minutes. The dye (0.75 g., 85% yield) separated on chilling and crystallized from methyl alcohol (700 cc. per g.) in a brownish felt of crystals with m. p. 308–309° dec.

Anal. Calcd. for $C_{23}H_{21}IN_2S_2$: I, 24.58. Found: I, 24.85.

The bluish-red methyl alcoholic solution had $\lambda_{max.}$ of 5555 Å.

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The Elastic Element of Skeletal Muscle

BY HENRY B. BULL

Within recent years there has been great interest shown in rubber-like elasticity and the statistical theory of such elasticity has been formulated. It is the purpose of this note to show the close analogy between the contraction of rubber-like materials and that of muscle.

An immediate difficulty is encountered when a comparison between rubber and muscle is attempted. The resting state of a muscle is its extended state, while the resting state of rubber is its contracted state. When a muscle is allowed to contract isometrically, the tension exerted becomes progressively less as the length of the muscle is made smaller relative to that of the length of the resting muscle. The plot of the isometric tensions as a function of the length of the contracted fiber is clearly a stress-strain curve of muscle. The problem is then to extrapolate this stress–strain curve to zero stress from which the length of the completely contracted fiber can be estimated. The experiments of Ramsey and Street[1] allow such an extrapolation to be made. These workers have measured the isometric tensions exerted by single muscle fibers from the semi-tondonosus muscles of frogs (*Rana pipiesus*).

Out of the several experiments selected by Ramsey[2] as representing in his opinion the most perfect of his measurements that identified as 12-20-38 allows the best extrapolation into the region of low tensions. For this fiber, the tension values extrapolate to zero at about 30% of the resting length. This length is assumed to represent the length of the completely contracted fiber and is analogous to rubber in its unstretched state. Assigning the value of unity to the length of this completely contracted fiber, the lengths of the fiber at tensions greater than zero have been expressed relative to this completely contracted length. The tensions have been expressed in terms of dynes per sq. cm. of cross section of the completely contracted fiber. These tensions are plotted against the relative length of the fiber and the results are shown in Fig. 1.

(1) Ramsey and Street, *J. Cellular Comp. Physiol.*, **15**, 11 (1940).
(2) Ramsey, private communication.

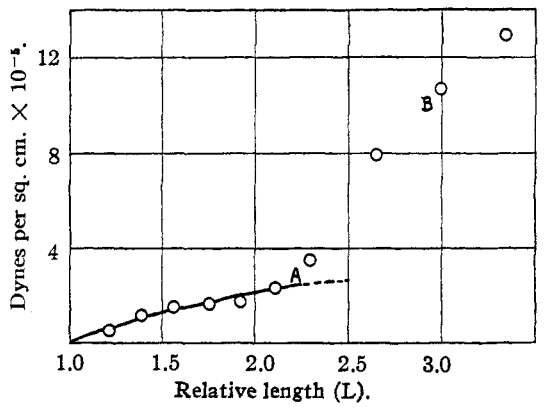

Fig. 1.—Isometric tensions plotted against the relative extension of the completely contracted fiber. The points represent the recalculated data of Ramsey and Street. The solid line is a plot of equation 1.

Comparison of Fig. 1 with the stress–strain curves for vulcanized rubber shows[3] a striking similarity between the stress–strain character of rubber and that of muscle. According to statistical theory, the region from the origin to A represents the straightening of randomly kinked molecular chains of the polymer while the region from A to B represents for the most part a crystallization of the polymer.

The statistical equation[4] which expresses the force exerted by a fiber in the region from the origin to point A has the form

$$F = \alpha\left(L - \frac{1}{L^2}\right) \qquad (1)$$

where F is the force exerted by the elastic fiber at constant temperature, α is a constant and L is the length of the fiber relative to that of the completely contracted length. Equation 1 has been fitted to the data plotted in Fig. 1 and the best curve drawn in. The numerical value of α is about 1.2×10^5 dynes per sq. cm. The modulus of elasticity of the fiber at zero extension is evidently 3α or is 3.6×10^5 dynes per sq. cm.

The interpretation of the stress–strain curve for muscle is complicated by the fact that skeletal muscle is made up of alternate birefringent and isotropic disks. These disks are known as A- and I-disks, respectively. When a muscle contracts, the A-disks contract but the I-disks extend. Naturally, the A-disks contract more than the I-disks stretch, so that the net effect is that the muscle shortens.[5] It would be impossible with our present information to correct for the contribution to the length of the fiber made by the I-disk. Such a correction would be particularly difficult to apply in the case of the greatly contracted state and the effect of the I-disks on the stress–strain curve of muscle has been neg-

(3) Anthony, Caston and Guth, *J. Phys. Chem.*, **46**, 826 (1942).
(4) Guth and James, *Ind. Eng. Chem.*, **33**, 624 (1941).
(5) Buchthol, Knappeis, and Lindhard, *Skad. Arch. of Physiol.*, **73**, 163 (1936).

lected. In this connection, it is well to point out two things. First, the contribution of the I-disks to the length of the muscle fiber would not change the general shape of the stress–strain curve of muscle and, accordingly, would not destroy the close analogy of this curve to that of rubber and second, if the I-disks were considered, the extension for a given tension would become greater. This would decrease the calculated modulus of elasticity.

According to statistical theory the modulus of elasticity of randomly kinked molecular chains at zero extension is $3RTW/M$ where R is the gas constant, T is the absolute temperature, W is the weight of the elastic material per cubic centimeter, and M is the molecular weight of each chain. Kuhn[6] has considered the case of randomly oriented rigid rods connected end to end by flexible links and imbedded in an isotropic fluid matrix. The modulus of elasticity at zero extension which he obtained for such a system is $9RTW/5M$.

It is generally agreed that the protein, myosin, is responsible for the active elastic properties of muscle. It has been established that the only part of the muscle which contracts is made up of the so-called A-disks, and accordingly, it is probable that myosin is confined to the A-disks of the muscle. Myosin makes up about 10% of the total muscle[7] and A-disks occupy about half of the muscle. This means that about 20% of the A-disks is myosin or W is about 0.2. Ramsey and Street worked at 284° and R is 8.37×10^7 ergs per degree per mole. Then for randomly kinked flexible chains the molecular weight of each chain is about 40,000 and for randomly arranged rigid rods the molecular weight of each rod is about 24,000.

Only one of the several experiments of Ramsey and Street has been used. The choice of this experiment was solely a matter of convenience; it was easier to extrapolate to zero extension. It should be emphasized, however, that all the experiments of Ramsey and Street show the same type of stress–strain curve. Indeed, Ramsey and Street comment rather extensively on the "knee" (portion of the curve from the origin to A) shown in Fig. 1. They call this portion of the curve the delta region. A characteristic feature of a muscle which has once entered this region is that it will not spontaneously return to its initial resting length. In terms of the picture presented in this paper, the myosin has become so randomly arranged that it is no longer possible for it to recrystallize. Also characteristic of the Ramsey–Street experiments is the steep upswing of the stress–strain curve at lengths greater than the δ region. As we have pointed out above, this closely parallels the behavior of rubber and it is generally considered that this portion of the curve reflects a crystallization of the polymer. That this is a valid interpretation for muscle is indicated by the recent experiments of Fischer[8] who was able to show that for muscle undergoing contraction, the birefringence rose rapidly as the length of the contracted muscle approached that of the resting state.

According to the kinetic theory of muscle contraction outlined above, the contraction of a muscle should involve the absorption of heat. Actually, experiments indicate that heat is liberated when a muscle contracts.[9] This problem is not a simple one and cannot be gone into here. It is probable, however, that the complexity of the chemical reactions which proceed, accompany and follow muscle contraction is such that no safe conclusions can be drawn regarding the elastic nature of muscle from heat change studies. Many of the chemical reactions may be exothermic and completely obscure the heat absorption involved in the actual motion of the elastic element of muscle.

This theory also demands that the tension exerted by a muscle should increase with increasing temperature. Ramsey has kindly placed at my disposal 27 unpublished experiments in which he varied the temperature over the range from 2.4 to 22.6° Due to the extreme difficulty of this technique, there is considerable variability. These data have, however, been reduced to a common axis and the best straight line through the points calculated by the method of least squares. From this calculation, it was found that the factor of proportionality between the isometric tension and the absolute temperature at the resting length of the muscle fiber is 8.4×10^{-3} with a probable error of the mean of 3.6×10^{-3}. If the tension were directly proportional to the absolute temperature, the factor of proportionality would be 3.7×10^{-3}. These data certainly do not prove that the contraction of a muscle is rubber-like in nature, but they are in keeping with such an interpretation.

The problems outlined in this note have been discussed with a number of people and I am grateful to all of them for their comments. I wish especially to thank Dr. Robert W. Ramsey for sending me the detailed data for his tension-length experiments and for his kind permission to use some of his unpublished data.

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(6) Kuhn, *Kolloid-Z.*, **87**, 3 (1939).
(7) Edsall, personal communication.
(8) Fischer, *J. Cellular Comp. Physiol.*, **23**, 113 (1944).
(9) Brown, "Muscle," in Fenn, "Biol. Symp.," **3**, 161 (1941), The Jaques Cattell Press, Lancaster, Pa.
(10) Original manuscript received January 8, 1945.

Tensile Strength in Relation to Molecular Weight of High Polymers

BY PAUL J. FLORY

Sookne and Harris[1] have shown recently that the tensile strength of cellulose acetate depends

(1) A. M. Sookne and M. Harris, *Ind. Eng. Chem.*, **37**, 478 (1945); *J. Research Natl. Bur. Standards*, **30**, 1 (1943).