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NOTES AND NEWS

FIFTH INTERNATIONAL CONGRESS ON RHEOLOGY

FIFTH INTERNATIONAL CONGRESS ON RHEOLOGY

KYOTO INTERNATIONAL CONFERENCE HALL; KYOTO, JAPAN

7–11 October, 1968

(From Prof. S. Oka)

THE CONGRESS was held under the auspices of the International Committee of Rheology and the sponsorship of the Science Council of Japan, the Society of Materials Science, Japan and the Society of Polymer Science; with Japanese Organisations as hosts. The Honorary President was Professor J. D. Ferry. The Co-Chairmen of the Organizing Committee were Professor M. Horio, (Kyoto) and Professor B. Tamamushi (Tokyo).

The Congress consisted of an opening ceremony and an opening lecture on October 7th and 28 working sessions on each day of the Congress from Monday, October 7th, to Friday, October 11th, inclusive, at which 276 original scientific contributions were presented. At the opening ceremony, an opening address was given by Professor B. Tamamushi, a speech of welcome by Professor S. Tomonaga, President of the Science Council of Japan, messages of congratulation by Professor F. H. Müller, former Honorary President, Dr. A. Okuda, President of Kyoto University, and Mr. K. Tomii, Mayor of Kyoto City. The opening lecture entitled "An example of a Rheological Conceptual Scheme" was given by Professor J. D. Ferry, Honorary President, with Professor S. Oka in the Chair. About five hundred and fifty participants joined the Congress from nineteen countries including about three hundred participants from Japan.

An exhibition of a variety of rheometers including viscometers, related instruments and books, was held at the Kyoto International Conference Hall during the Congress. More than ten companies exhibited their products and goods.

There was a delightful social program which included a ladies program, social gatherings and a post-congress excursion to Nara. At the social gatherings, a Reception was given by the President of the Science Council of Japan at the Kyoto Tower Hotel and a banquet was held at the Miyako Hotel with a special evening show given at Gion Corner.

NOTES ON SCIENTIFIC PROGRAM

The scientific program consisted of 5 general lectures, and 23 invited papers and contributed papers. Each contributed paper was limited to 15 minutes, followed by a discussion period of 5 minutes. Sixty minutes were given for each general lecture and 40 minutes for each invited paper. General lectures and invited papers were as follows:

General lectures

[G.L. I] STAVERMAN, A. J.: Thermodynamics of Rheological Behaviour.

[G.L. II] MEREDITH, R.: Dynamic Mechanical Properties of Textile Fibres.

[G.L. III] MÜLLER, F. H.: Reversible thermomechanische Effekte im glassigen und viskoelastischen Zustand.

[G.L. IV] MARVIN, R. S.: Rheological Models and Measurements.

[G.L. V] KAWAI, H.: Mechanical Anisotropy of Crystalline Polymer in Relation to Molecular Orientation.

Invited papers

COPLEY, A. L.: Some problems in Hemorheology.

DINTENFASS, L.: Microrheology of Human Blood in Health and Disease.

FUKADA, E.: Piezoelectric Dispersion in Oriented Polymers.

HIRONE, T.: Rheological Approach of the Internal Stress in Cooling Steel Ingots.

JOLY, M.: Study of Macromolecular Deformation by Surface Viscometry.

KIRSCHKE, K.: Characteristics of Different Methods in Viscometry at High Rates of Shear.

LODGE, A. S.: Concentrated Polymer Solutions.

MARKOVITZ, H.: Small Deformations Super-Imposed on Steady Viscometric Flows.

MASON, S. G.: The Kinetics of Flowing Dispersions in Non-Newtonian Media.

MESKAT, W.: On the Theory of Extrusion and Spinning.

MURAYAMA, S.: Dynamic Behavior of Clays.

NARAYANAMURTI, D.: Some Investigations on the Rheology of Wood.

READ, B. E.: Dynamic Birefringence of Natural Rubber and PVC. Comparison with Earlier Data on PMA, Polyacetaldehyde and PMMA.

REHBINDER, P.: On the Rheology of Thrixotropically Structurized Disperse Systems.

RIVLIN, R. S.: Topics in Mathematical Rheology.

SCHURZ, J.: Rheological Structure Investigations with Concentrated Polymer Solutions.

SCHWARZL, F.R.: On the Rheology of Filled Elastomers.

SMITH, T. L.: Strength and Extensibility of Elastomers.

STEIN, R. S.: Recent Progress in Rheo-Optical Studies at the University of Massachusetts.

THIRION, P.: Théorie Statistique de l'Élasticité d'un Réseau de Chanîes Non Gaussiennes Indirectement Couplées à un Continuum Élastique.

WADA, Y.: Mechanical Relaxations in Crystalline and Glassy Polymers.

WHITMORE, R. L.: Drag Forces in Bingham Plastics.

ZIABICKI, A.: Structural Theories in Polymer Rheology.

SESSIONS ON BIORHEOLOGY

The Sessions on Biorheology comprised (i) Blood and Blood Vessels and (ii) Other Biological Systems. The former was held in the afternoon of October 8th and in the morning of October 9th, while the latter was held in the afternoon of October 9th.

ABSTRACTS

Abstracts of papers on Biorheology together with those of papers closely related to Biorheology are listed below. Where there is an asterisk placed against the name of the author this indicates that the author was invited by the Organizing Committee to contribute the paper to the Congress.

BLOOD AND BLOOD VESSELS—I

1. Model Studies of the Hydrodynamics Characteristics of the Erythrocyte and of the Erythrocyte–Wall Interaction. G. BUGLIARELLO, TIN-KAN HUNG and C. E. JAMES, JR., Carnegie-Mellon Univ., U.S.A.

The detailed hydrodynamic characteristics of an erythrocyte, both isolated and interacting with other erythrocytes or other boundaries, are of fundamental importance to the rheology of blood—e.g. for linking the microscopic characteristics of blood to its bulk flow and transfer properties.

At present, determination of such characteristics through *in vivo* studies offers almost unsurmountable difficulties, and so does a mathematical simulation. This paper presents the results of experimental measurements of the drag characteristics of isolated rigid erythrocyte models, and of the interaction of such models with a boundary.

The models were installed in a large glycerine-filled towing tank at Reynolds numbers (based on the towing velocity and the diameter of the model), ranging from 0·25 to 6·4. Measurements of the drag coefficient of the model as a function of the Reynolds number show that the coefficient, if plotted in terms of a Reynolds number based on a characteristic length which is proportional to the projected area of the erythrocyte model in a direction normal to the flow, is constant for all angles and falls on the same line for a sphere or a disk oriented at 90° with respect to the flow.

As the distance between the erythrocyte model and a boundary decreases, the drag coefficient increases, but the curve of the drag coefficient versus Reynolds number remains parellel to that for the case of no boundary. Measurements of the pressure exerted by the erythrocyte model on the boundary yielded pressure contour curves, which show a complex pressure pattern characterized by double peaks in correspondence of the central portions of the erythrocytes. The peaks are strongly influenced by the shape of the erythrocyte—a single peak being, e.g. present in the pressure field generated by a flat disk or a sphere.

2. On the Interrelation between Blood Viscosity and the Erythrocyte Sedimentation Rate.

Y. ISOGAI, K. ICHIBA, A. IIDA, and H. NAGAOKA, Jikei Univ. School of Medicine, Japan

Changes in blood viscosity which occur in various diseases produce great effect on the flow property of the blood. As factors which are closely related to blood viscosity, the aggregation of red blood cells, hematocrit, internal rigidity of red blood cells, and the viscosity of blood plasma may be given. Also, these factors have a close relation to the sedimentation mechanism of erythrocyte sedimentation rate (E.S.R.). Consequently it is of great interest from the clinical physiological stand-point to investigate the hemorheologic flow property when raise in E.S.R. is observed.

Blood viscosity was ascertained by measuring various shear rates (230, 115, 46, and 23 sec^{-1}) by means of a cone-plate microviscometer (Brook-field). Besides using a cone-plate viscometer, plasma viscosity was measured also by means of a microcapillary viscometer. Materials used were blood taken from 40 normal adults and also from 300 patients suffering from varying diseases.

Results may be summarized as follows:

(1) A high degree of interrelation was noted between hematocrit value and specific viscosity of whole blood.

(2) When hematocrit levels were identical, an interrelation between viscosity of whole blood and that of plasma was observed.

(3) In blood which showed raised E.S.R., plasma viscosity, generally, revealed high values, and a close relationship between plasma fibrinogen and globulin concentrations was noted.

(4) In the group with identical hematocrit levels, by changing the shear rate from 230 sec^{-1} to 23 sec^{-1}, the rate of increase of specific viscosity of whole blood was found to be definitely greater in those with raised E.S.R. than in those without raised E.S.R.

From the foregoing it is inferred that the increase in viscosity due to decrease in shear rate is greater in the blood that show raised E.S.R. when compared to blood which does not show raised E.S.R.

3. Microrheology of Human Blood in Health and Disease. Effect of Blood Subphases (I.A., The Internal Viscosity and Aggregation of the Blood Cells) on blood Viscosity and Microcapillary Flow, Occlusion and Infarction.

L. DINTENFASS,* Univ. of Sydney, Australia

A study of blood and packed red cells was carried out by means of the rotational (cone-in-cone and ring-in-ring) and the capillary (parallel-plate slit and cylindrical) viscometers. Blood employed was either anticoagulated (heparin, EDTA, or acid citrate dextrose) or freshly-shed. The donors were either healthy volunteers or patients suffering from coronary heart disease, peripheral arterial thrombosis, polycythaemia, macroglobulinaemia, diabetes, haemophilia, Heinz bodies, or sickle-cell disease.

As a result of these studies a conclusive picture emerges in which the contribution of the various subphases of blood to the viscosity of blood comes to the fore in varying degree depending on the type of disease. Thus, for instance, excessive aggregation of red cells is the dominant feature of coronary diseases, high plasma viscosity is the dominant feature of Waldenstrom's macroglobulinaemia, high concentration of red cells of polycythaemia, and increased rigidity of the red cell of acidosis and sickle cell diseases.

This picture is oversimplified as the internal viscosity of the red cell is of paramount importance in the blood circulation and, especially, the microcirculation. The changes of the internal viscosity of the red cell under conditions of hypoxia, acidosis and sickling—at different shear rates or pressure drops become crucial in the development of capillary occlusion, tissue ischaemia and necrosis. Tentative rheological pathways to infarction and thrombosis will be discussed.

In principle, blood may be treated as a triple-thixotropic fluid, the three main thixotropic (or shear thinning) phases being the aggregation–disaggregation of the red cells, the sol–gel–sol transformation of the interior and membrane of the red cell, and the properties of plasma. While the latter is nearly Newtonian in many normals, it becomes extremely thixotropic (and highly viscous) in the states of macroglobulinaemia, cryoglobulinaemia and in some cases of leukaemia.

It is possible to set out tentative equations which will relate the viscosity of blood to the internal viscosity of the red cell, haematocrit and plasma viscosity; these equations covering the conditions of homogeneous velocity gradients and of axial-train flow. In the microcirculation, the basic rheological pattern of blood is modified by the Fahraeus–Lindqvist phenomenon and by an *inverse* phenomenon in which, at some critical radii of capillaries, a sudden increase in the resistance to flow takes place. The latter depends greatly on the internal viscosity of the red cell.

The importance of the ratio of the internal viscosity of the red cell to the viscosity of plasma is illustrated.

4. The Rotatory Relaxation of Fibrinogen in Mucopolysacccharide Solution Detected by Fluorescence-Depolarization. K. BABA and S. ISHIZAKA, Keio Univ., and St. Paul's (Rikkyo) Univ., Japan

It is a matter of rheological concern to observe the molecular behaviour in inhomogeneous systems, such as in a biological system. The fluorescence-depolarization method based on inelastic and incoherent scattering of the light may be competent to produce specific information on certain materials in inhomogeneous systems. The present paper deals with molecular behavior in a streaming inhomogeneous system. For this purpose the rotatory relaxation was detected by fluorescence-depolarization.

The fluorescent molecule used was bovine serum fibrinogen conjugated with fluorescein-isothiocyanate. The fluorescent molecule was mixed in an aqueous mucopolysaccharide solution. In order to grade the velocity in the solution a new apparatus with a thermoregulator was designed. The apparatus was composed of a front glass plate fixed in a horizontal position, a glass plate stroking parallel to the front glass plate. The fluorescent mixture poured into the narrow chamber between two glass plates was irradiated by the polarized light of the maximum absorbed wavelength from the incident angle of 45° with the front glass. The polarized light vector was set always horizontally and at any angle with the direction of the stroke, when the apparatus was rotated on a horizontal plane. The radiated fluorescent light in the vertical direction was analyzed into two polarized components: parallel and orthogonal to the incident light vector. Since both components were always tangential to the surface of the front glass, the fluorescent intensities of two components were measured and were reduced to the fluorescence-depolarization.

The detection of rotary relaxation by fluorescence-depolarization in an inhomogeneous system under velocity gradient has been established which was proved to be applicable in biological systems.

5. Theory of the Steady Flow of Blood in a tapered Tube and in an Assembly of Branching Tubes. S. OKA and T. MURATA, Tokyo Metropolitan Univ., Japan

Our first subject is the steady slow motion of a non-Newtonian fluid through a slightly tapered tube. Concerning the steady slow motion of a Newtonian fluid through a slightly tapered tube, general formulae for the shear stress, velocity and flow have been obtained by one of the authors. However, similar formulae for a non-Newtonian fluid have not yet been obtained. It is assumed that the fluid is characterized by a time-independent flow curve and that the tapering angle is very small. It is further assumed that the coefficient of viscosity which appears in the relationship between the stress and the strain rate of a non-Newtonian fluid is not a constant, but a function of the strain rate. From the momentum equation we have obtained general formulae for the velocity and flow in terms of the shear stress at the wall for an arbitrary flow curve. The general formulae have been applied to a fluid obeying Casson's equation like blood, and the velocity and flow have been expressed in terms of the yield value and the shear stress at the wall. These relationships are similar to those for a straight tube of uniform cross section.

Our second subject is the steady flow of blood in an assembly of branching tubes as a model of a peripheral vascular bed. From the standpoint of microcirculation the flow of blood in the peripheral vascular bed is most important. Although blood shows non-Newtonian behavior and the sigma phenomena, we have assumed that blood is a Newtonian fluid for the sake of simplicity. We have treated purely a branching of the assembly as the junction of three tubes and no account has been taken of the details of fluid motion associated with a

bifurcation. Any segment in the assembly is treated as a straight tube of uniform cross-sectional area. The Poiseuille's law may then be applicable to any segment. We have calculated the pressure-flow relation in the assembly for a given cross-sectional ratio, that is, the ratio of the sum of areas after bifurcation to the area of the parent branch, taking the distribution of length of the segments into account.

BLOOD AND BLOOD VESSELS—II

1. Fluid Flow in the Tissue Spaces. Y. NISIMARU and H. SASAKI, Atomic Bomb Casualty Commission, and Hiroshima Jogakuin College, Japan

Lymph circulation is discussed in recent literature. However, many histologists hold that while there is interchange of water, salts, ions and organic substances in the amorphous stroma of tissues due to the interrelation of blood and tissue fluid, these are two different phenomena and no concept of circulation is applicable here. If that is the case, it is not lymph circulation but lymph flow. It can be considered a fact, however, that blood components other than erythrocytes flow into tissue fluid from blood capillaries. It is also a fact that when Ringer solution, dye solution, etc. are injected into the vein of a dog they readily flow into the lymph in various parts of the body. In the frog, one can see for oneself in microscopy the dye solution that has permeated from the blood capillary to tissue space flows into the lymph capillary, and in measuring the pressure in the capillary artery, tissue spaces, capillary vein, and lymph capillary, that it is 145, 27, 100, and 7 mm H_2O, respectively. From the viewpoint of hydraulics, therefore, it can be considered that tissue fluid would easily flow into the lymph capillary but that it would be impossible for it to flow into the capillary vein

Further, comparative physiological studies show that the concept of circulation holds for tissue fluid. That is, it is observed in the Invertebrata that as the protein content of the body fluid increases, the caliber of the arteriole decreases and finally capillary vessels appear. Whereas body fluid is observed only in the tissue spaces and grooves where the blood vessels are open, tissue cavities and lymph vessels appear in addition to the tissue grooves and spaces where the blood vessels are closed. Therefore, it is important to study tissue fluid and fluid flow in the tissue spaces in the mammal also.

2. The Dynamic Viscoelasticity of Blood during Coagulation. E. FUKADA, M. DATE and M. KAIBARA, The Inst. of Physical and Chemical Research, Japan

The dynamic elastic modulus (E') and loss modulus (E'') of blood and plasma during coagulation were measured by a newly developed apparatus. About 1 ml of whole blood or plasma was filled in a gap between two coaxial cylinders, and the outer cylinder was vertically oscillated at a frequency of 10 c/s and with an amplitude of 60 microns to cause the shear strain to the sample.

In a few minutes after adding coagulant to the sample, E'' first began to increase, followed by the rise of E'. Then both E' and E'' increased rapidly and approached gradually to the saturated values. The time required for E' and E'' to reach saturated values was several hours for whole blood but less than 1 hr for plasma.

Two kinds of equation were proposed to describe the relation between elastic modulus E and time t, which was measured from the moment of adding coagulant. One is an equation $\log [E\infty/(E\infty - E)] = kt$, where $E\infty$ is the saturated value of E and k is a rate constant, which varies its value at around $t = 10$ min. The other is an equation $E = \alpha t^{\beta}$, where constants α and β vary their values at around $t = 10$ min.

The process of coagulation of blood will be divided into three stages in view of viscoelastic measurements. The first increase of E'' would indicate the onset of polymerization of fibrinogen into fibrin. The rapid increase of E' and E'' would show formation of network of fibrin fibers. The following slow increase of E' and E'' would indicate the completion of firm network involving the bonding between red blood cells and fibrin fibers.

3. Some Problems in Hemorheology. A. L. COPLEY,* Hemorrhage and Thrombosis Research Laboratories, V.A. Hospital, New York Medical College, Newark College of Engineering, U.S.A.

Our laboratories are actively engaged in experimental studies of different aspects of hemorheology. The lecture will give a brief account of the multi-disciplinary effort in which several investigators are involved. An attempt will be made to correlate our studies with those reported in the literature.

The first requirements for any extracorporeal study on the flow properties of blood is that the sample is representative without the superimposition of artefacts from collection and preservation techniques. The controversial role of anticoagulants in extra vivum measurements of viscosity was studied with R. G. King.

The data on whole blood were obtained with the Weissenberg Rheogoniometer over a wide range of shear rates (1×10^{-3} to 1×10^{4} sec^{-1}).

Studies with R. M. Jacobs and J. L. Martin are designed to probe the physical and physiological sources of the observed reduction in the apparent viscosity of blood systems in contact with certain polymers. It is also intended to provide further information on the proper boundary conditions for flow of blood systems or other biological fluids in contact with biological surfaces.

An understanding of cell distribution in capillary vessel plays an important role in such phenomena as local shear stress and energy requirements in blood flow. Red cell flow patterns near a wall as a function of flow velocity and static pressure will be reported. This work with M. J. Levy and A. U. Meyer is primarily experimental. Preliminary results will be reported with two experimental approaches. One involves a device utilizing electrical measurements. This apparatus, built at our laboratories, permits measurements of red cell concentration profiles over ranges between 0 to 5 and 0 to 100 microns. The second is an optical approach which makes use of the Baez image-splitter television microscope method.

These laboratories have demonstrated that certain enzymes at relatively low concentrations in blood, such as thrombin 10^{-3} NIH units per milliliter, can cause red cell aggregation with large changes in blood viscosity, and a decreased sedimentation stability (A. L. Copley, B. W. Luchini and E. W. Whelan, in: *Hemorheology Proc. I. Internat. Conf., Univ. Iceland,* 1966, Ed. A. L. Copley, Pergamon Press, Oxford, 1968, p. 375). The coagulation enzyme thrombin can initiate an alternate pathway of the fibrinogen-fibrin transition at these concentrations where coagulation does not occur. In the alternate pathway, soluble high molecular weight complexes of fibrinogen and a fibrin monomer are formed. The physiological and pathological relevance of this work will be discussed.

Of special interest is our study with R. G. King, B. W. Luchini, B. M. Scheinthal and M. Thaller on the formation of fibrin gels and their rheological properties. Findings of light scattering will be correlated with data of the properties of fibrin gels obtained in rotational and oscillatory shear with the Weissenberg Rheogoniometer. This study is particularly of practical significance in relation to certain hemorrhagic and thrombotic conditions, since gelation promoting (geloplastic) and gelation inhibiting (antigeloplastic) agents can then be better identified.

A critical appraisal will be given on the significance of some of the phenomena presented to unsolved problems in hemorheology.

This work was aided in part by the Office of Naval Research, United States Department of the Navy under contracts Nonr 2754(03) and NR 305–776 with New York Medical College.

4. Intravascular Coagulation Syndrome. M. MATSUOKA, Niigata Univ. School of Med., Japan

Some investigations were conducted (1) on coagulation and fibrinolysis systems and histology of various organs of rabbits administered thrombin or tissue thromboplastin by intravenous injection and (2) on the coagulation system in 5 patients with hemorrhagic tendency induced by Dextran. Results: (1) Thrombin made a marked decrease in platelet counts, fibrinogen, and factors V and VIII, caused prolongation of Quick's prothrombin time, and induced the development of cryofibrinogen. And these changes were observed fairly in parellel with the amount of thrombin administered. The same results were obtained by injection of tissue thromboplastin. Autopsy confirmed petechiae and thrombi in lungs, kidneys and in peritonea. (2) Five patients who were administered Macrodex D or Aminodextran (molecular weight 70,000) showed prolongation of bleeding time and Quick's prothrombin time, decrease of platelet counts, fibrinogen and factors V and VIII. In one patient readministration of Dextran produced the same changes in the coagulation system as mentioned above. Conclusions: (1) Hemorrhage in intravascular coagulation syndrome is attributed to thrombosis and enhancement of fibrinolysis following thrombosis. (2) The tissue thromboplastin is one of many triggers to hypercoagulability. (3) Hemorrhage induced by Dextran is involved in intravascular coagulation syndrome.

5. Rheological Properties of Large Arteries. T. AZUMA, M. HASEGAWA and T. MATSUDA, Shinshu Univ., Japan

Longitudinal and circumferential strips were excised from various portions of the aorta and large arteries of dogs. Static viscoelastic properties of these strips were studied in physiological saline of 30°C by means of an universal tensile testing instrument and compared with those of longitudinal strips of the tendon, nuchal ligament and *Tenia coli* which are composed, for the most part, of collagen, elastin and smooth muscle respectively.

Slight directional and regional differences in stress relaxation curves and hysteresis loops were observed among the strips excised from different parts of the aorta. Stress relaxation and hysteresis were hardly observable in longitudinal strips of peripheral arteries, making a striking contrast to the marked relaxation

and loop shown by circumferential strips of the corresponding portions. A linear correlation existed between relaxation strengths at one second after stretch and ones at 300 seconds irrespective of portions and direction of excision of strips. Plastic deformation always occurred after the first relaxation test. The greater the relaxation strength, the higher the degree of the deformation. Repetition of the test decreased the degree and the relaxation strength and increased the magnitude of the maximum stress. Stress relaxation, hysteresis and plastic deformation were negligible in the nuchal ligament, slight in the tendon and quite conspicuous in the *tenia coli*. Magnitude of the maximum stresses generated by 50 per cent stretch was in the order of 10^6 dynes per cm^2 in the ligament and *tenia* as well as in vascular tissue. In the tendon, however, the magnitude by 10 per cent stretch was about a thousand times greater than the above mentioned order. These findings support the following suggestions. (1) Viscoelastic properties of the aorta and peripheral arteries are determined mainly by their elastin and smooth muscle fibre contents. Contribution of collagen fibres seems to be much less. (2) Longitudinal tension of peripheral arteries is largely supplied by elastin fibres. (3) Circumferential tensions of the aorta and peripheral arteries is composed of two constituents, the one originates from elastin and the other from smooth muscle fibres. The more distal the portion, the more prominent contribution of the latter becomes.

6. Rheological Significance of Species Differences in Erythrocyte Deformability. M. I. GREGERSEN, S. USAMI, C. A. BRYANT, S. CHIEN and V. MAGAZINOVIC, Columbia Univ., U.S.A.

A series of calibrated Nuclepore filters (polycarbonate sieves) with mean pore diameters from 2·4μ to 6·8μ were used to determine the smallest pore size through which suspensions of washed erythrocytes (RBC) could be filtered without change in concentration at 10 to 20 cm of H_2O pressure. RBC's in freshly drawn heparinized blood of goat, sheep, dog, man, elephant and turkey were washed three times in Ringer or Eagle solution containing 0·25% human albumin (Gregersen *et al.*, Science, 157: 825, 1967) and suspended in the same medium at concentrations of approximately 50,000 RBC/mm^3. RBC counts in the filtrate and the original suspension were made with a Coulter electronic counter (Hialeah, Florida) to determine percent RBC transmission.

For RBC's of elephant (major diameter 9·2μ, MCV 112μ^3) and man (m.d. 7·2μ, MCV 87μ^3), 100% transmission occurs with 3μ pores. However, for goat RBC (m.d. 3·5μ, MCV 18μ^3) only 40–50% transmission is obtained with the same 3μ pores, whereas 100% transmission requires 3·5 to 4·0μ pores, which is sufficient even for the large nucleated RBC of the turkey (m.d. 14–16μ, MCV 136μ^3).

Species differences in flexibility and deformation of RBC's are also indicated by differences in the degree of maximal packing of RBC obtained with centrifugation. This in the normal, deformable RBC suspensions ranges from 91% for goat to 99% for man (Chein *et al.*, *Proc. Soc. Exp. Biol. Med.* 119: 1155, 1965). When the RBC's are hardened and nondeformable, the maximal packing becomes only 60% (Chein *et al.*, *Proc. Soc. Exp. Biol. Med.*, 127, 1968, in press).

It is apparent from the viscometric properties of RBC suspensions that deformability of the RBC's serves to maintain the fluidity of blood as well as facilitate passage of RBC's through the smallest capillaries; and that, besides rouleaux formation, deformation of RBC's also influences the viscometric behavior.

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7. Viscometric Behavior of Hardened Erythrocytes in Relation to Deformability and Size. S. USAMI, S. CHIEN and M.I. GREGERSEN, Columbia Univ., U.S.A.

The viscosity of normal erythrocyte suspensions is non-Newtonian and its values are reduced by high shear condition because of the deformation of erythrocytes (Gregersen *et al.*, Science 157:825, 1967). In an attempt to analyze the influence of erythrocyte deformability and size on the viscosity of blood, the viscosity of suspensions of erythrocytes hardened with acetaldehyde (Heard and Seaman, *J. Gen. Physiol.*, 43:635, 1960) has been measured in a modified version of GDM viscometer (Gilinson *et al.*, *Trans. Soc. Rheol.*, 7:319, 1963; Gregersen *et al.*, *J. Appl. Physiol.*, 20:1362, 1965) at 37°C. The hardened erythrocytes studied were prepared from the blood of five animal species with the mean corpuscular volume covering a sixfold range (goat 18μ^3, sheep 37μ^3, dog 72μ^3, man 87μ^3, and elephant 112μ^3). In all five species the viscosity of hardened erythrocyte suspensions is essentially independent of shear rate from 52 to 0·052 sec^{-1}, indicating a Newtonian behavior. Therefore, in agreement with previous studies on human and dog hardened cells (Chien *et al.*, Science 157:827, 1967), the present results on all five species indicate that the reduction in viscosity at high shear rates seen in the suspensions of normal erythrocytes is no longer observed when the erythrocytes are rendered nondeformable. In each species, the viscosity is elevated progressively with increasing cell percentages and rises

toward infinity when the cell percentage approaches 60%, which is the maximal packing possible for the hardened erythrocytes (Chien *et al.*, *Proc. Soc. Exper. Biol. Med.*, 127, 1968, in press). The relationship between viscosity and cell percentage shows no significant difference among the five species studied. It is concluded that the suspension viscosity of mono-disperse and non-deformable erythrocytes is determined by cell percentage rather than cell size.

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OTHER BIOLOGICAL SYSTEMS

1. Study of the Deformability of Macromolecules by Surface Viscometry. M. JOLY,* Service de Biophysique, Institut Pasteur, France

The structure of the monolayers of amphiphilic substances spread on water, and the significance of the surface viscosity are briefly reminded.

By applying to the laminar flow of surface layers the general theory of viscosity considered as an activation process, it is possible to calculate the surface viscosity as a function of the molecular interactions. Since the water molecules in contact with the polar groups of the amphiphilic molecules are rigidly bound to them, they perform the same displacements during the flow. The contribution of these water molecules to the activation energy of flow of the surface layer can be calculated directly. It depends only on the temperature and molecular area. Therefore, the part of activation energy flow due to the amphiphilic molecules can be derived from the experimental values of the surface viscosity. If the amphiphilic molecules are not deformable, the corresponding activation energy of flow is only depending on the energy of interaction between these molecules.

In the case of monolayers of macromolecules, assumed to be rigid molecules, the activation energy of flow due to the bound water molecules, is very high. The corresponding theoretical value of surface viscosity, in almost every cases, is much higher than the experimental value. The surface flow data are therefore incompatible with the hypothesis of rigid macromolecules.

This result leads to consider the relative motion of the monomers inside of each macromolecule. The deformability of the macromolecule can be characterized as follows:

For the flow of independent kinetic units having surface area equal to that of one monomer, it is possible to derive an interaction energy between each kinetic unit and its neighbours the value of which leads to a surface viscosity equal to that of the macromolecular layer, as given by experiment. This fictitious interaction energy between monomers can be used to characterize the deformability, and to define the apparent internal cohesion energy of the macromolecule spread on water.

From the experimental data obtained by several authors the deformability of a great number of high polymers, synthetic polypeptides and proteins is studied as a function of various parameters such as molecular surface area, temperature and pH of the subphase. The main results are discussed from a structural point of view.

2. Rheological Properties of Sputum. S. NAGAOKA and Y. FUKUSHIMA, Municipal Hiroo Hospital, Japan

In many cases of chronic bronchitis and bronchial asthma, difficult expectoration of viscid sputum is one of the important symptoms.

In order to observe the rheological property of sputum, the sputum in test tube was pulled at negative pressure. It was observed then that sputum is a non-Newtonian fluid which shows yield point and its behavior was similar to the plastic flow of tooth paste and the yield values varies considerably from patient to patient.

It is no easy matter to observe the rheological property of sputum in the natural state as it is in the air way. Yield value of intact sputum was measured by means of modified J. C. White's method and using this value as the index of consistency various causes were observed. The results were as follows.

1. There was a correlation to some extent between consistency of sputum and symptoms of air way obstruction.
2. Due to administration of mucolytic agent, a large proportion of these patients showed a remarkable decrease in the viscosity of sputum.
3. The parallelism was not necessarily observed between the change in the clinical manifestation and that in the consistency of sputum.

Sputum was divided into solid layer and liquid layer and then the flowing velocity of the liquid layer, which was thought to be relatively homogeneous, was measured with Ostwald's viscometer.

Then, the same sputum specimen was stirred and the flowing velocity was measured in two bines.

It was observed that the flowing velocity was reduced in order.

Furthermore after being rested at room temperature for 30 min, the flowing velocity of the same specimen indicated the same as that in the first measurement.

This is thought to be thixotropic phenomenon and it gives a Patho-Physiological suggestion as to relation the action of cilia in epitheliar cell lining the air way and the consistency of bronchial mucus immediately surrounding the cilia. Some experiments to prove this hypothesis were performed.

Namely, in most cases of airway diseases ciliary action is impaired, and it is thought to be one of the causes of increased viscosity of sputum.

In these cases, as it is thought that the tissue force by cough causes expectoration of sputum, studies were made on relation between volume and consistency of sputum and dynamics of cough.

3. Simultaneous Determination of Viscosity and Surface Tension of Several Biological Liquids by Adachi's "Capillary Fall" Method. Y. MURAKAMI, Shinsei-Kai, Japan

"Capillary Fall" method was devised by Dr. Adachi (University of Telecommunication, Yokyo) when he was a research associate at Tokyo University. It is similar to "Capillary Rise" method, but a more dynamical one. The rate of the fall of a liquid in a vertical capillary tube can be shown as $(-\mathrm{d}l/\mathrm{d}t)$ in the following equation.

$$\pi a^2 l\rho g\cos\theta + \mathrm{d}\{\pi a^2 l\rho(-\mathrm{d}l/\mathrm{d}t)\}/\mathrm{d}t - 2\pi al\eta\cdot\mathrm{d}w/\mathrm{d}z - 2\pi a\gamma\cos\alpha = 0 \quad (1)$$

where
- l = length of the liquid colunm passing down the capillary, i.e. the height of the meniscus
- a = internal radius of the capillary
- θ = declining angle of the capillary from the vertical line
- g = acceleration of the gravity
- ρ = density of the liquid
- η = viscosity of the liquid
- γ = surface tension of the liqiud
- α = contact angle between the liquid and the internal surface of the capillary
- $\mathrm{d}w/\mathrm{d}z$ = velocity gradient in the capillary of the liquid.

The second term of this expression represents the inertia, and simplification can be achieved by noting that, in capillaries of the order of size involved here, inertia is negligible. The third term representing viscosity can be written as $8\pi l\eta\cdot\mathrm{d}l/\mathrm{d}t$. The equation (1) then reduces to

$$\pi a^2 l\rho g\cos\theta + 8\pi l\eta\cdot\mathrm{d}l/\mathrm{d}t - 2\pi l\gamma\cos\alpha = 0 \quad (2)$$

$$\therefore\ v(=-\mathrm{d}l/\mathrm{d}t) = a^2(\rho g\cos\theta - 2\gamma\cos\alpha/al)/8\eta. \quad (3)$$

The last equation shows a linear relationship between v and $1/l$.

Thus the η of the liquid is obtainable from the following equation (4) by inserting the value of the v_∞ into it and the γ can be derived from the equation (5).

$$\eta = a^2\rho g\cos\theta/8v_\infty \quad (4)$$

$$\gamma\cos\alpha = -\frac{4\eta}{a}\,\mathrm{l}\mathrm{d}v/\mathrm{d}(\mathrm{l}/l)\mathrm{l}. \quad (5)$$

Both v_∞ and $dv^*/d(\mathrm{l}/l^*)$ can be determined experimentally and diagrammatically from $(\mathrm{l}/l^*)-v^*$ plot. The $(\mathrm{l}/l^*)-v^*$ line was straight in most cases but a few kinds of solutions of some surface active agents gave curves. The tested substances are as follows.

(A) Naturally ocurred surfactants as fatty acid, cholates etc.
(B) Human serum
(C) Polypeptides
(D) Lipopolysaccharides
(E) Other bio-polymers as protein, starch etc.
(F) Artificially modified bio-polymers
(G) Synthetic substances which have similar structures to those of naturally occured surfactants and bio-polymers.

Human serum could be very easily handled with this instrument but some other substances as egg-white could not. The merits of this method consist in the capability of speedy and simultaneous determination of η and γ with very small quantity of the specimen (less than 0·1 ml).

4. Circulatory Role of Protoplasmic Streaming in Cells. Y. NISHIDA, Univ. of Hiroshima, Japan

Many factors not solved experimentally have been noted in problems on circulation in tissues and in cells, and consequently concept on circulation has not been clearly established from the standpoint of circulation physiology.

On the other hand, the term "circulation" or especially "microcirculation" recently used in physiological science has not been used precisely in the same sense, as the definition of the same term as used in physical science.

Moreover, it is a fact that the intracellular circulatory domain is still not involved even by the term "microcirculation" in physiological science.

These facts have made problems more complicated, and made unification or generalization of the concept concerning circulatory function widely existing in living bodies difficult, both in plant and animal societies.

On the contrary, regardless of the above contradictions the term "circulation" in cells has been used for description of some definite patterns of intracellular movement.

In seeking a clue to settle these difficulties, the stamen hair of Tradescantia virginica are used here as an experimental model, and some results are discussed centering on the relation between the protoplasmic streaming in cells and the positive contribution on the material transport, and also on the circulatory role defined here in the cells.

5. Mechanism of Phagocytosis: Ingestion of Solid Particles by Macrophage. E. YOKOMURA, N. ITOH, and S. SENO, Okayama Univ. Medical School, Japan

The macrophae adsorbs metal colloid particles of negative charge when they come into contact with the cell membrane, and it ingests the particle in due time, by the phenomenon we call phagocytosis. The living cell may be considered to be a kind of colloidal system composed of a complex gel whose specific molecular arrangement is supported by the energy produced in the living cytoplasm. A variety of factors and components in the environment may act to disturb the molecular configuration of living cytoplasm, e.g. various ions or ionized molecules coming into contact with cell membrane may largely induce the disintegration of some weak bondings among the high molecules in the local cytoplasm by the so-called cooperative phenmenon or the reversible gel to sol transformation. Local lysis in the geled cytoplasm may induce a morphologic change in that area. Present observation indicates that the phagocytosis is triggered by the adhesion of the charged particles to the cell surface followed by the formation of engulfing and processing at the area probably due to the local lysis of the geled cytoplasm. The phagocytic vesicles thus formed may sink depeer in the cytoplasm but it keeps communication with the cell surface through a small connecting tubule for a long period without being pinched off unlike the general concept. Through these connecting tubules the colloid particles are further transferred into the phagocytic vesicle. Thus the vesicles grow to the vacuoles of tremendous size, by which the cell is enlarged to several times the original volume. The mechanism is understood only by the sliding movement of the cell membrane carrying the colloid particles, probably by the movement of the outer half of the bimolecular lipid layer, which is the essential structure of cell membrane.

6. The Stiffness Change and the Activation Process During Muscle Twitch. H. MASHIMA, Juntendo Univ., Japan

Two component model, contractile and series elastic components, was adopted to analyse the dynamic properties of activation and contraction of the skeletal muscle. A small bundle isolated from semitendinosus muscle of the frog was prepared, one end was fixed to the isotonic lever and the other end to the tension recorder. The preparation was soaked into Ringer solution between a pair of platinum foil electrodes and stimulated by transverse electrical current pulse with the duration of lmsec. The muscle was released by about 5% of the length after the stimulus in order to remove the stress of the series elastic component, and then it was stretched quickly (50cm/sec) by the same length as released. The stiffness of the contractile component at that moment was estimated from the tension developed by the quick stretch. The stiffness thus obtained was increased for about 20msec after stimulus and more rapidly for successive 20msec at 10°C. Assuming that the rate of stiffness increase is a mechanical representation of the activation process, it is apparent that the muscle filaments were activated in two steps. Probably the first rapid activation within 20msec after stimulus is due to synchronized activation of many cross bridges between filaments. When two stimuli were applied within an interval of 15msec, no change was observed in the first rapid activation, although the second step was enhanced to the full activation by the second stimuli. The third or further stimulus has no enhancing effect on the rate of stiffness increase.

7. Rheological Understanding of Origin of Inner-Ear Acoustic Fatigue and Trauma. H UCHIYAMA and T. NEGISHI, Inst. for the Deaf, Tokyo Medical and Dental Univ., Japan

Mechano-electrical transduction in auditory process is performed by the receptor cells which are situated in the vibratory structure of the inner ear. The output of this biological transducer to acoustic stimulation is known as receptor potentials, referred to as microphonic-for AC-and summating potential for DC component. The energy for the potentials is supplied, like in a carbon microphone, not by the input mechanical energy itself but by living tissue batteries, so that the change of the receptor potentials should be brought about by changes either of the mechanical property of the vibratory structures or of the source potential of the biological batteries.

When the ear is under a *strong* acoustic load, the receptor potential to a low-level constant load shows a change either recoverable or irrecoverable; the recoverable is an effect of *acoustic fatigue* while the irrecoverable is of *acoustic trauma* (the "fatigue" used here is a physiological term, different in definition from that in material science). And such potential changes are believed by many investigators to be due entirely or mainly to a change of metabolic process of the potential source by overstimulation.

The aim of our presentation is to suggest, in contrast to current opinion, a strong possibility to ascribe the origin of the above bioelectrical phenomena to the underlying viscoelastic behavior of the vibratory structures. The essential part of our hypothesis is that the process of acoustic fatigue is the retarded elastic deformation of non-linear Voigt element occurring somewhere in the inner-ear vibratory structures, and that at least a part of the process of acoustic trauma is the plastic flow above the yield point, inclusive of the fracture with a further increase of load. This well explains the following phenomena: an exponential time course in the recoverable change of the microphonic as well as of the summating potential (an irrecoverable creep-like potential change being added by an increased load), a hysteresis loop as observed on the load-potential diagram which is called "intensity function" in physiological acoustics, and some other phenomena such as non-linearity in the potential change as a function of load, a wave form distortion of the microphonic potential and a change of the time course as a temperature effect.

SUBJECTS CLOSELY RELATED TO BIORHEOLOGY

1. The Kinetics of Flowing Dispersions in Non-Newtonian Media. S. G. MASON,* McGill Univ., Canada

Particles in a dilute suspension undergoing shear are acted upon by surface forces, and translate relative to one another. As a result they can assume preferred orientations, can be deformed, and can undergo collisions with one another. An extensive series of theoretical and experimental studies of the rotations, deformations, orientations, n-body collisions ($n \geqslant 2$), and wall effects of a variety of particles shapes, types and sizes in dilute and concentrated suspensions undergoing laminar shear flow in Newtonian suspending fluids has been completed

When non-Newtonian suspending fluids are used, a number of significant differences in microrheological behaviour are observed and which will be described.

2. Hydrodynamic Behavior of an Elastic Rod-Like Particle in Poiseuille Flow. J. NISHIMURA and S. OKA, Showa Denko K.K., and Tokyo Metropolitan Univ., Japan

In the preceding investigation, (J. Nishimura and S. Oka, *Reports on Progress in Polymer Physics in Japan*, X, 107 (1967), we have treated the hydrodynamic behavior of a slightly curved rigid rod in a simple shear field. According to the study, the curved property of the rod has relatively great influence on its motion and consequently on its energy dissipation.

In this study, we extend the above treatment on two points. One is to add the bending elasticity to the rod and the other is that the shear field is not linear. When the rod is in a linear shear field, no bending moment acts on it which is straight in the stress-free state. This means that the intrinsic viscosity, for example, differs to some extent according to the measuring method adopted for the present case. If the rod is very thin and the deformation is very small, we can regard the rod as an arc and can express it by the power series of the curvature, the coefficients of which are function of the contour length of the arc. The curvature is to be related to the bending moment. We determine the force to act on the rod from the Oseen's formula as usual and the motion of the rod, by the balancing condition of the force and the moment of force.

As the result we can show the translational velocity of the rod is perpendicular to the direction of the flow. This effect seems to be induced in defect of the point-symmetry of the particle. We can also estimate the intrinsic viscosity and can introduce its shear dependence caused by the deformation of the rod.

3. Pulsatile Flow of Suspensions through Tubes. M. TAKANO and S. G. MASON, McGill Univ., and Pulp and Paper Research Inst. of Canada, Canada

The translation, rotation and radial migration of neutrally buoyant single rigid spheres, rods and discs, as well as the deformation and radial migration of single fluid drops were studied in suspensions of Newtonian liquids subjected to oscillatory and pulsatile flow in rigid circular tubes over a range of the α parameter from 1·8 to 20 and at particle to tube radius ratios b/R, from 0·04–0·54. At $b/R > 0{\cdot}1$ the axial displacements were in accord with the theory of Womersley except for particles close to the tube wall; the rotation and deformation of the spheres and cylinders could be accounted for by theory applicable to steady flow if the oscillating velocity gradient was inserted into the equation of motion.

Rigid patricles exhibited the tubular pinch effect and drifted radially to eccentric equilibrium positions determined by α and b/R. At the same time, rigid cylinders, unless initially very close to the wall, gradually assumed rotational orbit corresponding to maximum energy dissipation. In contrast, deformable liquid drops always migrated inward as previously found in steady flow.

Studies were also made in concentrated suspensions up to 40% by volume of disperse phase, combining visual observations of particle inward migration and interaction at the tube periphery with measurements of the change in axial displacement profiles and power dissipation in the tube with time. Larger rigid spheres at low concentrations were found to accumulate in groups approximately equally spaced in a central core in which the velocity profiles were blunted. At concentrations above 10% and at all b/R, a particle depleted layer developed at the wall. This was reflected in the displacement profiles and power dissipation of the suspensions. The power dissipation in fluid drop suspensions decreased with time at all b/R and contracentions corresponding to an observed inward migration and packing of drops in the centre of the tube.

Some results of studies on particle behaviour in visco-elastic liquids in convergent and elastic tubes will also be presented.

4. Drag Forces in Bingham Plastics. R. L. WHITMORE,* Univ. of Queensland, Australia

The problem of calculating the drag experience by a two or three dimensional body immersed in an Bingham plastic has so far defied rigorous analysis. When the flow rate is high an approximate solution, based on the assumption that the plastic behaves as a simple liquid possessing a viscosity equal to the plastic viscosity, is reasonably satisfactory but under creeping flow conditions it is quite unsatisfactory. Solutions based on a model of an immobile region of Bingham plastic surrounding the body, whose thickness depends upon the flow rate are shown experimentally to be of doubtful validity and alternative models are suggested.

5. Mechanical Denaturation of Silk Fibroins. E. IIZUKA, K. HIRABAYASHI and Y. GO' Shinshu Univ., and Aichi Univ. of Arts ,Japan

As one of the common natures of the silk fibroin, it undergoes mechanical denaturation under shearing stresses in the silkgland. This is a result of the conformational transition in which a change from internal to external hydrogen bonding is involved and this accompanies the precipitation of fibroin molecules.

The conformation of silk fibroin in solution is specific to the subfamily to which it belongs. The types of the conformation found so far are: coiled (Bombyx and Anaphe groups), α-helical (Saturniinae group) and β-form (Stenopsyche griseipennis and Margaronia pyloalis). Among these, Saturniinae fibroins contain polyalanine sequences in the molecular chain. It is known that poly-L-glutamic acid precipitates as the β-form by shaking only when α-helical and coiled conformations coexist and that polyvinyl alcohol with high syndiotacticity forms fibre under shearing stresses. These lead to the following idea that the ordered and disordered conformations coexist in the molecular chain when the polymer shows the property of mechanical denaturation. The coiled chain of Bombyx fibroin is composed of alternate arrangement of hydrophillic sequences and hydrophonic ones, instead.

The molecular chain of Bombyx fibroin is considered to be folded in some way. Two molecules located at different distances from the central line of the anterior silkgland flow at different velocities parallel to the line, which causes the collision and joining of the molecules. As the shear rate increases toward the outlet, the junctions would be cut off, however, new joining of the molecules occurs more frequently. Finally unfolding of the molecules is generated to form nuclei for the fibrols of the fibre structure, when viscoelastic resistance of the folding structure is overcome by the shear stresses.

One of the two components of such blockpolymer-like molecules would play a role in joining of the molecules. The overall structure of the molecule then would be suitably arranged to be unfolded.