

THE HISTORICAL DEVELOPMENT OF THE ENGINEERING ANALYSIS OF BLOOD FLOW

by **A. R. GIAQUINTA**

Assistant Professor of Mechanical & Aerospace Engineering and Bioengineering,
University of Missouri-Columbia, Columbia, Missouri.

Presently, Research Associate,
Institute of Hydraulic Research, University of Iowa,
Iowa City, Iowa.

Introduction

Interest in the flow of blood in living animals probably originated the first time that blood was spilt. Most certainly, curious man must have wondered about this strange fluid which appeared at the site of a wound. Engineering interest in this life sustaining fluid was obviously not developed until much later, and although some of the more basic questions about blood may have been answered, they were replaced by more complex ones. Even today researchers are continuing to study blood, both as a fluid undergoing certain conditions of flow, and as the fluid necessary for health and life.

This paper traces the historical development of the engineering analysis of the flow of blood. What is meant by engineering analysis is the application of general physical laws of fluid flow and mathematical descriptions of fluid motion to the particular problem of the flow of blood in living animals. Presently there is a great deal of interest in the flow of blood (and other biological fluids) as an engineering problem. Studies are being made on almost every aspect of the motion and the properties of this peculiar fluid. This historical survey is not so ambitious as to treat every aspect of the development of the present "state of the science" or to give credit to the contributions of every investigator, but it is limited to a few topics and to the work of only a small number of researchers. The period of time from antiquity to the fifteenth century is briefly discussed in general terms. Beginning with Leonardo da Vinci in the fifteenth century, the contributions of four scientists representing the most significant

advances in the engineering analysis of blood flow up to the beginning of the nineteenth century are presented in detail. Some contributions after about 1850 are merely listed, and reference is made to other historical surveys already in print. Included in this presentation are some facts related to topics of more general engineering interest such as flow in capillary tubes, measurement of fluid viscosity, and flow in elastic conduits.

Contributions of antiquity

Many ancient cultures exhibited varying degrees of interest in the circulatory system, the heart, and blood; and there was an almost universal concern in the heart beat, the pulse, and the relationship of blood to life. Some of the ancient ideas were centered in the religious life of particular civilizations as can be illustrated in the practice of blood sacrifices, both human and animal, the former occurring in the Aztec world and the latter found among the ancient Hebrews, for example. There was very little that could be classified as an engineering analysis of blood flow, although the Chinese, the Hindu, and the Egyptian cultures appreciated something about the relationship of the pulse to the heart beat. Much of the ancient Chinese philosophy concerning the blood and the heart (and other aspects of medicine) has been passed on by tradition although some has been preserved in written form. The great significance assigned to the condition of the pulse is illustrated in *The Yellow Emperor's Classic of Internal*

Medicine [1](*). This classic represents the basis of Chinese and Japanese orthodox medicine, and it is regarded in China as perhaps the most influential medical work in existence. The concepts and ideas could hardly be considered as engineering contributions and attention must be focused on other cultures to find the roots of any rational analysis applied to the flow of blood.

The most sophisticated ideas about the circulatory system came from the Egyptians [2]. One of the greatest surviving treatises on medicine from this civilization is the Papyrus Ebers [3]. This document, written around 1550 B.C., includes a section dealing with the movements of the heart and the relation of the heart to the pulse. It contains, however, no indication of an understanding of the primary role of the heart, i.e., pumping the blood. There is also the explicit statement that the breath which enters the nose goes into the heart from the lung [3]. This concept may have influenced later writers and is significant in the development of the analysis of the circulatory system as will be seen later.

The Egyptian philosophy had a very strong influence on the development of Greek medicine, and it is from the contributions of the Greeks that further advancements in the understanding of the flow of blood were based. These contributions were limited in scope partially because scientific endeavor was closely associated with the efforts of the philosophers. Explanations of various phenomena through physical and mathematical principles were not considered important and in some respects not possible (indeed, mathematics was not really developed by this time), and inductive reasoning was the key tool for research. However, some of the opinions of the ancient Greeks will be mentioned as examples of early ideas of the cardiovascular system, particularly those concepts which survived the test of time and affected the thoughts of later investigators.

As early as the sixth century B.C., Alcemon of Croton contributed the concept that the blood is transported in vessels originating in the heart. He is also credited with being the first Greek to have practiced dissection [4].

In the Hippocratic Corpus (fifth century B.C.) an early suggestion of the circulation of blood is found. The treatise *On the Localities of Man* contains the following statement [4]:

"The vessels communicate with one another and the blood flows from one to another. I do not know where the commencement is to be found, for in a circle you can find neither commencement nor end, but from the heart the arteries take their origin and through the vessel, the blood is distributed to all the body, to which it gives warmth and life;..."

This statement is probably the first reference to a closed circulation system, which was not formally presented until 1628 by William Harvey.

Empedocles of Agrigento, originated the doctrine of the four elements. He also contributed the idea of the blood transporting "innate heat" and issuing from the heart and returning to it, moving forward and backward by tides and pulsations [4].

Phylition of Locroi (fourth century B.C.) has been given credit for the authorship of a Hippocratic document entitled, *On the Heart*. This treatise contains an amazingly accurate description of the heart and of the large vessels.

However, because the document was so far ahead of its time, and because it broke the continuity of the development of ideas, the authenticity of its authorship has been challenged, and it is believed that *On the Heart* was added to the Hippocratic Corpus at a later date [4].

The conquests of Alexander the Great led to the spread of Greek thought to other parts of the world, and after Alexander's death the center of scientific research and learning moved to Alexandria. There, Ptolemy I Soter, king of Egypt (and his son) built the Museum and the Library. The greatest scientists and physicians of the time gathered here, and an important change in viewpoint took place. Scientific research became independent of philosophy and pursued its proper goal, the explanation of natural phenomena.

The atmosphere at Alexandria stimulated two great physicians, Herophylos of Chalcedon and his assistant and rival, Erasistratos of Chios, through whom the development of some engineering concepts of blood flow can be traced (third century B.C.). Herophylos, for example, showed that the heart transmits its blood and its pulsations to the arteries and he studied in detail the rhythm of the arterial pulse with a clepsydra [4]. Erasistratos presented the concept of separate systems for the transport of blood and air. He also studied the anatomy of the heart and presented excellent descriptions of some of the valves of the heart.

Perhaps the most important link between antiquity and more modern times was Galen of Pergamon (131-201 A.D.). Galen had an excellent education in many fields, and he knew of most of the medical knowledge which had accumulated for centuries before him. His travels took him through Alexandria where he learned of the contributions of Herophylos and Erasistratos. Later Galen became the physician of the Emperor Marcus Aurelius.

The significance of Galen's interpretation of how blood flows in the body is made apparent by the fact that the Galenic system was spread throughout the ancient world, translated into many languages, and was accepted almost without question until the sixteenth century. (The Arabian physician, Ibn Nafis, has been given credit for rejecting some Galen's errors in the thirteenth century.) Some of Galen's ideas were quite correct and represented definite advancements in the state of knowledge of the motion of the blood. For example, he understood how the direction of blood flow from the heart was governed by the cardiac valves. On the other hand, many of his concepts contained gross errors such as the notion that air and blood mixed in the heart and that blood passed directly from the right to the left ventricle through invisible pores in the interventricular septum. The blind acceptance of the Galenic teachings by so many cultures and for so many years was indeed unfortunate, and in the fifteenth century, serious questioning and revising of the traditional dogma was initiated. It was into this atmosphere that Leonardo da Vinci entered when his interests became focused on the cardiovascular system.

Leonardo da Vinci

Before considering the contributions of Leonardo da Vinci (1452-1519) to the understanding of the mechanics of blood flow, the events in his life and the circumstances which led him to study the human form will be mentioned. Leonardo's contributions to art, engineering, and science were so numerous that only a detailed biography could

(*) Numerals in brackets refer to the references at the end of the paper.

amply treat all of them. Such detail is beyond the scope of the present paper, and attention is centered only on his treatment of the circulatory system, and then, not from the viewpoint of an anatomist, but as an engineer. Naturally art and anatomy must be mentioned because it was through these subjects that Leonardo's interest in blood flow was developed.

It is generally believed that da Vinci worked with the artist Verrocchio from about 1466 until 1481 [5, 6]. At Verrocchio's studio, da Vinci met Pollaiuolo, Botticelli, Uccello, and others who probably introduced Leonardo to the "anatomical point of view" in drawing. At this time, art was the central object of many scientific endeavors; anatomy, geology, mechanics, and botany were all studied, but mainly from the point of view of an artist wishing to understand his human subject and his surroundings more completely. Appreciation of mathematics was also encouraged at the studio as Verrocchio, Uccello, and da Vinci believed that mathematics, in particular geometry, contained the root of all art—and science [5].

After leaving Verrocchio's studio, Leonardo became more interested in anatomy and physiology from a scientific point of view. His most intensive studies of the anatomy of the heart were performed about 1513.

Much of da Vinci's work was devoted to the study of mechanical principles and their applications. That he recognized the general importance of mathematics and mechanics is clear [5] (*).

"Mechanics is the paradise of the mathematical sciences, because by means of it one comes to the fruits of mathematics. Therefore, O students, study mathematics, and do not build without foundations."

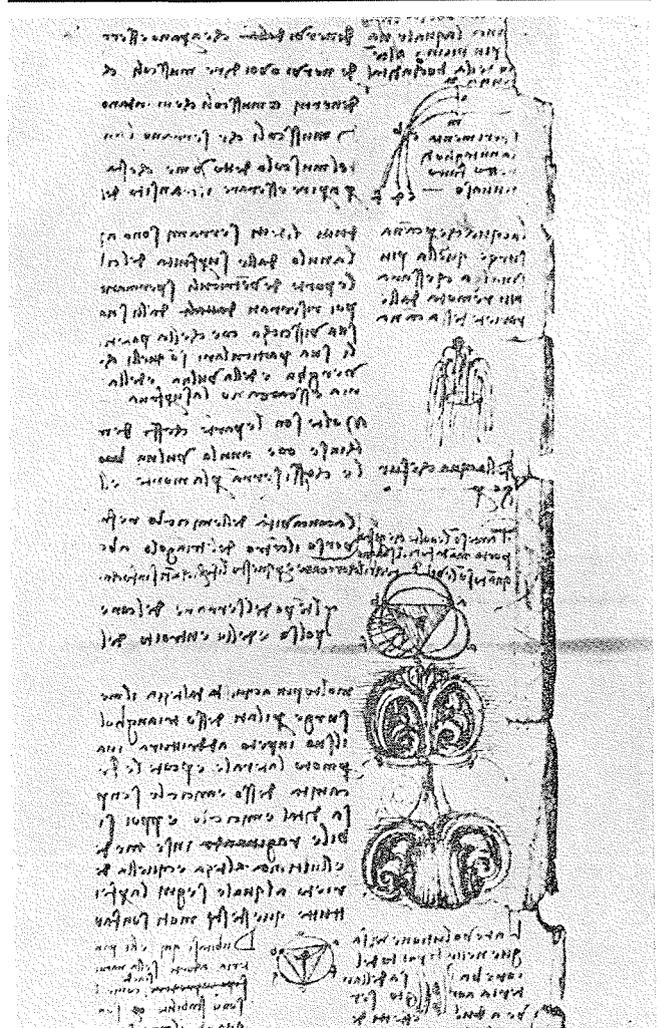
His manuscripts were liberally cross referenced from one subject to another, and it can be seen that the theories formulated were applied to many fields. Results obtained in mechanics, for example, were applied to biology. The same principles were used to discuss the flow of water in a river and the flow of blood through the aorta. An example of the application of "general laws" is seen in the treatment of eddy formation, applicable to a river discharging into the sea or the stream of blood entering the aorta, the former described verbally, and the latter seen in various sketches, as illustrated in Figures 1-3.

"Universally all things desire to maintain themselves in their natural state. So moving water strives to maintain the course pursuant to the power which occasions it, and if it finds an obstacle in its path it completes the span of the course it had commenced by a circular and revolving movement. So when water pours out of a narrow channel and descends with fury into slow-moving currents of mighty seas—since in the greater hulk there is greater power and greater power offers resistance to the lesser—in this case, the water descending on the sea beats down upon its slow-moving mass, and this cannot make a place for it with sufficient speed because it is held up by the rest of the water; and so the water that descends, not being willing

to slacken its course, turns round after it has struck, and continues its first movement in circling eddies, and so fulfills its desire down in the depths for in these same eddies it finds nothing more than its own movement, which is attended by a succession of circles one within the other; and by thus revolving in circles its course becomes longer and more continuous, because it meets with no obstacle except itself."

Another interesting example is related to Leonardo's treatment of the effect of friction.

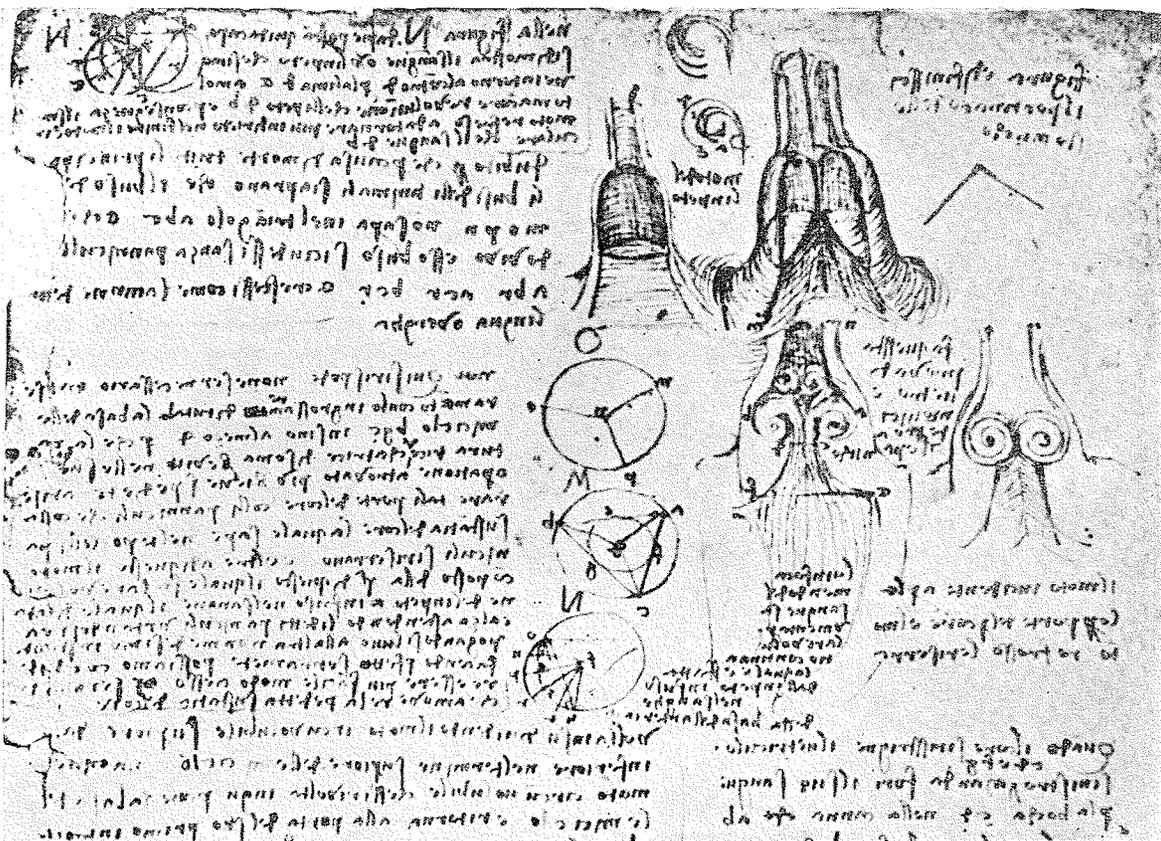
"The action of friction is divided into two parts, of which one is simple and all others compound. Simple is



1/ The formation of eddies in the blood entering the aorta. Blood flow passing the aortic valve is compared to a combination of the flows described in the figure. The top sketch shows the deviation of water impinging on an edge; the next below shows water spouting from a pipe. The lowest sketch shows the flow past the triangular orifice of the aorta as a combination of the two simpler flows [5].

La formation de tourbillons dans le sang à l'entrée à l'aorte. L'écoulement sanguin par la valve aortique est assimilé à une combinaison des différents écoulements définis dans la figure. Le croquis du haut représente la déviation d'un jet d'eau au contact d'un bord franc; celui du milieu représente un jet d'eau issu d'un tuyau. Le croquis du bas représente l'écoulement au droit de l'orifice tricuspide de l'aorte, sous forme de combinaison des deux écoulements plus simples [5].

(*) Unless otherwise indicated, all of the quotes from Leonardo da Vinci concerning blood flow are from reference [5] which is a secondary reference. The primary references are listed here for completeness. Manuscripts A-I, Institut de France. Quaderni d'Anatomia I-IV, Royal Library, Windsor. Forster Bequest Manuscript II, Victoria and Albert Museum. Arundel Manuscripts, No. 263, British Museum. Codice Atlantico, Manuscript formerly in possession of Earl of Leicester.



2/

2/ The flow of blood through the aortic orifice. The relative dimensions of the orifice are shown, and the formation of "contrary" eddies is indicated in the central figure [5].

L'écoulement sanguin par l'orifice tricuspide. Les dimensions relatives de l'orifice sont représentées sur la figure; le croquis du milieu indique l'établissement de tourbillons « contraires » [5].

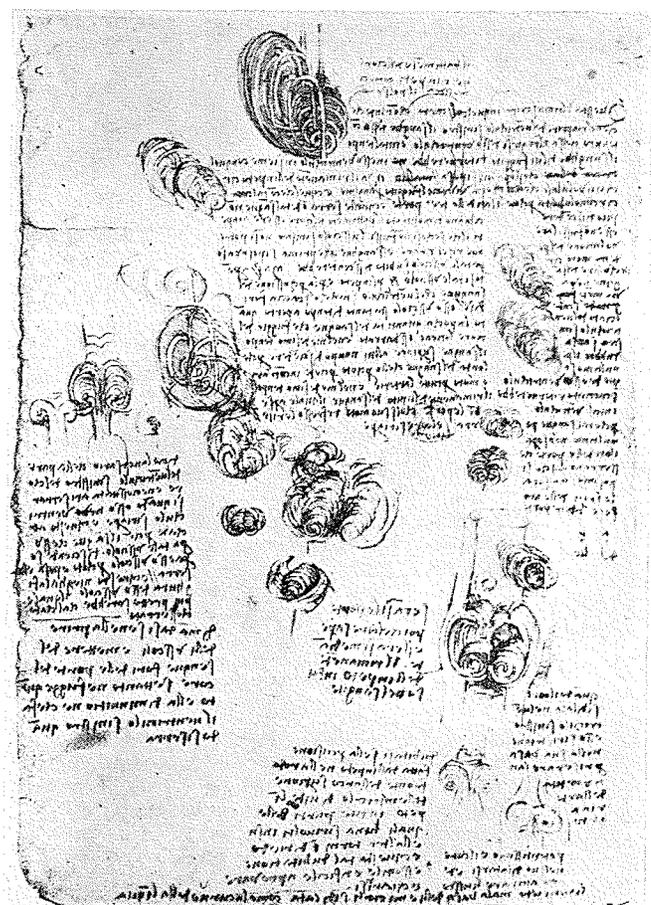
3/ Eddy formation in the blood entering the aorta. The eddies closing the aortic valve cusps are shown [5].

L'établissement de tourbillons dans l'écoulement sanguin à l'entrée à l'aorte. On y remarque les tourbillons obturant les sommets de la valvule aortique [5].

4/ Diagram of the heart according to Avicenna. Note the large middle ventricle and the absence of the atria [5].

Schéma du cœur, d'après Avicello. Ce schéma met en évidence la grande ventricule centrale; on y remarque l'absence des atria [5].

5/ Sketch of the heart showing the right atrium [5]. Croquis du cœur, sur lequel figure l'atrium droit [5].



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when the object is dragged along a plane smooth surface without anything intervening, this alone is the form that creates fire when it is powerful, that is it produces fire."

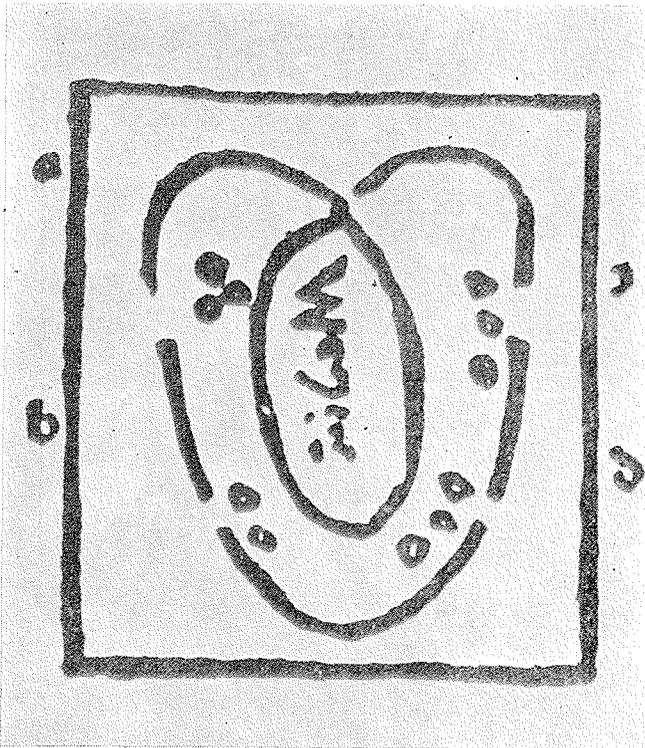
He applied this idea to explain the "innate heat" of the heart (as described by Galen) as not mysteriously innate but caused by the friction of the blood flowing in its chambers. Leonardo's error in this analysis of the heating of the blood results from his appreciation of the work which preceded him. He accepted and revered the writings of the ancient masters which led to his difficulty in casting aside old findings. At the same time that he would demand exactness of observation and experimentation in his own work, he was very reluctant to question the old theories. Even when some of his observations cast doubt on an old view, he would present both sides of the argument—both for and against his own results. This respect of ancient authority cost him many opportunities to advance the state of knowledge, particularly in anatomy and physiology.

The most authoritative (although erroneous) anatomical work related to the cardiovascular system then available was that of Galen and the various degenerations of Galen, particularly by Avicenna and Mondino da Luzzi. Galen's erroneous views included the concept of the heart as a respiratory organ (drawing in air directly from the lungs), the concept of "innate heat", and the manufacture of "vital spirits". Galen's heart had only two chambers (the ventricles) and his ideas of the vascular system were also in gross error. (The circulation of blood as is now accepted was not considered until Harvey, 1628.) Galen accepted the existence of minute and invisible pores in the interventricular septum allowing communication between the left and right sides of the heart. (These pores do not exist.) He also considered the blood to flow back and forth in the same vessels (ebb and flow movement).

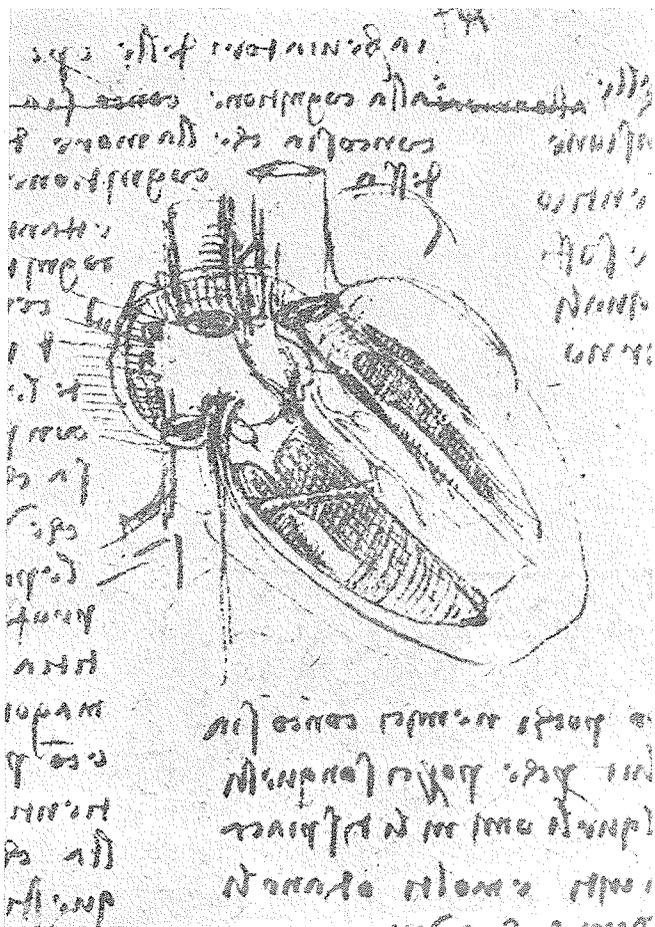
Avicenna's work was essentially a résumé of Galen with the addition of some of his own errors, the most important being the introduction of a large cavity instead of the interventricular pores (Fig. 4). Mondino's presentation is also a summary of Galen's work with few changes. It is seen, therefore, that the available information which Leonardo could refer to was not very helpful. Coupled with his respect for the ancient authorities was the fact that he could not perform experiments to prove or disprove many of these ancient theses. Therefore, although Leonardo did make many important contributions in the area of cardiovascular anatomy, the Galenic conception of the movement of blood was left essentially unchanged.

One point where Leonardo did differ with Galen was on the number of chambers of the heart. Leonardo discovered the four chambers of the heart, and since this finding contradicted the Galenic concept, a great deal of effort was made to justify the discovery. Among the arguments presented for the necessity of the two additional chambers (the auricles or atria) which he called the upper ventricles (Figs. 5, 6) was the erroneous idea related to the heating of the blood by friction.

"...the right upper ventricle is necessary for the flux and reflux of the blood, which is produced by means of this ventricle. And the revolution which the blood makes within itself, whirling round in diverse eddies, and the friction which it makes against the walls, and the percussions in these depressions, are the cause of the heating of the blood, and of making it thick and adhesive, subtle and pene-



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trative, and suitable for streaming from the right into the left ventricle through the narrow porosities of the wall which is placed between the right and left lower ventricle. And this could not take place if there were on the right side only one ventricle..."

With this and similar arguments, da Vinci rejected Galen's concept of innate heat. Also in arguments related to the existence of the auricle, Leonardo abandoned the Galenic idea of air entering the heart to cool the innate heat, but replaced it by an equally erroneous concept.

"...and thus by such flux and reflux, made with great rapidity, the blood is heated and subtilises, and becomes of such heat that but for the help of the bellows called lung, which by dilating itself draws in fresh air, and presses it, and touches the coatings of the ramifications of the veins and refreshes them, this blood would become of such a heat that it would choke the heart and deprive it of life."

Through many careful dissections, Leonardo had established the existence of the auricles. Then he set out to justify their existence, calling into use various principles of mechanics, etc., and in this way he refuted the ancient teachings. With respect to the pores in the interventricular septum, however, da Vinci could offer no contest; these were supposed to be invisible. This concept was accepted and various arguments were used to justify their existence (Fig. 6).

"The extraction of blood out of the right ventricle, which penetrates through wide porosities, the wall interposed between the right and left ventricle, which porosities narrow themselves with pyramidal concavities till they pass into unperceptible pores through which the viscous blood penetrates and goes on subtilising itself to great subtlety."

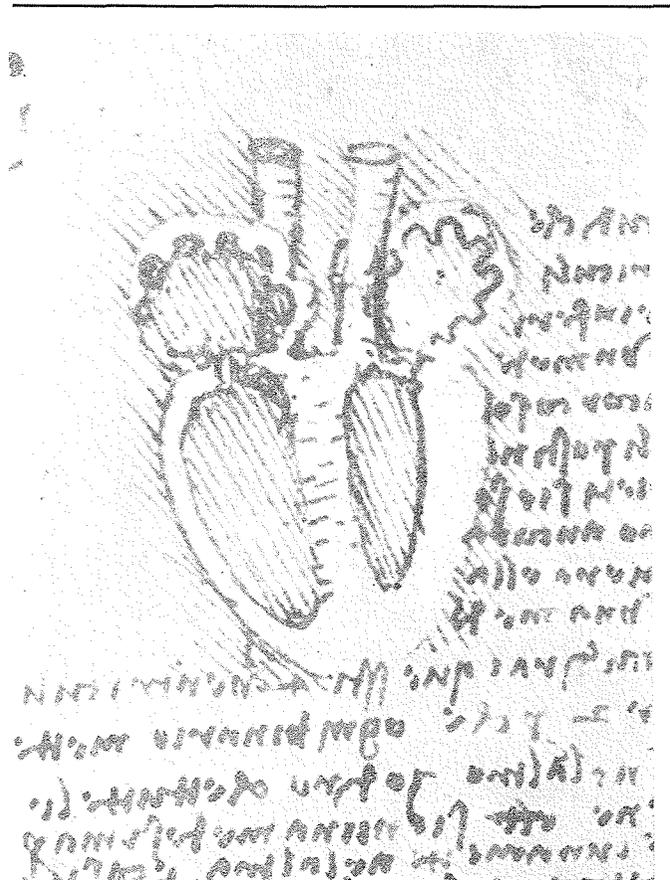
The cardiac valves received much attention from Leonardo who considered them from the point of view of a hydraulic engineer. Compared with the work of Galen, who had not improved upon the description of Erasistratus (275 B.C.), da Vinci's studies contributed greatly to the understanding of the functions of the heart valves. In his investigations of the aortic valve, Leonardo constructed a glass model in order to observe the movements of the valve cusps during the passage of fluid. (Figs. 7, 8) The purpose of the model was,

"To see in the glass what the blood does in the heart when it shuts the openings of the heart."

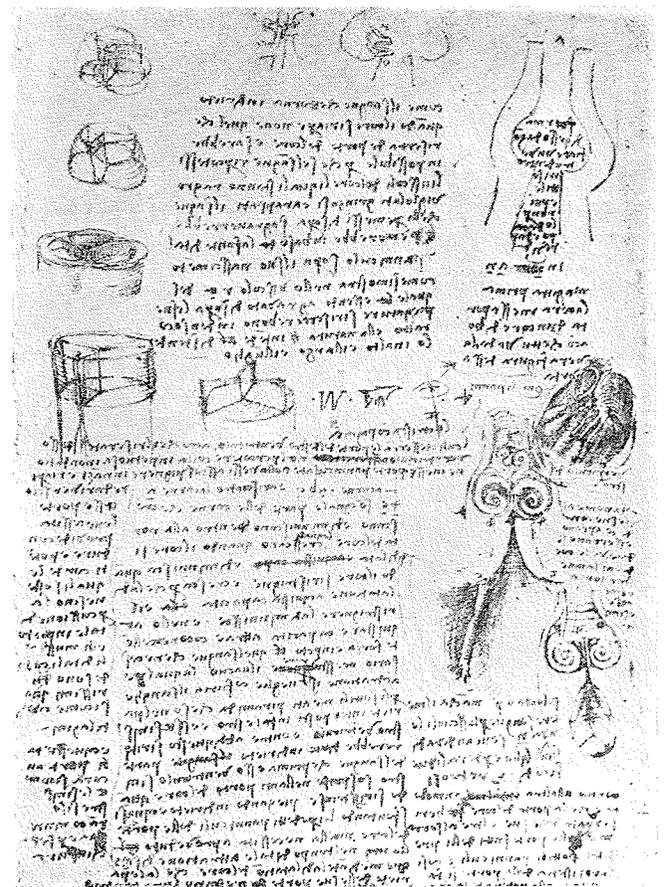
The particular method of flow visualization used in these experiments is not described, but it was probably one of the techniques described elsewhere. He may have used

"a few grains of panic-grass because by the movement of these grains you can quickly know the movement of the water that carries them with it. And from this experiment you will be able to proceed to investigate many beautiful movements which result from one element penetrating another," or "colored water falling blindly into clear water," or perhaps "millet or fragments of papyrus mixed into it so that one can see the course of the water better from their movements."

In analyzing the jet of blood passing through the aortic valve into the aorta, Leonardo starts with the problem of



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water spouting from a pipe which is shown by a sketch (Fig. 1) with the explanation,

"The water that rises through a pipe—that rises the highest which will be remotest from the walls of the pipe."

This water spout is compared to the blood flowing through the triangular orifice formed by the open aortic valve.

"Much more elevation is acquired by the middle of the blood which rises through the triangle a, b, c, than that which rises along the sides of this triangle, because that in the middle of the triangle sends its impetus directly upwards, and that which rises at the sides spreads its impetus by lateral motion and percusses the fronts of the arches of the hemicycles, always deflecting till it percusses the concavity of the base of such hemicycle, and then goes upwards with a reflected motion and goes on turning itself round in a gyratory motion on itself till it consumes its impetus."

In considering the velocity of the blood passing through the aortic valves, Leonardo correctly applied the continuity principle as he had previously done in regard to river flow [7]. His description is shown in Figure 2.

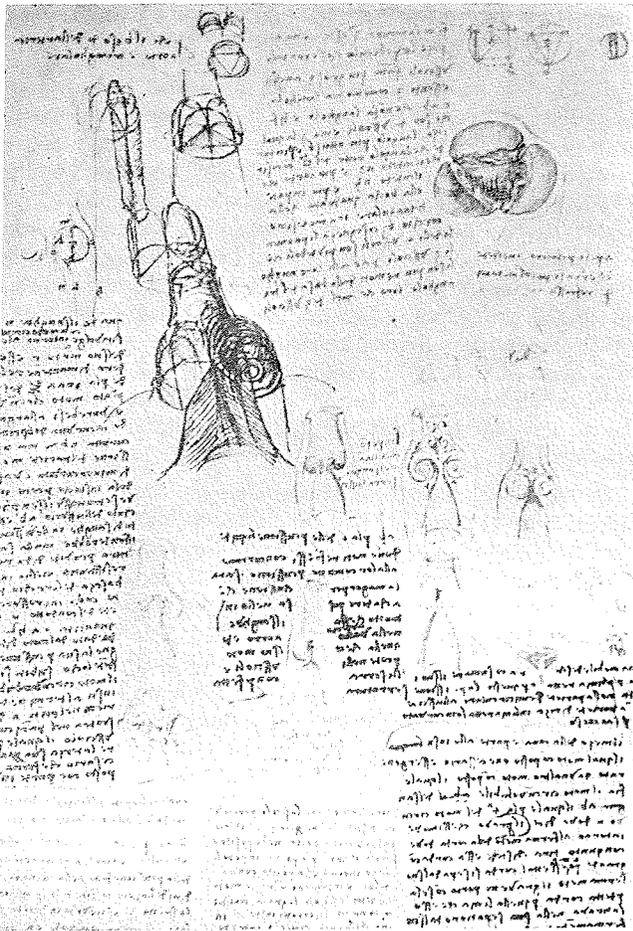
"When the heart contracts itself the left ventricle c, d, e, f, g, sends out its blood through the orifice c, d, into the pipe a, b, n, m, which in its base had three semi-ventricles (sinuses of Valsalva) as will be demonstrated in its place. But the velocity of the blood at the entrance to the ventricles has its motion varied, seeing that the velocity of this blood in the same time, will be in proportion to the various dimensions of the pipe. But the proportions will be inverse, i.e. the greater velocity in the passages of smaller dimension, and the less velocity in the greater dimension, as is demonstrated in the third part of the discourse 'On the Water'."

Consideration of the quantity of blood passing through the heart is of major importance. It was at this point that Harvey deduced the concept of the circulatory system and postulated the existence of the capillaries even though he had not seen them. Leonardo also wondered about the great quantity of blood that had to be accounted for.

"How much blood is the liver able to give it through the opening of the heart? It gives as much as it consumes, i.e. a minimum quantity, because in one hour about 2,000 openings of the heart takes place. There is great weight."

Even though he made no calculations of the flow rate, he recognized that even a small amount multiplied by 2,000 would result in a large quantity in an hour. To account for this amount of fluid, Leonardo, bound to Galen's theory of the ebb and flow movement of the blood, presented the concept of how the blood is either consumed by tissue at the periphery or discarded from the body. Missing the idea of circulation, Leonardo assumed that the blood becomes stagnant at the periphery since the kinetic energy of the blood flow is dissipated by the spreading of eddies up the aorta, *"contrary to one another, successively and so consume the forward impetus of the blood (Fig. 2)."*

Leonardo wrote at some length on the movement of the blood in the vessels, but as previously implied, there



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6/ Diagram of the heart showing the atria and the interventricular pores [5].

Schéma du cœur, comportant les atria, ainsi que les pores inter-ventriculaires [5].

7/ Model study of the aortic valve. A sketch of a cast of the aorta is shown in the upper right; the buckling of an aortic valve cusp is shown in the top center, and a sketch of eddies closing the aortic valve cusps is shown in the lower right [5].

Etude sur modèle de la valvule aortique. Le croquis en haut à droite représente un moulage d'une aorte; celui en haut au centre montre le flambement d'un des sommets de la valvule aortique, et celui en bas à droite l'obturation des sommets de la valvule aortique par des tourbillons [5].

8/ Movements of the aortic valve cusps during systole and diastole [5].

Mouvements des sommets de la valvule aortique lors de la systole et de la diastole [5].

has been no evidence yet found to suggest that he understood the concept of blood circulation. He wrote of the parallel motion of the blood along veins and arteries in the nature of ebb and flow, and nowhere did he state that the blood flowed from the arteries to the veins. The movement of the blood was believed to be caused by three motive forces: the pulsation of the heart, the heat of the blood, and gravity. As in other applications, heat (or its absence) was considered to be the prime mover.

"Heat and cold proceed from the propinquity of the sun. Heat and cold produce the movement of the elements."

"As the natural warmth spread through the human limbs is driven back by the surrounding cold which is its opposite and enemy, and flowing back to the lake of the heart and liver fortifies itself there..."

One last point to be considered in da Vinci's analysis of blood flow is related to his analogy of macrocosm and microcosm—observations made and laws postulated for the macrocosm (motions of terrestrial waters) should have application in the microcosm (circulatory system). Statements quoted on the movement of blood can be compared to what approaches an explanation of the hydrologic cycle.

"The waters range with perpetual movement from the lowest depths of the seas to the topmost summits of the mountains, not following the law of heavy things, and in this instance its action resembles that of the blood of animals which is always moving from the sea of the heart and flowing towards the summit of their heads..."

"The heat of the fire generated within the body of the earth warms the waters which are pent up within it in the great caverns and other hollow places; and this heat causes the waters to boil and pass into vapor, and raise themselves up..."

"The cause which makes water move in the springs contrary to the natural course of its gravity works in the same way in all the humors in all species of animated bodies. And just as the blood from below surges up and then falls back should a vein burst in the forehead, so the water rises from the lowest depths of the sea to the summits of the mountains, and there finding the springs burst open, is poured out through them, and returns to the depths of the sea."

To properly assess the contributions of Leonardo da Vinci to the engineering analysis of blood flow, emphasis should be directed toward his general techniques of investigation rather than toward what he actually theorized. Most of his ideas were in gross error, and in them no real contribution can be found (*). But when his methods are considered, a definite advancement in the "state of the art" can be seen. Leonardo was probably the first investigator to apply engineering principles to the problem of blood flow. In this he may be considered as the founder of "Biofluid Mechanics." His use of glass models and flow visualization was unique. His applications of "general laws" in different fields and the analogy of the macrocosm and the microcosm, although used incorrectly, did much to help establish rational analysis in the complicated subject of blood flow.

(*) Of course Leonardo's contributions to anatomy are obvious and are not referred to in this statement.

After Leonardo (William Harvey and others)

There were numerous anatomists interested in the motion of blood who lived and worked during the time shortly after Leonardo's death. This group, including Miquel Serveto (Michael Servetus) (1511-1553); Andreas Vesalius (1514-1564); and Realdus Columbo (Columbus) (1516-1559), helped to raise some questions concerning Galenic dogma. All three of these men doubted the existence of pores in the interventricular septum, and Serveto and Columbo showed that blood and air mixed in the lungs and not in the heart. Other anatomists were also chipping away at the cornerstone of Galen's system, but it took the work of the Englishman, William Harvey (1578-1657), to halt the acceptance of the ancient scholasticism and to begin modern physiology and medicine.

In his book, *Exercitatio Anatomica de Motu Cordis et Sanguinis in Animalibus* (An Anatomical Dissertation Concerning the Motion of the Heart and Blood in Animals) (*), [8], Harvey demonstrated that the blood must move in a closed circulatory system. By a simple appreciation of the principle of continuity, he reasoned that the amount of blood ejected from the heart during a certain period of time exceeded the total volume of blood in the body and that, therefore, the same blood must be circulating in a closed system. These ideas on the circulation of blood were first presented as lectures before the Royal College of Physicians and later published in Frankfurt in 1628.

Included in the celebrated volume of only 72 pages which revolutionized the medical world were Harvey's interpretation of: 1) the action of the heart during systole and diastole, 2) the correct relationship between the heart beat and the pulse, 3) the correct relationship of the atria and the ventricles of the heart with each other, 4) the continuous process of the circulation and the connection between the arteries and the veins, 5) the pulmonary circulation, and 6) the function of the heart as the prime mover of the blood in the circulatory system. It is of interest to note that Harvey never viewed the capillaries since he had no microscope. His appreciation of their existence was based on his interpretation of an endless circulatory system. The capillaries were first viewed in 1661 by Marcello Malpighi.

Two other investigators should be mentioned at this point because of later reference to their work. Giovanni Borelli (1608-1679) of Pisa proposed the application of the laws of hydraulics to the circulatory system. He attempted to calculate the force of systolic contraction under the following assumptions: 1) muscular contractile force is proportional to the volume of the muscle, 2) the ventricular volume is approximately equal to the volume of the masseter and temporal muscles, and 3) the force of contraction is measured by the weight supported by the elongation of the muscles. Borelli's computations resulted in a value of 980 kg. for the force of ventricular contraction.

In 1718, James Keill reported in *Tentamina Medico-Physica*, that the force of the ventricular contraction was approximately 0.340 kg., differing from Borelli by about 3000 fold. Keill's results were as extraordinarily small as Borelli's were large. It would be the task of later generations to resolve the differences.

(*) The book is usually referred to by the truncated title, *de Motu Cordis*.

Stephen Hales

More than one hundred years passed after the publication of *de Motu Cordis* before the next significant advancement in the engineering analysis of blood flow was presented. In his *Statical Essays: Containing Haemastaticks* published in 1733 [9], Stephen Hales (1677-1761) reported the first direct measurements of blood pressure in different animals as well as many other measurements, observations, and computations.

In addition to his important contributions in the analysis of blood flow, Hales also considered some other problems of fluid flow including the ventilation of jails, hospitals, and ships' holds; the distillation of fresh water from sea water; and the invention of a sea gauge for sounding.

Haemastaticks was published at the request of the president of the Royal Society. The volume comprises a series of papers on the mechanics of blood flow which was previously read before the Society by Hales, and it is the second volume of his *Statical Essays*; the first volume, *Vegetable Staticks* (1727), deals with plant physiology and animal respiration. The discussion of the mechanics of blood flow is treated as a series of twenty-five experiments. These experiments are followed by a discussion of some experiments on "Stones in the Kidnies [*sic*] and Bladder," and an appendix, "Observations and Experiments relating to several Subjects in the first Volume" and "A Description of a Sea-Gage, Wherewith to Measure unfathomable Depths of the Sea."

The accomplishments of Stephen Hales in the engineering analysis of blood flow are particularly impressive from the viewpoint of his quantification. These achievements include: 1) the first direct and accurate blood pressure measurements in both arteries and veins, 2) an approximate estimate of the left ventricular systolic output (volume flow rate), 3) correct computation of the blood velocity in the aorta, 4) an analysis of resistance to blood flow in the peripheral vessels, 5) an analysis of the mechanical properties of the pulmonary circulation as compared to the systemic circulation, and 6) an introduction of the "fire-engine" (Windkessel) theory explaining the phenomenon of pulsatile flow in the larger vessels.

Some of the motives of Hales and an insight into his thinking can be seen in his introduction to *Haemastaticks*. He expressed dissatisfaction with the results of Borelli and others, and he indicated his desire to apply the laws of hydraulics to the problem of blood flow.

"As an animal Body consists not only of a wonderful texture of solid Parts, but also of a large proportion of Fluids,... And as the healthy State of an Animal principally consists, in the maintaining of a due Equilibrium between those Solids and Fluids; it has, ever since the important Discovery of the Circulation of the Blood, been looked upon as a Matter well worth the enquiring into, to find the Force and Velocity with which these Fluids are impelled..."

"Several ingenious Persons have from time to time, attempted to make Estimates of the Force of the Blood in the Heart and Arteries, who have as widely differed from each other as they have from the Truth, for want of a sufficient Number of Data to argue from... Finding therefore but little Satisfaction, in what had been attempted on this Subject by Borellus and others..."

"For since we are assured that the animal Fluids move

by Hydraulick and Hydrostatick laws, the likeliest Way therefore to succeed in our Enquiries into the Nature of their Motions, is by adapting our Experiments to those Laws."

The methods used by Hales to obtain blood pressure measurements in living animals were, by modern standards, quite crude. He simply attached a vertical piezometer tube to the vessel of interest and measured the height of the column of blood sustained in the tube. Although this technique is simple, the problems involved in applying it to living animals are many, but Hales succeeded in obtaining many measurements from different points in the circulatory system and under many different conditions.

In Experiment I, Hales describes his method of measuring pressure in the left crural artery of a horse.

"... I inserted into it [the artery] a brass Pipe whose Bore was one sixth of an Inch in Diameter; and to that, by means of another brass Pipe which was fitly adapted to it, I fixed a glass Tube, of nearly the same Diameter, which was nine Feet in Length:... the Blood rose in the Tube eight Feet three Inches perpendicular above the Level of the left Ventricle of the Heart..."

It is important to note that although Hales apparently used what is now called a piezometer to obtain information about blood pressure, he did not, at this point, indicate an understanding of the relationship between his measurements and pressure. He, in fact, did not use the term "blood pressure" at all in this experiment, but rather the "force of the blood in the crural artery."

In Experiment III, a description is given of the method which Hales used to make an estimate of the aortic velocity and the quantity which he referred to as the force of the heart. To make these computations he needed to know the internal volume and surface area of the chambers of the heart. These measurements were made by obtaining a wax cast of the cavities of the heart. The interior volume of the heart was determined by measuring the water displaced by the cast, and surface area was found by fitting pieces of paper to the surface of the cast and measuring the total area of the paper. Considering the details of the computation of the force, Hales introduced the word "pressure."

"... the Sum of the whole Pressure of the Blood against all the Sides of that Ventricle, at the Instant when it begins first to contract, so as to sustain the Pressure of the arterial Blood, will be that Surface or Area multiplied into the perpendicular Height of the Blood in the glass Tube..."

Hales then multiplied this product by the specific weight of blood to obtain a result of

"...113.22 Pounds which is the Sum of the Pressure of the Blood, which this Ventricle sustains, at the Instant when it is going to exert a contractive Force, sufficient to propel it with considerable Velocity into the Aorta."

If this computation of force is considered in a different order, i.e., the product of the specific weight times the height of the blood in the tube resulting in a pressure intensity which is then multiplied by the area to give force, it is then seen that Hales not only used a piezometer for measurements of head but may very well have understood

the relationship between pressure and head. If it is also noted that such measurements were probably made in a dog as early as 1709 [10], then perhaps Hales should be given some credit for the first use of the piezometer; a contribution which is usually ascribed to Daniel Bernoulli [7, 11].

In computing the velocity of the blood entering the aorta at the end of systole, Hales showed an understanding of the continuity principle for incompressible fluids. Knowing the cross-sectional area of the aorta, the interior volume of the left ventricle, and rate of the heart beat, and assuming (or knowing) that the time of systole is about one third of the time elapsed between each beat of the heart, Hales computed the velocity of the blood entering the aorta (of a horse) to be about 1.45 feet per second.

While discussing various measurements made by Hales it is also of interest to mention his use of a mercury manometer. Experiment XIX gives a description of the manometer which he made.

"That I might know with what determinate Force I impelled Air into the Vessels, I prepared the following Instrument, viz. I fixed to a common brass cylindrical Air Force an Elder Stick, which was two Feet long, and two inches Diameter; thro' which a Hole of half an Inch Diameter was made from end to end: One end of an inverted Glass Syphon was laterally fixed into a Hole in the middle of the Elder Stick; then four Inches Depth of Mercury being poured into the Syphon, its other Orifice was closed up with Cement and a Piece of Bladder tied over it. When this Instrument was by means of a brass Pipe fixed to any Vessel of an Animal, I could by the Height of the Mercury in the mercurial Gage, see with what Force Air was impelled."

An application of a similar manometer was then described in Experiment XXII in which an attempt is made to determine the strength of certain blood vessels by pumping in air until they burst. By this instrument Hales found the bursting strength of the carotid artery of a dog to be about 5.42 atmospheres.

The final comments to be made concerning Stephen Hales are in regard to his introduction of the "fire-engine" concept of pulsatile flow in large vessels. One particular aspect of blood flow which has gained much attention is its pulsatile nature. The analysis of pulsatile flow in distensible tubes is usually approached in either of two ways. One method models the phenomenon as a lumped parameter system. With this model, a single elastic chamber, the heart, propagates a pulse having an infinite wave velocity, and the pressure and flow pulses change simultaneously. The pressure-flow relationship at any point in the system is then determined. This theory which has come to be referred to as the "Windkessel theory" was introduced by Hales in Experiment III. While writing of the mechanism through which the pulsating nature of the blood flow entering the aorta is converted to an almost steady flow in the finer vessels, Hales made the following analogy:

"... By which curious Artifice of Nature, the Blood is carried on in the finer capillaries, with an almost even Tenor of Velocity in the same manner as the spouting Water of some fire-Engines, is contrived to flow with a more even Velocity, notwithstanding the alternate Systoles and Diastoles of the rising and falling Embolus or Force;..."

These thoughts continue with an explanation of the working of the fire-engine and the completion of the analogy to the circulatory system.

The examples of Hales' work presented herein are illustrative of the many contributions which he made in the engineering analysis of blood flow. There is one major flaw in this work, however. Hales apparently did not have a strong enough background in mathematics, and he was not able to generalize his experimental results, or to formulate any useful relationships from his findings. Contemporary with Hales, however, in other parts of Europe, some very able mathematicians were establishing the basic laws of fluid flow and applying them to the blood flow problem.

Eighteenth century

If the development of the engineering analysis of blood flow is thought of as a kind of "family tree" stemming from Leonardo da Vinci, then Stephen Hales must be placed at the point on the main trunk where the branching begins. During the lifetime of Hales, the works of Newton and Leibnitz were published, and the fundamental laws of energy and momentum were applied to the problems of mechanics [7]. The eighteenth century saw not only the emergence of the science of hydrodynamics, but also the application of hydrodynamical laws to the blood flow problem.

In attempting to analyze such a complex physical problem as blood flow mathematically, many simplifying assumptions had to be made, and in making such assumptions, investigators began to study many different but related phenomena. In addition to those researchers specifically interested in blood flow, the field of knowledge of fluid mechanics in general began to grow which naturally contributed greatly to the understanding of blood flow.

Topics pertaining (directly or indirectly) to the study of blood flow on which research was initiated during the eighteenth century include: the work output of the heart, blood flow in the arteries, flow in rigid and elastic conduits, wave motion, fluid viscosity, and others already mentioned during the discussion of Hales' work. The scientists who presented these contributions, and who would be represented by the branches on the "family tree" previously alluded to include some of the best known mathematicians and physicists. Of this group three will be briefly mentioned, Daniel Bernoulli, Leonhard Euler, and Mikhail V. Lomonosov.

Daniel Bernoulli (1700-1782) contributed to the analysis of blood flow both directly and indirectly. He received formal training and a degree in medicine. With this background he combined education and interest in mathematics and physics. However, his contributions in the physical sciences far outweigh his contributions in the life sciences.

Bernoulli's work in blood flow is not very well known. He is given credit for applying the equations of hydrodynamics to the flow of blood and for the accurate computation of the work output of the heart.

Passavent, a doctoral student of Daniel Bernoulli, also performed computations related to the work of the heart. It is of interest to note that he used the data of Stephen Hales in the calculations which were published in his dissertation (1748).

Leonhard Euler (1707-1783) also applied his genius in the study of the mechanics of blood flow. In a paper presented in 1775, but not published until 1862, "*Principia pro motu sanguinis per arterias determinando*" (Principles for determining the flow of blood through the arteries) [12] (*), Euler derived many fundamental relationships related to blood flow in arteries and incompressible flow in elastic tubes.

The beginning of the paper is apparently missing since the article cited begins with paragraph fifteen. Euler treated arterial blood flow as the unsteady flow of an incompressible fluid in distensible tubes, assuming the fluid to be inviscid and the flow to be one-dimensional. He expressed the pressure gradient in the tube in terms of the spatial rate of change of the cross-sectional area of the tube as:

$$\left(\frac{dp}{dz}\right) = \frac{c}{(\Sigma - s)^2} \left[\Sigma \left(\frac{ds}{dz}\right) - \frac{s d\Sigma}{dz} \right]$$

in which Σ is the maximum area to which the tube can be distended, and s is the cross-sectional area at any distance z along the tube. This expression was used together with a differential form of the continuity equation:

$$v \left(\frac{ds}{dz}\right) + s \left(\frac{dv}{dz}\right) + \left(\frac{ds}{dt}\right) = 0$$

and the differential momentum equation which is now referred to as Euler's equation of motion:

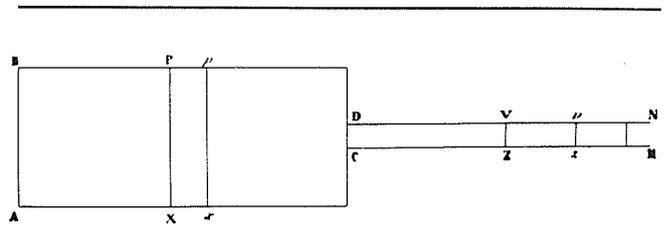
$$\left(\frac{dv}{dt}\right) + v \left(\frac{dv}{dz}\right) + 2g \left(\frac{dp}{dz}\right) = 0^{(**)}$$

From these three equations, Euler derived expressions to describe the motion of fluid in the flow system illustrated in Figure 9, which shows his treatment of the heart as a piston pump and the arteries as rigid or distensible tubes. Considering first the flow through a rigid tube, Euler explained the problem.

"Now let figure ABCD represent a pump which initially will be filled with fluid, while the connected tube CDNM will be completely empty, and let the size of the pump be determined everywhere = b. And then after time = t has past, let the fluid now be pushed forward by the action of the piston so that it now occupies the space XPMN, so that the mass of the fluid, which initially occupied the space ABPX, now fills the tube CDMN..."

To this model of the circulatory system Euler applied the equations previously noted. Through the use of these differential equations, Euler became the first to visualize the circulatory system as a distributed parameter system, as opposed to the lumped parameter Windkessel theory proposed by Hales. One of the goals of Euler's approach, now referred to as transmission theory, was to describe the velocity of wave propagation through the system, since from this viewpoint the contraction of the heart is assumed to propagate a wave through the arteries at a finite velocity.

After describing the derivation, Euler concluded with an equation for the pressure distribution and the comment,



9/ Euler's representation of the heart as a piston pump [12].
Assimilation du cœur à une pompe à piston, d'après Euler [12].

"Now the pressure of the fluid p can be defined at any time for any location of the tube Z ; and thus everything concerning the motion will become clear by this theory."

Following the successful solution for flow through the rigid tube Euler wrote,

"It is understood that the investigation of the motion through elastic tubes ought to be undertaken in a similar manner.

But if we should wish to undertake this treatment in a similar manner, we would fall into almost inextricable calculations; for the integration of the two basic formulæ will not come out so easily."

Euler decided that to attempt to integrate the basic equations for the case of flow through an elastic tube would be fruitless. He preferred instead to pose the problem in terms of an energy balance.

"To derive the second equation [an integrated momentum equation] let us consider the vital force [kinetic energy] of this same portion of fluid XPZV, which is determined when its individual elements are multiplied by the square of the velocity by which they are moved..."

After explaining this second method and applying it to flow in a rigid tube, Euler proceeded to investigate the motion of fluid through elastic tubes. However, his attempt at solving this problem ended with the statement,

"But since there is no direct way open of performing such a resolution, and since this investigation must be thought of as transcending human powers, we are forced to put an end to this labor here."

Euler concluded the paper with a humble admission that the greatest of human minds cannot compare with the infinite wisdom of the God of the Universe.

"Therefore in explaining the motion of blood, we meet the same insuperable difficulties which impede our carefully investigating all the works of the Creator; where we ought always increasingly to admire and venerate the greatest wisdom joined with omnipotence, since not even the greatest human talent can perceive and explain the true structure of even the smallest and most insignificant little movement."

It is not surprising that Euler was unable to complete the solution to this problem. Both of his approaches were fundamentally correct, but to attempt to solve the partial differential equations of motion by a direct integration or

(*) A complete English translation of this paper is being prepared by A. R. GIAQUINTA and R. J. ROWLAND.

(**) Using Euler's notation, the factor $2g$ represents the inverse of mass density.

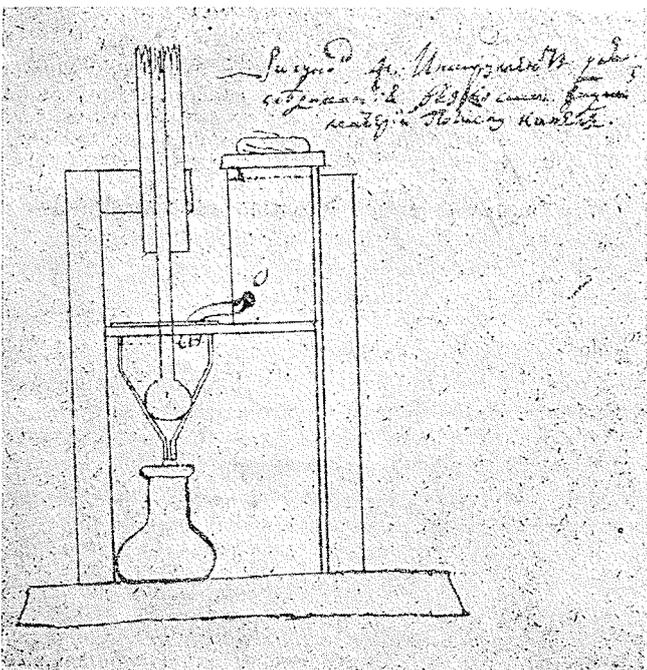
by an energy method is, even today, an ambitious task for such a complex problem.

The indirect contribution to the study of blood flow by the great Russian scientist Mikhail V. Lomonosov (1711-1765) involved the measurement of the viscosity of liquids. Lomonosov was talented in many areas; in fact, his contributions in many different and seemingly unrelated fields would remind one of the earlier accomplishments of Leonardo da Vinci. Lomonosov's thesis, "Meditations on the Origin of Heat and Cold," was presented in 1745. This work was quite controversial, but Russian historians report that Euler, who was in Petersburg at the time, praised Lomonosov for his great contribution [13]. It is interesting to note that Lomonosov is also given credit by his countrymen for the discovery of the laws of conservation of mass and energy.

The study of the viscosity of liquids is frequently considered a part of the science of rheology, the science of the deformation and flow of matter. The description of viscous resistance presented by Newton in 1687 could be regarded as the origin of rheological studies from the fluid viewpoint.

Measurements of fluid viscosity were attempted somewhat later. One of the earliest capillary tube viscometers, shown in Figure 10, was designed and built by Lomonosov [14]. This viscometer was presented to the Academy of Science on March 21, 1751, where it was described as "an instrument for the investigation of the viscosity of a fluid according to the rate of dripping."

Lomonosov's interest in the molecular-kinetic theory of matter led to the construction of the instrument because of his desire to measure the cohesive forces in pure fluids and solutions such as alcohol, acids, and bitumen. Due to this contribution in the measurement of liquid viscosity, Lomonosov is considered as one of the founders of the science of rheology in Russia.



10/ Sketch of Lomonosov's capillary viscometer [14].
Croquis du viscosimètre capillaire de Lomonosov [14].

About seventy-five years after Hales published his book, another English physician and scientist, Thomas Young (1773-1829), made the next significant contribution in the analysis of blood flow. Young's work could be considered, in a sense, to be a continuation of Euler's since Young described the relationship for the velocity of propagation of a wave through an incompressible fluid flowing in an elastic tube, which Euler failed to do. As will be mentioned later, Young referred to the experimental data of Hales frequently and in that sense his work could be thought of as following logically after that of Hales.

Young's major interest was apparently in the area of wave theory which is evident from the way he was able to use his understanding of wave motion in one medium to explain other seemingly unrelated phenomena. This type of reasoning was used to aid Young in one of his most important contributions. In 1803 Young demonstrated the wave theory of light which was in disagreement with the then accepted corpuscular theory of light which had been previously presented by Newton. Young's most significant experiment in proving the wave theory was his demonstration of the phenomenon of the interference of light waves. He reasoned that if light were transmitted in the form of a wave, then it should experience the same behavior as other forms of wave transmission. A readily observable phenomenon of sound transmission is the occurrence of beats when individual waves superpose causing reinforcement or annulment of sound. Assuming that light waves should behave in an analogous manner, Young performed experiments illustrating that light did indeed superpose in such a way that could only be explained in terms of wave theory.

Perhaps the most significant contributions of Thomas Young to the engineering analysis of blood flow are contained in two papers presented to the Royal Society in 1808. The first one was read on May 5, 1808 and was entitled "Hydraulic Investigations subservient to an intended Croonian Lecture on the Motion of Blood" [15]. This paper discussed many general ideas related to the theory of fluid flow in rigid and distensible tubes and in rivers. The second paper, the Croonian Lecture, read on November 10, 1808, was entitled "On the Functions of the Heart and Arteries" [16]. As the title indicates, the Croonian Lecture was involved more specifically with the analysis of blood flow, and the general theories presented in the earlier paper were applied to that specific problem. This pair of papers is an excellent example of the interdisciplinary accomplishments that are being performed today in the field of Bioengineering.

It appears that the original intent of the Croonian Lecture may have been more closely related to the field of medicine than it actually turned out to be. Young, as a medical doctor, was interested in understanding the nature of inflammation and fever, but in the course of his investigations, it became apparent that a more detailed study of fluid mechanics was needed, and his original subject received only secondary attention. The introduction to the first paper explains his reasoning [15].

"Having lately fixed on the discussion of the nature of inflammation for the subject of an academical exercise, I found it necessary to examine attentively the mechanical principles of the circulation of the blood,..."

Following this comment, Young mentioned the various problems of hydraulics that he would treat. In the introduction to the Croonian Lecture, after summarizing his intentions with regard to the study of blood flow, he commented on the secondary attention that his original problem would receive [16].

"I shall lastly add some observations on the disturbances of these motions [arterial blood flow], which may be supposed to occur in different kinds of inflammations and fevers."

In "Hydraulic Investigations..." [15], Young considered five different problems of hydraulics which were to serve as useful background material for his later lecture. In the first analysis, "Of the Friction and Discharge of Fluids running in Pipes, and of the Velocity of Rivers," Young criticized the earlier work of DuBuat on the same subject as not being general enough (*). Young argued that DuBuat's analysis of pipe flow resistance was "completely erroneous" when the pipe was very long or very narrow. He also stated that the proper relationship "...to calculate the velocity for any given pipe or river, and any given head of water" should be:

$$f = a \frac{L}{d} v^2 + 2c \frac{L}{d} v$$

in which f is the head needed to overcome the resistance, v is the velocity, and L and d are the pipe length and diameter respectively. An equation of this form for flow resistance has been attributed to Coulomb [7], but Young does not acknowledge this fact even though he used some of Coulomb's data to verify some of his computations. Young substantiated his choice of the resistance formula by comparing the experimental results of DuBuat, Couplet, Bossut, Gerstner, and himself with computations based on both his formula and DuBuat's. He concluded that over most of the range, in both pipe flow and river flow, "...the accuracy of the two formulae may be considered as precisely equal with respect to these experiments" However in experiments which he made with very fine tubes, DuBuat's formula failed completely, while Young's gave satisfactory agreement.

The second investigation presented in this paper was "Of the Resistance occasioned by Flexure in Pipes or Rivers." Young again criticized DuBuat's treatment of the same subject. After tersely describing DuBuat's method, Young wrote,

"It is, however, easy to see that such a rule must be fundamentally erroneous, and its coincidence with some experiments merely accidental, since the results afforded by it must vary according to the method of stating the problem, which is entirely arbitrary."

As before, Young presented his own analysis of the problem and compared his results with those of DuBuat, finding that his own analysis was applicable over a larger range of pipe curvature.

In the next section of the paper entitled "Of the Propagation of an Impulse through an Elastic Tube," Young presented a significant contribution through his analysis of the velocity of transmission of a pulse wave in an elastic

tube. It should be recalled that this problem was considered by Euler but was abandoned before he reached any definite conclusions. Unfortunately, Young's presentation was so vague that his equation for the pulse wave velocity was not recognized, and it was rederived in 1850 by E. H. Weber and published in 1866 by his brother W. E. Weber [17]. Young initiated his description of the pulse wave velocity in the third section of "Hydraulic Investigations..." by comparing the problem with other examples of wave transmission.

"The same reasoning, that is employed for determining the velocity of an impulse, transmitted through an elastic solid or fluid body, is also applicable to the case of an incompressible fluid contained in an elastic pipe;..."

The explanation of the technique which followed was not very lucid which, in addition to the lack of an explicit equation for the pulse wave velocity, probably explains why this work was not well recognized.

The elastic modulus of the tube wall material was related to the height of a column of fluid which would produce an increase of pressure causing a change in the tube diameter. Young considered that there would be a certain column height which would cause an infinite increase in the tube diameter and that this height, which he called the modular column of the pipe, was directly related to twice the value of the modulus of elasticity. The velocity of a pulse wave at any point was then described as being equal to half of the velocity of a body passing through the corresponding point in the modular column.

The last two sections of the paper are entitled "Of the Magnitude of a diverging Pulsation at different Points," and "Of the Effect of a Contraction, advancing through a Canal." These studies, related to the transmission and reflection of waves through fluids in rigid and elastic tubes and in rigid canals, were referred to in the Croonian Lecture.

The introduction to the Croonian Lecture [16] contains Young's thoughts on the role that an engineering analysis would play in regard to the understanding of certain physiological problems.

"As far, therefore, as the functions of animal life depend on the locomotions of the solids or fluids, those functions must be capable of being illustrated by the consideration of the mechanical laws of moving bodies:... the circulation of the blood... must become simply a question belonging to the most refined departments of the theory of hydraulics."

"In examining the functions of the heart and arteries, I shall inquire, in the first place, upon the grounds of the hydraulic investigations which I have already submitted to the Royal Society,..."

Young then wrote that he would consider the problems of the flow of blood through rigid tubes, the transmission of the pulse from the heart through the arteries assuming them to be elastic tubes, an investigation of the musculature of the arteries, and finally, as mentioned before, some observations related to inflammation and fever.

In studying blood flow in rigid tubes Young assumed that the flow would be uniform and steady and that the inertial resistance may be neglected. His interest was focussed on the pressure which originated at the heart and its relationship to the viscous resistance of the internal surface of the blood vessels.

(*) These criticisms were also made in an earlier lecture by Young on the history of hydraulics.

"The magnitude of the pressure has been ascertained by Hales's most interesting experiments on a variety of animals,... and for determining the magnitude of the resistance, I shall employ the theorems which I have deduced from my own experiments on very minute tubes..."

Using the data which were presented by Hales and others and the formula for resistance which he had given in "Hydraulic Investigations...", Young determined the viscous resistance of the capillary bed in humans—as if water were flowing rather than blood. He next recognized the need to determine the relationship between the viscosity of different fluids, and he performed a number of experiments on the flow of different fluids through capillary tubes. It is of particular interest to note that Young's experiments with capillary tubes preceded the work of P. S. Girard by more than five years and particularly that Young considered the motion of non-Newtonian fluids. The fluids studied by Young were water, milk, and sugar solutions of which the latter two are now recognized to be non-Newtonian. Young noted that the resistances of the milk and sugar solutions were much greater than those of water, and that they varied with the tube diameter. A more detailed investigation of this non-Newtonian behavior would have established Young as a pioneer in the field of rheology. The major conclusion of these experiments was that blood was more viscous than water, and by choosing a factor of four (the number commonly accepted today is 3.5), Young's analysis agreed well with the experimental results of Hales for the resistance of the capillary bed.

In discussing the propagation of the pulse, Young again mentioned the analogy with other types of wave propagation.

"The successive transmission of the pulsations of the heart, through the length of the arteries, is so analogous to the motion of the waves on the surface of water, or to that of a sound transmitted through the air, that the same calculations will serve for determining the principal affections of all these kinds of motion."

Young used the results of Hales' experiments to describe the pulse wave velocity, and, as before, he presented his theory by an analogy with the velocity of a falling body.

"Hence, it follows that the velocity of the pulse must be nearly the same as that of an impulse transmitted through an elastic fluid, under the pressure of a column of the same height, as that which measures the actual arterial pressure: that is, equal to that which is acquired by a heavy body falling freely through half this height."

Throughout the remainder of the paper, Young discussed the problems listed earlier, applying the hydraulic theories which he had presented in the first lecture and referring to the experimental results of Hales whenever they were applicable.

Young emphasized one more idea in this lecture, and as in the past, the position he held was in opposition to what was generally believed.

"...I apprehend that it will appear to be demonstrable that they [the muscular fibres of the coats of the arteries] are much less concerned in the progressive motion of the blood, than is almost universally believed."

Young again proved his point with a combination of theory and experiment, but his proof lacked clarity as did his earlier derivation of the pulse wave velocity, and this idea was not well recognized and was reproven in the middle of the century by Volkmann [17].

Conclusion

The contributions to the analysis of blood flow following Thomas Young are well documented and will not be discussed herein.

Some examples of related studies which were performed include the work of P. S. Girard in 1815 on the flow of water in capillary tubes; J. L. M. Poiseuille's thesis presented in 1828, "Recherche sur la force du cœur aortique" (Studies on the Strength of the Aortic Heart), and other papers on blood flow which culminated with his more fundamental study on fluid flow in capillary tubes, "Recherches expérimentales sur le mouvement des liquides dans les tubes de très petits diamètres" (Experimental Studies on the Movement of Liquids in Tubes of Very Small Diameter) (1842).

Research on the problem of blood flow in distensible tubes was performed beginning in 1850 by the Weber brothers, Volkmann, and others. There is extensive literature on the blood flow problem beginning at about this time. Much of this work was reviewed and criticized in depth in 1950 and 1951 by Paul Lambossy in a pair of excellent historical reviews [17, 18].

During the nineteenth century the engineering analysis of the flow of blood developed into what could be considered its earliest stage of maturity. The basic tools of mathematics, physics, physiology, anatomy, and other related sciences were all fairly sophisticated by this time, and the application of these disciplines to the problem of blood flow resulted in many lasting contributions. The understanding of the complex phenomena associated with blood flow became more complete, and many of the results and methods of analysis and experimentation which were introduced during this time are still used today.

The presently growing field of Bioengineering in which life scientists and engineers combine their efforts to solve problems of mutual concern can be easily traced back to the researchers of the nineteenth century, but as seen in this presentation, credit for the origin of such interdisciplinary research should be given to Leonardo da Vinci. Leonardo's study of flow through the aortic valve of the heart which combined a careful anatomical investigation, construction of a glass model, and the application of principles of hydraulic engineering is one particular example. Another example of an early Bioengineering effort is the previously mentioned study of inflammation carried out by Thomas Young. His realization that the key to the understanding of the physiological problem of inflammation was found in a better comprehension of the physical laws governing fluid flow parallels the motivation behind present day studies.

The field of Bioengineering is flourishing today. With interests both in measuring the physical variables governing many of the functions and activities of various living organs and in designing and manufacturing artificial organs, scientists and engineers of varied backgrounds are working together for the advancement of medical science as well as engineering.

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