This figure shows diagrammatically the arrangement for the attachment of tissue and the diagram for plotting tensions and lengths for the determination of Young's modulus of stretch.

Small portions of tissue from various regions were cut into two centimeter lengths of uniform cross section. Each end of these tissue sections was slightly larger in cross section than the center which was 2 to 50 square millimeters. This widening of the ends prevented the ties attached to the ends of the tissue from slipping. In the uniform cross section central region, two thin pins were pushed through the tissue at points P_1 and P_2, about 10 millimeters apart. These pins served as the end markers for the region of tissue being studied. The upper tie of the tissue section was attached to a firm support and the lower tie to a light scale pan. The pan was loaded with various weights and the length (L) between the pins measured. The load (W) and the relative length (L/L_o) were plotted on the length-tension diagram in Figure 1. L_o is the unloaded length of the tissue determined from a plot of length against load. The loads were recorded in grams and the lengths in centimeters. Young's modulus (Y) was calculated from the formula:

$$Y = 980\, W \cdot L_o \,/\, (L_1 - L_o)\ A \text{ dyne/cm}^2 \qquad (1)$$

where A is the cross sectional area (cm^2) of the center portion of the tissue. The value of A was determined by measuring the weight (M) in grams of the section of tissue between pins (shaded area in Figure 1), the density of the tissue (d grams per cc) and the resting length of the tissue (L'_o centimeters). For example,

$$A = (M/dL'_o)\ \text{cm}^2 \qquad (2)$$

The breaking strengths (B kilograms/cm^2) of the tissues were computed from the breaking tension (K) in kilograms and the cross section area A. For example, breaking strength (B) is given by the equation

$$B = K/A\ \text{kg/cm}^2 \qquad (3)$$

Another quantity was also computed from the observations. This quantity is called the "breaking index" and is determined by dividing the breaking strength (dynes/cm^2) by Young's modulus (dynes/cm^2). Since Young's modulus represents the tension required to double the length of a tissue, the breaking index is a measure of the fractional increase in length necessary to attain the breaking point.

The tissues measured were removed from the animal immediately after sacrifice. In the cases of the dog studies, the dogs were all healthy animals. In the case of the human material, on which only a small amount of work was done, the tissues were taken at autopsy and were, in general, from subjects who had not been perfectly healthy. The tissues, after excision, were labeled and placed in normal saline and taken to the laboratory for measurement. The first measurements were started within an hour of the excision of the tissues. Subsequent measurements were made, where possible, at daily intervals up to 5 days. A complete test usually took from 10 to 20 minutes, and the average time between successive measurements was about 40 seconds.

The direction of stretch in the tests for Young's modulus and the breaking strength was, in general, in the direction in which tension would be applied in the body. In the tables, these directions, and the location of the tissues, have been indicated where possible. For example, a section of the esophagus called "esophagus, upper section, longitudinal" indicates that the tissue was taken from the upper third of the esophagus and cut so that the direction of the test was in the axial direction of the esophagus. Similarly, "esophagus, upper section, transverse" will indicate that the tissue was taken from the upper third of the esophagus and cut so that the direction of the test was circumferentially around the esophagus.

RESULTS

Table I presents the values of Young's modulus in dynes per square centimeter for twenty-five different tissues. Table II presents the values of the breaking strength in kilograms per square centimeter for the same tissues. The values vary considerably from tissue to tissue. In general, there was no great change in the values obtained from the sections cut on successive days from the same piece of tissue. The values of both Young's modulus and the breaking strength of a specific tissue varied considerably from animal to animal. This variation was much greater than the day to day variation in sections of the same tissue. Since the standard deviation in the measurements on each tissue is rather large, the standard error of the mean for each tissue is of the order of 25%. These mean values, in the case of the tissues of the dog are made on the results of between ten and forty sections of tissue. The portion of these tissues actually studied, as illustrated in Figure 1 between points P_1 and P_2, weighed between twenty and five hundred and thirty-three milligrams. Examination of the data demonstrated considerable change in the average value of Young's modulus and the breaking strength as related to the cross section area of the tissue studied. In Tables I and II, the results are based on tissue cross sectional areas greater than two square millimeters.

In general, the values of Young's modulus of the tissues of the dog are lowest in tissues from the aortic arch and largest from the skin of the abdomen, and in the longitudinal direction in fibers from the esophagus. It is interesting that in the case of the esophagus, the value of Young's

Table I

Young's Modulus - Dynes/cm^2 x 10^6

Tissue	Dog Static	Human Static	Dog Dynamic
Ligament of Treitz	8.5	29.6	41.0
Ileocecal Ligament	20.8	19.8	10.9
Omentum	15.7	-	40.3*
Esophagus - Upper - Longitudinal	108.0	15.1	37.8
Esophagus - Upper - Transverse	24.8	25.8	5.1*
Esophagus - Middle - Longitudinal	96.0	12.8*	21.1
Esophagus - Middle - Transverse	50.0	3.7*	7.9
Esophagus - Lower - Longitudinal	65.4	22.6	34.4
Esophagus - Lower - Transverse	28.0	8.6	23.6
Stomach	19.8	13.0	18.1
Intestine - Small - Longitudinal	27.2	14.8	12.1
Intestine - Small - Transverse	22.1	17.2	15.6
Intestine - Large - Longitudinal	16.5	24.5	18.6
Intestine - Large - Transverse	14.6	7.8	21.1
Aorta - Ascending - Longitudinal	15.1	-	-
Aorta - Ascending - Transverse	15.2	30.4*	-
Aortic Arch - Longitudinal	7.8	15.2*	14.2
Aortic Arch - Transverse	5.7	13.3*	10.2
Aorta - Thoracic - Longitudinal	23.1	4.9*	13.6
Aorta - Thoracic - Transverse	12.0	23.6*	38.4
Diaphragm - Central	90.2	-	67.3
Diaphragm - Attachments	52.0	14.8	31.2
Skin - Abdominal	110.4	56.0	108.5
Trachea - Longitudinal	62.0	-	-
Rectus Abdominis Muscle	16.5	17.8	20.5

* Based on one case, at least, or one observation.

Table II

Breaking Strength - Kgm/cm^2

Tissue	Dog Static	Human Static	Dog Dynamic
Ligament of Treitz	3.9	7.2	7.3*
Ileocecal Ligament	4.8	7.2	-
Omentum	3.5	-	4.3*
Esophagus - Upper - Longitudinal	25.4	5.4	-
Esophagus - Upper - Transverse	17.4	8.0	-
Esophagus - Middle - Longitudinal	17.2	4.4*	-
Esophagus - Middle - Transverse	20.9	1.1*	-
Esophagus - Lower - Longitudinal	16.9	5.8	-
Esophagus - Lower - Transverse	12.4	2.7	-
Stomach	8.5	5.6	-
Intestine - Small - Longitudinal	8.5	6.4	-
Intestine - Small - Transverse	7.6	7.2	4.8
Intestine - Large - Longitudinal	7.5	8.7	7.5
Intestine - Large - Transverse	7.4	4.4	2.3*
Aorta - Ascending - Longitudinal	5.6	-	-
Aorta - Ascending - Transverse	6.9	7.2*	-
Aortic Arch - Longitudinal	4.3	5.4	1.8*
Aortic Arch - Transverse	3.3	4.0*	-
Aorta - Thoracic - Longitudinal	7.0	2.4*	8.1*
Aorta - Thoracic - Transverse	6.0	8.1*	4.5*
Diaphragm - Central	21.2	-	14.6*
Diaphragm - Attachments	13.3	4.4	7.4
Skin - Abdominal	44.4	37.2	-
Trachea - Longitudinal	21.4	-	-
Rectus Abdominis Muscle	4.4	6.0	2.4*

* Based on one case, at least, or one observation.

modulus is always larger for longitudinal than for transverse stretch. This same difference holds for the large and small intestine, for the aortic arch and for the descending aorta. For the ascending aorta, values for the longitudinal and transverse directions are almost identical.

The values of Young's modulus and breaking strength for the human are in only fair agreement with the value for the dog. In some of these observations, indicated by the asterisk, the observations are insufficient in number to make a comparison valid.

The measurement of breaking strength of the tissues of the dog under static load, Table II, yielded a range between 3.3 kilograms per square centimeter for the transverse direction around the aortic arch and 44.4 for the skin of the abdomen. Tissues showing the lowest breaking strength are the ligaments of Treitz, the ileocecal ligament, the omentum, the aortic arch and the rectus abdominis muscle. For all of these, the breaking strength is less than five kilograms per square centimeter. The next range of values is between 6.0 and 8.5 kilograms per square centimeter. The tissues in this group include the small and large intestines, the stomach, the ascending aorta and the thoracic aorta. The third range of values from 12.4 to 25.4 kilograms per square centimeter includes the esophagus, the trachea and the diaphragm. The greatest breaking strength was found in the skin of the abdomen.

Observations of the human material provided values which have less overall range, varying only from 2.7 to 8.7 in all tissues except the abdominal skin where the value of 37.2 is close to the value for the abdominal skin of the dog. In the case of the human material, the values are not considered exact, since the number of observations was small and since the material available for study came from non-healthy subjects, so that the tissues cannot be considered categorically as normal.

Previously defined in the report is the term, "breaking index." The value of this quantity for the tissues of the dog ranged from 0.17 to 0.84 in observations made by static method. This index indicates that one tissue will break when its length is increased by 17%, whereas the other tissue requires an 84% increase in its initial length before breaking occurs. For these observations the standard error of the mean is about 15%. Inspection of the data in Table III indicates that the minimum values for the breaking index are obtained for the longitudinal direction in the esophagus. For these tissues the breaking index is less than 0.3. For the ileocecal ligament, the trachea, the rectus abdominis muscle, and the diaphragm, the values of the index lie between 0.30 and 0.37. Values above 0.39 are found for all

Table III

$$\frac{\text{Breaking Strength} \quad \text{dynes/cm}^2}{\text{Young's Modulus} \quad \text{dynes/cm}^2} = \text{"(Breaking Index)"}$$

Tissue	Dog Static	Human Static	Dog Dynamic
Ligament of Treitz	0.45	0.24	0.17*
Ileocecal Ligament	0.23	0.36	-
Omentum	0.22	-	0.11*
Esophagus - Upper - Longitudinal	0.23	0.35	-
Esophagus - Upper - Transverse	0.69	0.30	-
Esophagus - Middle - Longitudinal	0.18	0.34	-
Esophagus - Middle - Transverse	0.41	0.29	-
Esophagus - Lower - Longitudinal	0.25	0.25	-
Esophagus - Lower - Transverse	0.43	0.31	-
Stomach	0.42	0.42	-
Intestine - Small - Longitudinal	0.31	0.43	-
Intestine - Small - Transverse	0.34	0.41	0.30
Intestine - Large - Longitudinal	0.45	0.35	0.39
Intestine - Large - Transverse	0.50	0.55	0.11*
Aorta - Ascending - Longitudinal	0.36	-	-
Aorta - Ascending - Transverse	0.45	0.23*	-
Aortic Arch - Longitudinal	0.54	0.35	0.13*
Aortic Arch - Transverse	0.56	0.29*	-
Aorta - Thoracic - Longitudinal	0.30	0.48*	0.58*
Aorta - Thoracic - Transverse	0.49	0.34	-
Diaphragm - Central	0.23	-	0.21*
Diaphragm - Attachments	0.25	0.29	0.23
Skin - Abdominal	0.39	0.65	-
Trachea - Longitudinal	0.34	-	-
Rectus Abdominis Muscle	0.26	0.33	0.12*

* Based on one case, at least, or one observation.

other tissues studied. An interesting observation relating to the magnitude of the breaking index is that fibers in the longitudinal directions of all portions of the esophagus, of the large and small intestine and of the ascending aorta and thoracic aorta are less than the magnitudes for the transverse direction in these regions. This difference indicates that in the longitudinal direction, these tissues will stretch less before breaking than in the transverse direction. It is also worthy of note that in the aortic arch, where in activity, the aorta expands both in length and transverse diameter, the values are relatively large.

The values of the breaking index from the data on human tissues are approximately in the same range of that found in the tissues of the dog. These results are less accurate, since based upon less information than was available in the studies on the dog.

DISCUSSION

In considering the data presented in this research, it must be remembered that the objective was to find values of the elastic properties of body tissues so that first order approximation to the behavior of the components of the body under mechanical oscillatory stress could be evaluated. It is obvious that tissues behave as elastomers and therefore, when strain is plotted against stress, the curves are concave toward the stress axis. Therefore, in many cases, there is no slope of the curve which remains constant over a wide range of values. The procedure in the present research was to plot the data so that the strain component is plotted on a more contracted scale than is the stress component. This makes it possible to select within the limits of experimental error, a straight line through many of the experimental points. It is the slope of this line from which the value of Young's modulus is computed. Although future analysis of the data may provide more elegant formulation of the results, nevertheless, for the purpose of the specific problem under discussion, the procedure used is adequate and provides satisfactory comparison of one tissue with another.

The results that we have obtained here for aortic tissue differ only by a factor of 2 or 3 from the values reported by Roy (ref 1) of 1×10^6 to 3×10^6 dynes per square centimeter. Our values, therefore, are of the magnitude of those customarily found by the static method in dog or other mammalian tissue.

The report by Mayeda (ref 2) based upon a dynamic method gives values which are of the order of 2×10^9 to 50×10^9 dynes per square centimeter for similar aortic tissue. This is a factor of approximately 1,000 times the values reported by Roy. Recalculation of Mayeda's data gives values of the order of 2 x 10^6 dynes per square centimeter. It appears that he has multiplied unnecessarily by the factor 980. We suggest, therefore, that there is agreement between the static values and the dynamic values when the frequency of oscillation does not exceed 5 cycles per second.

The standard error of the average values reported here is rather large, being of the order of 25%. The reason for this does not lie in the experimental observations, in which the accuracy is quite good, but rather in the difficulty of selecting tissue of uniform constitution. In this work, in which the attempt was to measure practical values of Young's modulus, breaking strength and breaking index, no attempt was made to specifically select one type of tissue from the wall of an organ. Rather, the tissues were chosen at random, except insofar as the choice was of longitudinal or transverse direction. For the objectives of this report, these results can be considered to be of practical value.

The size of the section of tissue tested in this work has a bearing on the magnitude of Young's modulus and the breaking strength. Examination of Table 4 indicates that the average values of Young's modulus and the breaking strength for tissue sections of cross section greater than 2 square millimeters is larger than when the average is restricted to those tissue sections greater in area than 10 square millimeters. However, the value of the breaking index is scarcely affected by the cross sectional area of the tissue studied.

Table IV

	Young's Modulus x 10^6 dynes/cm^2		Breaking Strength Kgm/cm^2		Breaking Index	
Tissue from Dog	Cross Section		Cross Section		Cross Section	
	$>2mm^2$	$>10mm^2$	$>2mm^2$	$>10mm^2$	$>2mm^2$	$>10mm^2$
Esophagus-Lower Longitudinal	65.4	49.9	16.9	11.2	0.28	0.23
Esophagus-Lower Transverse	28.0	17.9	12.4	7.1	0.52	0.52
Stomach	19.8	11.4	8.5	5.7	0.54	0.58
Intestine-Small Longitudinal	27.2	15.9	8.5	4.6	0.39	0.41
Intestine-Small Transverse	22.1	11.5	7.6	4.4	0.46	0.48
Intestine-Large Longitudinal	16.5	11.2	7.5	5.7	0.63	0.64
Intestine-Large Transverse	14.6	6.2	7.4	4.0	0.70	0.82

The relative agreement of the values of Young's modulus, breaking strength, and breaking index in the dog and human tissues make it possible to use the factors and findings in the studies of the dog in the evaluation of human reaction to mechanical stress. For example, the observation that the breaking index in the ascending aorta and in the thoracic aorta are larger for the transverse direction than for the longitudinal direction suggests that the rupture pattern under stress may be a shearing across the vessel rather than a splitting in the longitudinal direction. "Biological analogy" between dog and human would invoke this explanation of shearing injury reported in certain types of accident (3).

SUMMARY

Measurements made by static determination of Young's modulus and by lower frequency dynamic measurements of Young's modulus show that for the dog, the results of the two are in essential agreement. The results reported have a standard error of the order of 25%. The values reported on some small amount of human tissue observed are different only to a small degree from the values of the corresponding tissue in the dog. This agreement is found for the values of Young's modulus, of the breaking strength, and of a quantity defined as the "breaking index". Briefly, Young's modulus varies from 5.7×10^6 dynes per square centimeter for the transverse direction of the aortic arch to 110.4×10^6 dynes per square centimeter for the skin of the abdomen of the dog, measurements being made by static methods.

For the breaking strength in the dog tissue, the values range from 3.3 kilograms per square centimeter for the transverse fibers of the aortic arch to 44.4 kilograms per square centimeter for the skin of the abdomen.

Finally, the value of the breaking index ranges from 0.18 for the longitudinal direction of the middle section of the esophagus to 0.69 for the transverse direction of the upper section of the esophagus. In an organ having both longitudinal and transverse stretch, the percentage stretch before breaking is greater for the transverse than for the longitudinal direction, i.e., where in normal activity the need for stretch is greater.

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