*Caltech answers the call for a change in engineering education with*

# A UNIQUE TEACHING METHOD

*by William H. Corcoran*

The development of artificial internal organs and the transplanting of such organs as the heart and the kidney are perhaps the most exciting advances in the field of medicine today. But equally exciting advances in technology have resulted from this work and have inevitably brought about a liaison between the medical and engineering professions—a liaison that is bound to lead to improved abilities in dealing with the technical aspects of difficult medical problems. These advances also furnish the basis for a new approach to engineering education—an approach which has met with great success at Caltech.

Last year, Caltech made a radical change in the teaching of chemical engineering. The introductory course in engineering for sophomores was built entirely around the study of problems based on hemodialysis and artificial kidneys. (Dialysis is the transfer of a dissolved substance across a membrane as a result of diffusion coupled with any bulk flow or fluid that might occur.) The course introduced such basic concepts as mass, energy, and momentum balances, stoichiometry, chemical equilibrium, and chemical kinetics by applying them to the problem of the treatment of kidney failure. The results of this new approach were so successful that the course has been made part of the regular curriculum.

The new framework not only allows a logical presentation of the concepts previously covered but introduces many other worthwhile principles of engineering interest. Because the course is introductory, all aspects of hemodialysis—engineering, medical, biological, and economic—are presented. Somewhat more than one-third of the three class hours per week are devoted to instruction by a member of the chemical engineering faculty on basic principles of thermodynamics, chemical equilibrium, and transport phenomena. These principles, including their use in mathematical models, are then applied to the problem of kidney failure.

Another one-third of the class hours are devoted to lectures by medical and professional people on such topics as renal function and failure; the design and function of necessary equipment for dialysis; sociological, medical, and economic problems of home and institutional dialysis; and the primarily medical problems of treatment for renal failure.

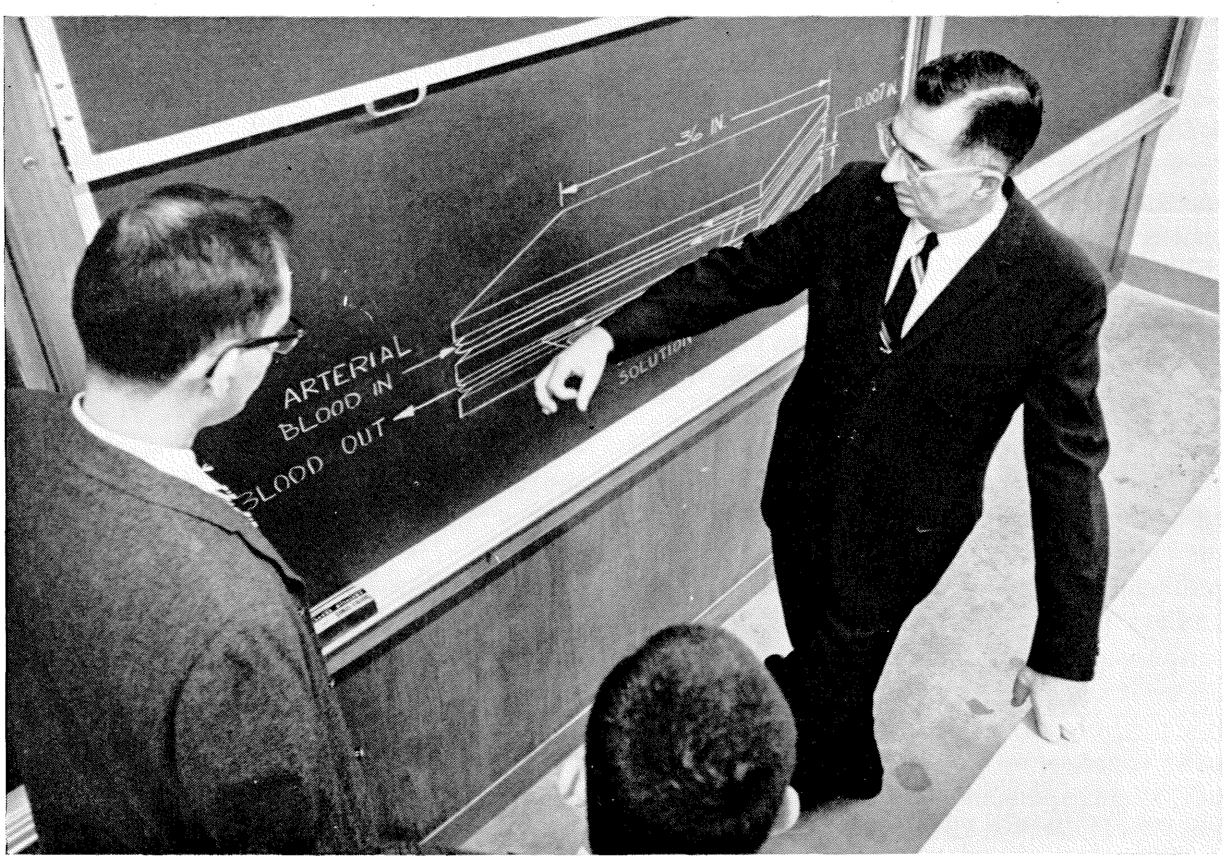
The remainder of the class time is spent on field trips to a hospital or manufacturing company to illustrate the application of information presented in the course.

The idea of using the artificial kidney to communicate engineering principles to students is based upon the fact that it demonstrates exceptionally fine examples of chemical engineering problems. The flow of blood from a patient's artery through an artificial kidney and back to the patient's vein—with the concurrent transfer of metabolic poisons to the dialysate fluid—presents excellent examples for study of fluid flow, material transfer, and energy transfer. In addition, the role of osmotic pressure in effecting solvent transfer across a cellophane membrane allows a real study of chemical equilibrium.

Combinations of these scientific and engineering principles in the framework of the capital costs of the equipment, its maintenance, and its efficient use provide good focus upon the techniques of cost accounting and the need for keeping economics continually in mind in the proper design of chemical systems.

Finally, in dealing with human beings, students get new insight into sociological needs and problems of human philosophy and psychology. In chronic kidney problems in human beings, the main avenue for removing undesirable metabolic waste products from the bloodstream is the use of hemodialysis exterior to the body. Techniques other than hemodialysis have been used, and practically every biological membrane has been tried. At the present time, though, peritoneal dialysis appears to be a useful technique for treatment of acute renal failure and removal of body poisons, while hemodialysis appears to be the preferred system for treating chronic renal failures.

Renal failure means simply that there is a loss of function, totally or partially, of the nephrons, which are filtration units of the kidney. There are some two milllion nephrons in the kidney, and when one is damaged and loses function, the process is irreversible. In normal excretion, one liter of fluid may be discharged per day by way of the kidneys. With renal difficulties, this quantity may be 70 percent less, with a concomitant building up of metabolic




Professor William Corcoran (right) and his teaching assistants use a blackboard drawing of the Kiil artificial kidney to demonstrate its design and function to a class in chemical engineering.

waste products in the blood plasma. Urea and creatinine are measures of the buildup of toxic waste products, and a toxic state known as uremia develops. The actual toxic substances which cause uremia have not yet been specified in physiological studies.

With normal renal function, the equilibrium concentration of urea nitrogen in the blood runs around 10 milligrams percent; this is 10 milligrams per 100 milliliters of blood. With 10 percent renal function, that number can approach 50 milligrams percent, and at that time the associated toxins would be influencing the body rapidly toward the state of uremia. Dialysis is then used to lower the content of the nitrogen-containing compounds of urea and creatinine and at the same time to remove the unknown toxic substances associated with uremia. Since the present methods allow removal of only 80 percent of the metabolic wastes, a person receiving hemodialysis treatment for renal failure is never completely well nor completely ill. Today an ordinary treatment for renal failure is one in which a patient receives two 12-hour dialyses during a week.

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*Today's patient pays as much as $12,000 annually to use an artificial kidney; the challenge to the engineer is to reduce these high costs by designing more efficient equipment.*

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Even though hemodialysis in an artificial kidney has been possible for at least 50 years, the first practical design was developed during World War II in Holland by Willem Kolff, M.D., who is now living in the United States. The design consisted mainly of a large rotating drum wound with cellophane tubing, with the unit immersed in a large bath of dialysate fluid. Blood which was heparinized flowed from the patient to a special coupling and then through the spiral path of tubing. Modifications of the Kolff design are in use in the United States and other parts of the world today.

In addition to the Kolff kidney, plate-type dialyzers have been developed which consist of sheets of cellophane mounted between flat parallel plates. One of the most common units of this type is the kidney first proposed by Frederick Kiil, M.D., of Norway and adapted by Belding Scribner, M.D., for use at the University of Washington Medical School. In his adaptation, cold dialysate fluid was circulated from a 380-liter tank through the dialyzer and returned to the tank. The dialysis is now carried out at essentially room temperature, but in the earlier work by Dr. Scribner it was performed at 20°C with the blood being rewarmed before return to the patient.

In the Kiil unit there is a low-pressure drop so that it is possible for the human heart to provide the pressure needed for reasonable flow of blood through the unit, whereas the Kolff system requires auxiliary pumping. The absence of a mechanical pump is helpful because of less trauma to the cell components of the blood.

Probably the main feature of the hemodialysis technique used today is the arteriovenous shunt, developed for convenience in getting into the patient's vascular system. This vascular prosthesis was developed in Seattle by Dr. Scribner and consists of a coil of Teflon or silicone rubber that is surgically and semipermanently mounted—typically in the forearm of the patient—providing a connection between an artery and a vein. When dialysis is necessary, the shunt and the exterior dialysis unit are connected. Thus a patient does not require a cutdown into an artery and a vein each time a dialysis is made. This is fortunate because the number of cutdowns possible within the framework of the body is finite due to the limited length of arteries and veins. These plastic shunts have been worn in place for periods up to a year and a half, and a new shunt has then been placed at a new site.

The cost for use of the Kiil kidney for hospitalized patients for two 12-hour dialyses a week for a year is roughly $8,000 plus an additional $4,000 for costs associated with occupancy of a hospital bed. The total cost of $12,000 may be somewhat low when considering that total annual costs as high as $35,000 have been reported. One of the major goals today is to reduce these costs. Significant progress has been made in this direction by way of a home unit for conduction of the hemodialysis procedure. Techniques for assembly and operation of equipment are learned in the hospital by the patient and another member of his family, and then the process is carried out in the home. Costs for home dialysis average from $4,000 to $10,000 per year including amortization of the equipment. Obviously, even further reduction in cost is desirable.

The challenge to the engineer, therefore, is to design equipment for hemodialysis that is convenient and comfortable and safe for the patient to use at low cost. Ideally such a unit would have a very small volume so that it could be contained readily on the exterior of a person's body and would be efficient relative to time required for reduction of metabolic wastes to an appropriate level. A small unit that would provide rapid removal of waste would, from a commonsense point of view, really be moving in the direction of the design of the natural kidney itself. Optimization studies show that the best type of unit, operating on pressure supplied by the human heart, would be one having essentially zero length in the direction of flow in the dialysis system, relatively low pressure drop, and hence significant width. Those boundary conditions come close to the human kidney system with its two million nephrons distributed between the two kidneys. Current efforts to produce a dialysis unit from many small-bore tubes mounted in parallel are moving in that direction.

A second technique, peritoneal dialysis, is not a dialysis system requiring transfers of blood from the patient to the exterior and return. Though it is simpler, it is not as effective as hemodialysis. It has had significant application in the treatment of acute renal failure because of the simple technique required in its use, whereas a hemodialysis system requires a team of specialists to equip the patient with the shunt and to get the equipment operating properly. In peritoneal dialysis, a catheter is inserted between the abdominal wall and the peritoneum by way of an incision near the umbilicus, and fluid is allowed to flow through the catheter into the peritoneal cavity. There is dialysis by way of transfer from the capillaries of the peritoneum to the fluid in the peritoneal cavity.

Because of the absence of flow in the peritoneal dialysis system in ordinary usage and the buildup of metabolites in the dialysate, the transfer of materials is not quite as rapid as in hemodialysis. That decrease in rate can be reduced somewhat by having the fluid move into and out of the peritoneal cavity on a continual basis, which requires significantly more dialysate fluid. Transfer can also be enhanced by vibration of the patient or by any other technique that decreases the effective thickness of the boundary layer in the transfer from the peritoneum to the fluid.

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*In actually seeing patients in a hospital, students get new insights into sociological needs and problems of human philosophy and psychology—problems they would not realize merely from classroom discussion.*

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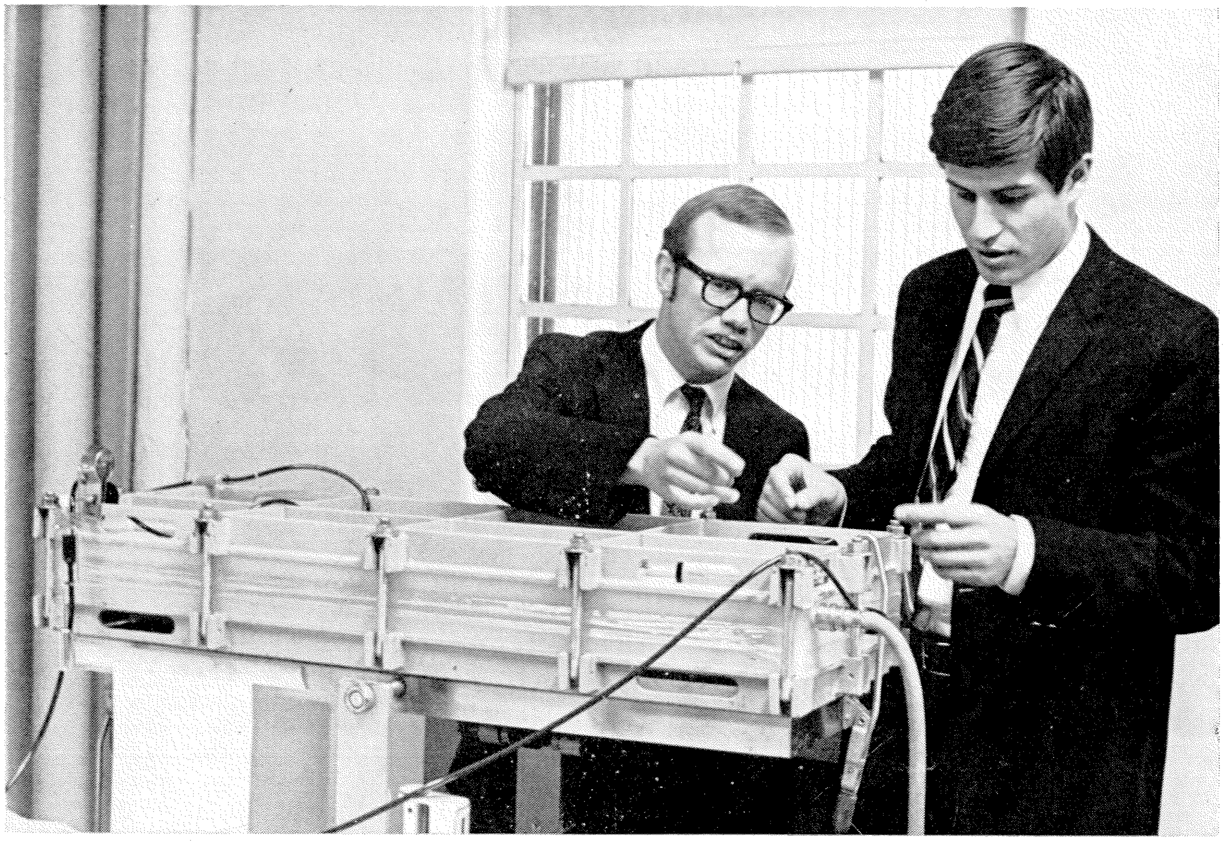
No doubt other techniques for removal of metabolic wastes will be developed in the future. At the present time, however, the use of hemodialysis in the Kiil or Kolff kidney is the most satisfactory for continuing treatment of chronic kidney failure. In each case, there is need for significant engineering design in the improvement of the necessary equipment. Because of the need for improved engineering thinking in the systems of hemodialysis and peritoneal dialysis and because of the obvious interest in the use of artificial internal organs, the studies of these systems provide extraordinary means for communication of engineering principles to engineering and science students.

At Caltech, during the final three weeks of the course, students work individually or in pairs researching a topic of their choice in the field of hemodialysis. Some have done cost-reduction studies while others have conducted research on new, more efficient methods of dialysis and various approaches to home and hospital dialysis.

The course in use at Caltech was developed



Larry Waterland and Bill Bradley inspect an artificial kidney in operation at a local hospital. The two sophomores are designing a new artificial kidney as part of their course in chemical engineering.

by Milton E. Rubini, associate professor of medicine at UCLA, visiting associate professor of chemical engineering at Caltech, and Chief of the Metabolic Section at Wadsworth Veterans Administration Hospital; E. A. Pecker, president of Biosystems, Inc.; Malcolm Morrison, a Caltech graduate teaching assistant in chemical engineering, and myself. Extraordinary assistance was provided by John R. De Palma, M.D., Mt. Sinai Hospital; Ralph M. Goldman, M.D., UCLA; and John E. Meihaus, M.D., USC. E. I. du Pont de Nemours & Company, Inc., provided financial support for the work at Caltech.

Subsequent course work in the style of that based on the artificial kidney can be imagined in the design of other artificial organs; however, it probably would not encompass the total combination of chemical and physical changes as seen in the framework of the artificial kidney. One of the most striking aspects of the artificial kidney study is the continuing development of the thought that, as improved equipment is obtained by way of engineering design, there will be more and more turning to the transplants of live organs. That opportunity would expand because of increasing ability to keep a person under appropriate physiological and medical control in the absence of kidney function until the time an appropriate transplant is put into place and is in operation. For example, with a very low-cost unit providing great efficiency in the removal of wastes, a person with renal difficulties would be put on that unit more readily than he is now on the more expensive system.

The artificial kidney is clearly the best artificial internal organ to study because it utilizes in a simple and straightforward fashion so many of the principles common to virtually all engineering problems. Other avenues have been used to introduce these engineering principles to students. None to date, however, has been quite as exciting as the use of the kidney, nor quite as complete relative to displaying the need for new approaches to the design of systems in which chemical reactions are occuring in the presence of flow.