1980
ADVANCES IN BIOENGINEERING

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FOREWORD

The American Society of Mechanical Engineers has served mechanical engineers for one hundred years. It has been and will continue to be the major forum of communication for mechanical engineers of all specialties. The Bioengineering Division of the Basic Engineering Department is one of the youngest divisions (1958) of ASME, but activities of biomechanical engineers trace back to the early years of the society. Exceptional growth of bioengineering in recent years, as illustrated by the large number of contributions to this meeting, indicates the vitality of this discipline. Growth, however, is always based on the contributions of those who come before us. It is fitting, therefore, that the theme for this 1980 Centennial Winter Annual Meeting is "Historical Prospectives in Bioengineering."

This theme is elegantly developed by our five distinguished keynote lecturers. We are very pleased to publish here the lectures of Dr. Albert H. Burstein, Hospital for Special Surgery, Cornell Medical School, "From Fairbanks Cranes to Finite Elements: The Maturation of Orthopaedic Biomechanics;" Professor John Chato, University of Illinois, "Reflections on the History of Heat and Mass Transfer in Bioengineering;" Professor Y. C. Fung, University of California, "The Lung: A Perspective of Biomechanics Development;" Dr. Lester Goodman, "Bioinstrumentation: Perspectives of a Mechanical Engineer;" and Professor Richard Skalak, Columbia University, "Mechanics of Blood Flow." I wish to express my sincere appreciation for their fine lectures and for their efforts in preparing manuscripts, which are included here.

Three special minisymposia, cosponsored with other divisions of ASME, have been planned for this meeting. The Heat Transfer, Ocean Engineering, and Dynamic Systems and Control divisions, have cosponsored the following sessions: "Bioheat and Mass Transfer," organized by Dr. Ronald Levin, National Institutes of Health; "Engineering Aspects of Diver Thermal Protection," organized by Mr. Marshall L. Nuckols, Naval Coastal Systems Center; and "Controllers and Effectors: Can They be Designed or Studied Independently?" organized by Dr. Woodie C. Flowers, Massachusetts Institute of Technology.

The invited keynote lectures appear in the front of this volume. All other papers are grouped sequentially as they appear in the sessions. In this manner, two of the minisymposia; "Bioheat and Mass Transfer" and "Controller's and Effectors: Can They be Designed or Studied Independently?" are grouped as they appear on the program. The "Engineering Aspects of Diver Thermal Protection" papers are available as full-length preprints. It is my hope that the large number of quality contributions to this year's *Advances in Bioengineering* will make this centennial volume a valuable reference source in Bioengineering.

In closing, I wish to express my appreciation to the professionals of ASME for their efforts in assisting me to plan and organize this meeting. Their efforts make our society the main forum for communication among mechanical engineers interested in solving biological and biomedical problems.

Van C. Mow
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THE HERBERT R. LISSNER AWARD IN BIOMEDICAL ENGINEERING

Dr. F. Gaynor Evans
Professor Emeritus of Anatomy
University of Michigan

F. GAYNOR EVANS RECIPIENT OF 1980 LISSNER BIOMEDICAL AWARD

This year the Bioengineering Division of ASME honors a pioneer in biomechanics, F. Gaynor Evans. The Lissner award was named in honor of Herbert R. Lissner who was a friend and colleague of Professor F. Gaynor Evans. They collaborated for over 14 years at Wayne University and did much of the pioneering work in impact biomechanics.

Gaynor Evans was born in 1907 in Iowa and was a magna cum laude graduate of Coe College in Cedar Rapids. He received his master's degree in 1932 and his Ph.D. degree in Zoology in 1939 from Columbia University. He taught at three East Coast universities before becoming an assistant professor of anatomy at Wayne State University in 1945. It was there that he met Professor Lissner who had already started his head-injury research. Their collaboration resulted in the construction of a unique research facility: a vertical accelerator housed in an elevator shaft of the old medical school building.

In addition to his work on crash injuries, Gaynor began a life-long study of the physical properties of bone under NIH sponsorship. He continued this work at the University of Michigan from 1959 to 1977 when he became professor emeritus.

Gaynor is known worldwide for his research on the macroscopic and microscopic properties of bone. He has published 86 papers and 66 abstracts most of which are related to biomechanics; he is particularly proud that 15 of these were co-authored with Professor Lissner. He has also written four books, two on anatomy and two on the properties of bone.

His extracurricular activities comprise a list that is too long to enumerate. His invaluable efforts as co-founder and co-editor-in-chief of the Journal of Biomechanics contributed to the success it now enjoys and are appreciated by the bioengineering community around the world. He is editor for eight other publications, and he organized two symposia for the International Congress of Anatomists.

Among the many presentations and lectures he has given, he is particularly proud of the invited paper delivered before the Accademia Nazionale dei Lincei in Rome; Galileo was one of the first members of this academy. Gaynor was also invited to present a paper on the relationship between the microstructure of compact bone and fracture at a NATO Advanced Study Institute in Ankara, Turkey. Illness in the family prevented him from making the trip in 1978, but his paper was published.

Among his awards, he was a Fulbright Fellow to Italy in 1956-57 and will be the recipient of the Founders Medal, a prestigious award given for only the second time by Coe College to distinguished graduates. He will receive the Medal on December 4, 1980.

He is affiliated with 11 professional societies and three honorary societies. He was the president of the American Society of Biomechanics in 1978 and a charter member of Biomeca of France.

Dr. Gaynor Evans is a soft-spoken professional who prefers to let his research work proclaim his numerous accomplishments and is always prepared to point out the good and the positive in the work of others. He is the epitome of a scholar. We are thankful for his valuable contributions to biomechanics and wish him well.

PREVIOUS RECIPIENTS

1977 Professor R.W. Mann
1978 Professor Y.C. Fung
1979 Professor R.F. Rushmore

HONORS COMMITTEE

E. Cravalho
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R. Skalak
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From Fairbanks Cranes to
Finite Elements: The Maturation of
Orthopaedic Biomechanics

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Development of Orthopaedic biomechanics in this country has occurred mainly in the last 25 years. During this period of time there was no unique source of inspiration and development but rather the coincident appearance of a number of factors both technical and personal which encouraged or even required growth of this interdisciplinary profession. Before the decade of the sixties the orthopaedic community in this country had practically no full-time personnel working in positions which we would now consider bioengineering. The orthopaedic community gradually realized that in order to solve certain of the more pressing clinical problems technological solutions would have to be employed. These problems centered mainly on the development of devices and the understanding of the interaction of these devices with the musculoskeletal system. With the development of such advanced devices came the need to associate with more technically trained personnel. Hence the earliest interactions between phycians and engineers was a direct result of the need for the phycian to have consultation on the design of experimentation and implantation devices. Once an interaction was established professional contact between engineers and orthopaedic surgeons naturally resulted in the realization that mutual benefit would be derived from a deeper and more continuing profession association.

Among the first people to recognize the possibility of such technology utilization was Dr. Paul Hirsch of Sweden. His early research into biomechanics and his willingness to train orthopaedic surgeons in the field of biomechanics was one major contributor to the growth of orthopaedic biomechanics in this country. Dr. Hirsch typified those phycians who utilized engineering technology for the purpose of developing experimental instrumentation. He then realized the usefulness of the same technology in describing the phenomena which he was observing. Other surgeons when introduced to the mechanical technology available through the biomechanician quickly realized the usefulness of the applications of such technology to the development of implants. Most of the integration of materials technology into orthopaedic biomechanics came through this route. In this lecture I shall attempt to trace the development of orthopaedic biomechanics through the processes of basic research, applied research and development and training of orthopaedic biomechanicians. I shall attempt to identify those centers that sprung up within the United States, the training programs and the research programs that produced the current population of professionals, both M.D. and Ph.D., who regard themselves as active biomechanicians.

REFLECTIONS ON THE HISTORY OF HEAT AND MASS TRANSFER IN BIOENGINEERING

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History can give us a sense of continuity and purpose; a base to start from as we try to chart our future. The history of such a broad interdisciplinary area as bioengineering can be viewed from different angles, each of which can give different perspectives. Even if we restrict ourselves to heat and mass transfer problems in bioengineering, we need to define the field in a way that allows us to bring various aspects in proper focus. In what follows, I am going to consider bioengineering as the application of the basic laws of physics and chemistry to biologically-oriented problems with special reference to heat transfer and, to a minimal degree, to mass transfer. Under this definition, for example, Galileo Galilei (1564-1642) of Pisa, who built an air thermometer, or Jean Rey (1583-1645), who constructed a water-in-glass thermometer cannot be considered as bioengineers even though they both studied medicine; whereas their contemporary, Professor Sanctorius (1561-1636) of Padua was definitely one, since he was trying to develop a thermometer for comparing temperatures of different persons. Another difficulty arises from trying to distinguish between a bioengineer and a biologist doing experimentation and analysis. As a matter of fact, until about one hundred and fifty years ago, the distinction could not have been made with the engineer; but, instead, it would have been made with a mathematician, scientist, or even philosopher.

Let us start, however, in more or less chronological order, with the ancient Greek philosophers, in whose thinking opposites, such as hot and cold, played a very important role. For example Aristotle, following previous writers, held that there were four primary and opposite fundamental quantities: hot and cold, wet and dry. Generally, warmth was considered more positive, life-giving and beneficial, but at the same time the balance of these opposites was also considered important. Alcmaeon of Crotona (5th century B.C.), Greek philosopher, physiologist, and doctor, suggested that health is due to the equilibrium of forces: wet and dry, cold and hot, bitter and sweet. If one of them dominates, it causes disease and destruction; thus sickness is caused by an imbalance and health is the result of a uniform mixture of these forces. In the Aphorisms of Hippocrates it is stated that if the same food is given to a patient in fever and to a person in good health, the patient's disease is aggravated by what strengthens the healthy person. In the Prognostics of Hippocrates among the signs of impending death "cold ears" are mentioned. It is, perhaps, an interesting historical sideline that these signs, sometimes referred to as Hippocratic facies, are described well by Shakespeare in the description of the death of Falstaff in Henry V.

Similar thoughts could be found in the botany and biology of those days, such as the biologist of the 4th century B. C. who claimed that the proper balance of hot and cold was essential for proper fruit bearing; that is, warm crops would bring a rich harvest in cold soil, and cold crops in the warm. Even animals were considered to be governed by similar laws.

By way of contrast from later times it is interesting to note that in the Latin literature there seems to be an interesting connection between cold and faith, lending cold essentially a more positive character. The connection apparently seems to be somewhat in the following order: cooling--being cooled in a protected place--trust in a protected place of this sort--trust (faith) in a super-natural being (God). Thus the word, refrigerium, is related to "cold" as well as to a "resting place". As an ultimate contrast, we might mention that whereas, for most of us, hell is associated with a hot place; among many people, particularly in the north, hell is associated with an icy freezing place. There is also a great deal of application of heat and cold among primitive people throughout history. The use of hot baths for the treatment of various ailments is apparent not only in the western world since before Hippocrates, but also in other parts of the world, such as the volcanic springs of Japan.

Let us turn now to the more scientific aspects. I have already mentioned Professor Sanctorius of Padua, contemporary of Galileo, who described a thermometer for comparing temperatures of different persons. This device, unfortunately, was a very unsatisfactory one. He also described an apparatus for comparing pulse rates. He also demonstrated that the body loses weight by mere exposure to the air, which he attributed to "insensible perspiration", signaling the beginning of the study of metabolism. Robert Boyle (1627-1691), better known for his famous law of gases, also froze the "humours of the eye of the oxen," and thus could be considered as the forerunner of cryobiology.

In 1752, René Antoine Réaumur demonstrated the power of gastric juices from birds to dissolve food in a test tube at body temperature.

Antoine Lavoisier (1743-1793), French chemist, may be considered the first scientist on biological mass exchange. He made quantitative examinations of changes, particularly of oxygen consumption, during breathing (also burning and calcination) and discovered the composition of respired air. He showed that carbon dioxide and water are the natural products of breathing. He also found that low environmental temperature, eating, and physical labor increased oxygen consumption.

It took over 200 years from Sanctorius to the second part of the scientifically fertile 19th century to develop proper measurement of body temperature. Wunderlich, in 1868, described his work of charting body temperatures in hospitalized patients. This century produced other significant investigations in this field. Robert Mayer (1814-1878), who held a medical degree from Tübingen, studied the physical bases of living organisms. From these investigations he discovered that heat and mechanical energy were related. His claims, however, were rejected by his contemporaries, most of whom were still believers of the caloric theory of heat. Supposedly as a result, Mayer became despondent and eventually lost his sanity.

Hermann von Helmholtz (1821-1894) is another outstanding example of the physician/physiologist turned physicist. Although he was primarily interested in physics, he decided on the medical training which he could obtain free by enlisting in the military service. During this service he wrote a treatise on the law of conservation energy which attracted the attention of Alexander von Humbolt. As a consequence he was released from the military, and was appointed to the Berlin Academy of Arts as a physiologist and lecturer in anatomy. He progressed from there to be professor of physiology and pathology at Königsberg, of anatomy and physiology at Bonn, of physiology at Heidelberg, and finally, professor of physics at Berlin in 1871. Among his many notable contributions to science, the one most significant for our purpose is the concept that the heat liberated by muscular activity constitutes an important source of animal heat. A related doctrine, that animal heat is the result of combustion, was developed by Justus von Liebig (1803-1873); and Carl Ludwig (1816-1895) showed that the law of conservation of energy, that is, the first law of thermodynamics, can be applied to glandular activity.

Another physician to be mentioned is Arsène d'Arsonval, who developed bacteriological incubators and, in cooperation with Claude Bernard, worked on the problem of oxygenation of blood. They showed that venous blood was warmer than arterial blood because of oxidation which occurred at the periphery. d'Arsonval made thermocouples which were inserted in the left and right ventricles to measure the small temperature difference between arterial and venous blood. He also studied the heat liberated by animals and the factors affecting dirunal temperature changes in human and animal bodies. He also measured expired carbon dioxide.

Although the use of fever or, to be more precise, of artificially elevated body temperature as a therapeutic agent, can be found throughout history among virtually all races of the world, the beginning of modern fever therapy can be most likely attributed to Wagner von Jauregg who in 1887 suggested the use of malaria for the treatment of various diseases. Following his report published in 1917, injections of various chemical agents, drugs, bacteria and other organisms to cause fever met with considerable success in spite of the disadvantages of difficulty of control and subsequent debilitating effects. In 1927 Neymann and Osborne discovered that high temperatures in the body can be produced by a high-frequency diathermy machine. This method was in use until the early thirties in conjunction with other devices, particularly the air conditioned cabinet, the most successfuly of which was named after Kettering. It was discovered, apparently by accident, that the diathermy was not needed in order to elevate body temperature because a properly functioning air conditioned cabinet was adequate by itself.

As we enter the twentieth century our task of charting the course of history becomes much more difficult because of the rapid expansion of technological activity. In order to maintain an overview, and keep this treatise within reasonable balance, I am going to discuss only a few broad areas most relevant to the study of heat and mass transfer in bioengineering. In addition, I wish to emphasize the areas where our society, ASME, has been particularly active. I will also try to mention only very few names with implied apologies to the many outstanding workers in this field.

The broadest and most significant area of study outside the field of medicine has been the human thermal regulation in various environments. These studies are still continuing today, and they include: the general thermal behavior of the body and its environment, the determination of the various physical parameters involved and their magnitudes, and the development of mathematical models to help in understanding the observed phenomena. The bulk of the work to collect physiological data on thermal comfort and tolerance limits can be attributed to a few well-equipped laboratories such as the ASHVE Laboratory in Cleveland, Ohio which was transferred to Kansas State University in the early sixties; the John B. Pierce Foundation in New Haven, Connecticut; and several laboratories of the armed services such as Wright-Patterson Air Force Base in Dayton, Ohio, the Biophysics Laboratory of the Naval Air Development Center in Warminster, Pennsylvania; the Army Research Institute in Natick, Massachusetts, and, starting with the space program, several NASA laboratories. The earliest publication from the

ASHVE Laboratory is on "Some Physiological Reactions to High Temperatures and Humidities" by W. J. McConnell, F. C. Houghton, and C. P. Yaglou, which appeared in the Transactions of ASHVE in 1923 and 1924. The earliest reference I could find in the ASME was an address presented by C. L. Taylor of UCLA at the Heat Transfer Division luncheon at the annual meeting of the Society in New York City in 1954 entitled "Heat-Transfer Applications in the Human Body". A condensed version of this address appeared in the June 1955 issue of Mechanical Engineering. With apologies to those I have missed, I would like to mention the following workers outstanding in this field. The researchers at the John B. Pierce Foundation Laboratory, under the capable leadership of J. D. Hardy for many decades, such as A. P. Gagge and J. A. J. Stolwijk produced copious amounts of new information on human thermal regulation and general thermal physiology, including modelling of the human thermal system. The leaders at the Kansas State University laboratory were R. G. Nevins, P. E. McNall, Jr., and F. H. Rohles, Jr. Dr. Alice M. Stoll, from the Navy Air Development Center, as well as Dr. Hardy, investigated such problems as radiative heat transfer to the human skin and burn studies. At the Army Research Institute I want to mention R. F. Goldman and J. R. Breckenridge. Professor C. L. Taylor from UCLA, whom I mentioned previously as a presenter of the first address on the subject to an ASME division, and W. V. Blockley worked with a group at Wright-Patterson Air Force Base. For studies in human calorimetry, the works of A. C. Burton, H. C. Bazett, and H. S. Belding should be mentioned. The results of all this work has been systematically organized into a book by P. O. Fanger of Denmark. Current interest in energy conservation should shift research from "comfort" to "tolerance during work".

The development of spacesuits actually started with protective garments designed for aircraft pilots, particularly during and after World War II. At first these suits were air-cooled; but in the early fifties the concept of a liquid-cooled garment, in which the body heat is removed by means of conduction to water-cooled tubes in direct contact with the skin, originated apparently in England and was brought over to the NASA space program by J. Billingham and his co-workers. The liquid-cooled garment proved to be more effective than the air-cooled one and became the basis for the Extra-Vehicular Activity (EVA) spacesuits in the Apollo Program.

The modelling of the biological, particularly human thermal systems has been done usually on two major levels: 1) the passive part, and 2) the entire thermoregulatory system including sensors and control mechanisms. The modelling of the passive live tissues involves only the mechanisms by which heat diffuses and the control functions appear only as perscribed variations of boundary conditions and parameters. One of the biggest problems in this field is the evaluation of the effect of blood perfusion. The earliest attempts simply utilized variable thermal conductivity in the heat conduction equation where the variation of the magnitude was linked to the variation in blood perfusion of the tissue. In 1948 H. H. Pennes, who, by the way, was not an engineer, published a model in which the blood perfusion was assumed to contribute sensible heat on a volumetric basis proportional to the difference between the arterial and venous blood temperatures. This equation is still widely used today and is usually referred to as the bio-heat equation. An additional assumption generally made is that the venous temperature is equal to the local tissue temperature. This method seems to be still the most useful approach to the calculation of temperature distributions in the human body because of its distinct advantage of modelling blood perfusion as a separate entity. Like all models, this one has some shortcomings too. Recent studies by M. M. Chen and myself indicate that the most significant heat transfer between the arterial system and the surrounding tissue should actually occur in the small arteries instead of in the capillaries as was generally assumed earlier. More detailed and sophisticated models, which include some aspects of the actual geometry of the vasculature, have been and still are under development. These, however, have still only limited applications, partly because some are limited by the vascular geometries assumed, some require too much detailed physiological information, and some are just too new to be used widely.

Modelling the transient behavior of biological systems requires the description of the control functions and, consequently, understanding of the control-type behavior of these systems. C. L. Taylor in his 1954 address mentioned above described efforts on modelling the human body as a series of parallel slabs consisting of thermal resistances and capacitances. This rather primitive model of essentially a single body element with various layers has been superseded my much more sophisticated models in which individual parts of the body, such as the limbs, are treated separately. With the advent of fast computer systems, modelling of the active thermal regulatory system has reached highly sophisticated levels, actually quite some time ago, which include even very sophisticated anticipatory feedforward-feedback mechanisms, as well as some relevant mass transport phenomena such as gas exchange in the lungs. As pointed out by C. E. Huckaba in 1974, work on theoretical control mechanisms may have far outstripped our ability to obtain experimental data to evaluate the models.

The measurement of temperatures and thermophysical properties of living tissues constitutes one of the most important engineering contributions to thermal physiology and its applications. The particular difficulties lie in 1) the relatively narrow temperature ranges encountered, 2) the variability and non-uniformity of biological materials from location to location as well as from individual to individual, 3) the active response of living systems to thermal stimuli, and 4) the effects of blood perfusion which generally requires an a priori model in the data reduction.

In the measurement of temperature we have progressed from Galileo's and Rey's air and water-in-glass thermometers to miniature thermocouples and diodes for extremely accurate measurements with minimal disturbance of the system. The measurement of thermo-physical properties of biological materials has started most significantly in the food industry, particularly in conjunction with freezing of foodstuffs. Early issues of publications of the ASRE and other journals related to food technology indicate copious amounts of work in this area. Various standard and non-standard measuring techniques have been utilized most of which originated in regular heat transfer research. In vivo measurements, however, were very rare because of the difficulties of placing the living material in the available apparatus. One notable exception was the measurement of the properties of skin which was, of course, easily accessible. The earliest quantitative data on the thermal conductivity of skin were obtained with the use of a known radiation source in conjunction with surface temperature measurements in the late twenties and early thirties. In 1968 I suggested a single-bead method of measuring the thermal conductivity and diffusivity in vivo. Subsequently, this method was improved by T. A. Balasubramaniam and H. F. Bowman, and by R. Jain. Recently, M. M. Chen suggested an alternate method of operation with a single bead which allows reduction of the size of the measuring probe. Also in 1968 G. J. Trezek and T. E. Cooper reported on the use of the long, cylindrical probe configuration for obtaining in vivo data. All of these methods require short duration, transient measurements, an absolute necessity for in vivo studies.

Since this is a history of engineering and not of medicine, I shall limit my remarks to some technological aspects of medicine only. One of the difficulties of trying to establish this viewpoint from the literature is that the medical publications tend to gloss over, and sometimes totally ignore the engineering contribution as an irrelevant input to the medical work. It has been only relatively recently that non-medical collaborators were included among the usually long list of authors in a medical publication. I have already discussed, or alluded to various effects of heat and cold on the human body both in the normal state and in various diseases. In surgery both heat and cold have been utilized effectively. The use of high frequency current to destroy tissue was based, of course, on pioneering work going back several decades, and is associated with such well-known names as Röntgen and Tesla. Applications of such diathermy in medicine may be attributed to Doyen in Europe and W. L. Clark in the United States. The method is quite simple and is widely used, for example, for the removal of warts. In addition to simplicity, the aseptic, cauterizing, hemostatic, and cosmetic effects are additional advantages of this method. More recently, miniature plasma arcs have been developed for similar purposes.

Another important application of heat in medicine is the use of thermography for the detection of vascular disorders, particularly breast cancer. The best known developers of this technique are J. D. Haberman, a medical doctor, working with T. J. Love, an engineer. Most recently the use of hyperthermia in conjunction with other treatments of cancer has given considerable boost to the amount of work done on methods of producing local increases in temperature. In addition to the long-existing diathermy, applications of microwaves and ultrasonic techniques are being explored.

The beginnings of cryosurgery, the application of cold for the destruction of tissue, are also somewhat obscured. I already mentioned Robert Boyle freezing the "humours of the eye of the oxen" in the 17th century. In 1883 S. Openchowski reported the use of cold for experimentation with the cerebral cortex of dogs. The cooling effect was obtained by rapid evaporation of ether by a warm jet of air. In 1899 and 1901 A. C. White reported on the use of liquid air in medicine and surgery. In 1907 W. A. Pusey suggested carbon dioxide snow. These freezing methods were predominantly used for the treatment of skin disorders. In spite of the availability of freezing techniques, the applications to surgery were extremely sporadic during the next five decades. In 1948 G. H. Haas and C. B. Taylor reported on a quantitative hypothermal method for production of local injury to tissue. In 1951 J. B. Arnott described the treatment of cancer by application of low temperatures. Cryosurgery seems to have accelerated suddenly around 1960, initially with reports on application to the surface of the brain, and then by the development of freezing cannulas which allowed localized cooling and freezing inside the central nervous system without affecting the peripheral tissues. I developed a probe utilizing standard fluorocarbon refrigerants for Dr. V. H. Mark in Boston who applied it for the treatment of cerebral palsy. About the same time Dr. I. S. Cooper in New York had the Linde Division of Union Carbide Corporation develop a liquid nitrogen probe for the treatment of Parkinsonism. During the next few years the utilization of similar probes has spread rapidly to other areas of surgery, such as ophthalmology, otolaryngology, dermatology, gynecology, and for the treatment of various tumors. G. J. Trezek and T. E. Cooper, working with D. L. Jewett, provided engineering input to cryosurgery, such as calculating and mapping the size of the frozen region around a cryoprobe in the brain.

There are some very specific advantages in using cold as the surgical agent in certain applications. In the nervous system, for instance, the initial cooling, without freezing, of the nervous tissue will create a reversible lesion which allows the surgeon to explore the effects of destroying the local tissue without actual destruction. In cataract removal the diseased lens will freeze to the probe, thereby creating a convenient means for removing the cataract. Perhaps the two major advantages of cryosurgery are its anesthetic and generally also hemostatic effects.

Many aspects of cryobiology can be classified under bioengineering. For example, understanding the exact mechanisms of cell destruction during freezing and thawing and the subsequent development of devices to follow rather precise protocols are indispensible for the improvement and expansion of cryopreservation of biological materials including complete organs. Starting around the late thirties, the modern pioneers of cryobiology, such as Father B. J. Luyet, and later, H. T. Meryman, were primarily concerned with blood transfusion and preservation. This very fragile fluid can be stored and preserved by freezing, but either too fast or too slow freezing, or improper thawing rates will destroy it. Some of the most significant insights into the mechanisms of freezing and thawing of biological cells has been provided by E. G. Cravalho and C. Huggins. The current protocol for long-term storage of blood involves the addition of a cryophylactic agent such as glycerol, a not too fast freezing rate, fast thawing, and finally the washing out of the cryophylactic agent. Considerable efforts in this area today are aimed at the preservation of whole organs.

Although we seem to be predominantly preoccupied with human-oriented problems, this discussion would be incomplete without mentioning some of the contributions of engineers to zoology and botany. R. C. Birkebak has been working on the various problems of heat transfer to animals and, particularly, on the role of the integuments. He has been reasonably successful, for example, in predicting the wintering places of migratory birds by considering the energy balance requirements. I read with interest his latest efforts in using fur-like material in solar