# Where Does Instrumentation Enter into Medicine?

Modern technology can help medicine meet growing demands through instrumentation and automation.

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The United States boasts of having the best medical care in the world. Yet this care is inadequate. A young house physician from one of our large metropolitan hospitals recently complained that he and two other doctors were forced to see and treat 180 patients in the course of a 3-hour clinic. This meant that the average patient had available to him only 3 minutes of a physician's time. The expanding demand for medical services that has resulted from Blue Cross and similar prepaid medical care plans cannot be met by our present facilities with present methods. To establish a diagnosis takes too long. To board and treat the hospitalized patient requires the time and attention of too many people. Coordination of the efforts of those responsible for the various aspects of medical care is too haphazard. The fact is that medical practice is where the manufacturing industry was at the beginning of the industrial revolution. All our work is piecework, and it is all done by hand.

It is true that medicine has special problems which set it apart from other industries. Each patient who presents himself for treatment differs from every other patient by virtue of differences in the progress of the disease and differences in age, nutritional status, reactivity to drugs, and responsiveness to therapy. Constant surveillance of the patient is necessary to detect changes in his condition. Each reaction to therapy, diet, or rest requires re-evaluation and possibly a change of regimen. The various aspects of medical care have become so complex that most of the physicians and technicians concerned with the patient are specialists, and many are subspecialists within their special fields of training—for example, the cardiopulmonary physiologist, the recovery-room nurse, and the intensive-care nurse.

Another important difference is that occasionally we must work with systems about whose mechanisms we have only a rudimentary knowledge. Until 39 years ago we had no idea what caused diabetes. Only in the past 12 years have we begun to appreciate the full significance of the complex hormonal balances which, day by day and hour by hour, efficiently regulate nutrition, cardiovascular homeostasis, and useful response to stress, disease, and inflammation. Even now our best men are scratching their heads over the most elementary aspects of the regulation of nervous activity, mental health, and emotional behavior. Growth itself, which is one of the most fundamental characteristics of living things, is still in large part a mystery.

## Practices in Anesthesia

The special problems associated with the practice of medicine do not excuse or justify the archaic methods we employ for collecting data, processing and interpreting it, transmitting it, and translating it into action. Let me take a few examples from my own specialty, anesthesiology, to illustrate this.

The responsibilities of the anesthesiologist are complex and demanding. He must acquaint himself with the physical and mental status of the patient. Then, taking into consideration the surgical requirements of the operation to be performed, he must protect the patient from all painful and emotionally disturbing stimuli. He must prepare a relaxed field for the surgeon to operate in. He must, moreover, guard the patient from harmful reflexes, support his respiration and circulation, and return him to full consciousness and self-sufficiency as soon as possible after the operation is over.

What does he have to work with to accomplish all this? If he is fortunate he can devote 10 or 15 minutes the evening before the operation to examining the patient's chart and seeing the patient. The chart is a conglomeration of disjointed notes and reports, recorded in a nonuniform manner in as many as 10 or 20 different handwritings. If the patient has had a previous admission, his chart may consist of two or more volumes, all of which may not be readily available for examination. The drugs and agents the anesthetist uses to induce anesthesia and relaxation are, in the main, substances which disturb normal nervous balances, depress respiration, interfere with circulatory homeostasis, and cause temporary deviations of hormonal balance and metabolic activity.

His equipment consists of a blood-pressure cuff and stethoscope, a watch, and a few open-ended controls to regulate administration of his drugs. The latter are regulating devices that lack feedback; they include needle valves on the anesthesia machine, which control the flow of gases; the ether vaporizer (notorious for its failure to deliver vapor at a constant concentration), and infusion drip regulators.

To judge the adequacy of respiration he observes the movements of a rebreathing bag. To determine the circulatory status he feels and counts the pulse and measures the blood pressure, whenever it occurs to him to do so. To evaluate the depth of anesthesia he relies primarily on his eye to observe the activity of a few reflexes. This is the manner in which, I would judge, 95 percent of our anesthesias are being administered today.

## Consequences

What are the consequences of this method of practice? At best, an occasional disaster or near disaster. The following are three actual case histories based on information recorded by the anesthesiologist.

*Case 1.* A young woman, 21 years old and weighing 131 pounds, with

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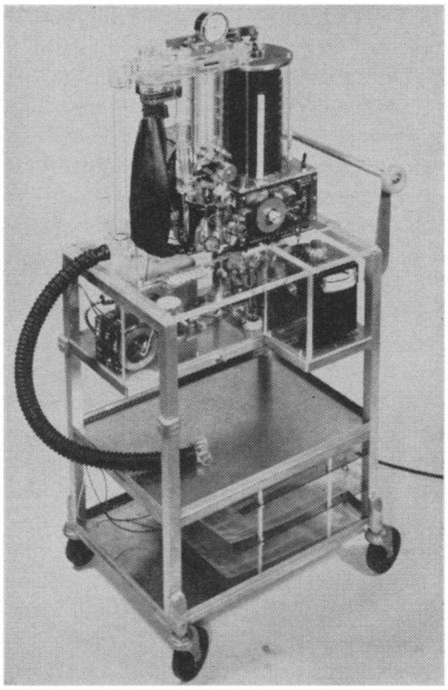

Fig. 1. The autoanestheton.

no known systemic disease except for chronic inflammation of the left middle ear, and with no known allergies, was prepared for mastoidectomy and tympanoplasty. Meperidine (60 mg) and scopolamine (0.4 mg) were administered intramuscularly 45 minutes before the induction of anesthesia. Anesthesia was begun with 125 milligrams of thiopental and was maintained with 3 liters of nitrous oxide and 1 liter of oxygen per minute and with intermittent intravenous dosage of thiopental and meperidine in small amounts. Succinylcholine, (40 mg) was given, and a rubber endotracheal tube, (size 40, French) was placed in the trachea 10 minutes after the induction of anesthesia. Five minutes later the flow of nitrous oxide was reduced to 2 liters per minute. The left mastoid region was infiltrated with 1-percent procaine containing eight drops of adrenalin solution. The skin was incised 25 minutes after anesthesia was begun. The blood pressure, as measured by auscultation, remained stable at 110 millimeters of mercury systolic, and 70 millimeters of mercury diastolic; the pulse was 80 beats per minute, and the rate of respiration fluctuated between 18 and 20 per minute. Four minutes after the skin incision was made the blood pressure was unobtainable and the peripheral pulse was not palpable, but respiration continued normally for several minutes. A rapid, irregular pulse was felt over the precordium.

Anesthesia was discontinued, 100-percent oxygen was given, and attempts were made to improve circulation by tilting the patient head down and giving vasopressors. Ten minutes later moist rales were heard in the lungs, and frothy, blood-tinged mucous was aspirated from the trachea. A diagnosis of pulmonary edema was made. Digoxin (1 mg) was given, and an infusion of 5-percent dextrose in water was started in a vein. Norepinephrine was added to the infusion. No central pulse was palpable or audible, and 27 minutes after the peripheral pulse disappeared the chest was opened and manual massage of a flabby, arrested heart was begun. Spontaneous contractions of the heart recommenced but, despite continued treatment, failed to sustain an effective circulation. Four hours after anesthesia was started the patient was pronounced dead.

*Comment.* Some unknown event, possibly related either to the administration of the general anesthetic or of the local anesthetic and adrenalin, caused a failure of the circulation. Although its occurrence was noted within 5 minutes at the most, the magnitude and significance of this failure were not recognized until 27 minutes after it was first noticed. All subsequent heroic efforts to restore circulation were ineffective.

An electrocardiogram or a continuously indicating blood-pressure monitor would have provided evidence of a change in the function of the heart as soon as it occurred, and an electroencephalogram would have provided clear evidence of circulatory inadequacy within a minute of its occurrence. Delay in establishing a diagnosis insured the fatal outcome of this case.

*Case 2.* A well-developed, febrile, male infant, aged 12 months, was admitted for treatment of right otitis media and acute mastoiditis. His temperature was 39.8°C, his pulse rate was 160 beats per minute, and his respiratory rate was 80 per minute. On physical examination he appeared acutely ill and irritable, but with no gross abnormalities of his head, chest, abdomen, or extremities. He received nothing by mouth on the day of operation. He was given 15 milligrams of meperidine by hypodermic injection at 11:45 A.M. At 2 P.M. anesthesia was induced with ether, and it was maintained with 50-percent ethylene and ether in oxygen. One hundred milliliters of 5-percent dextrose in water was administered during the operation. A simple mastoidectomy was performed, the operation lasting 60 minutes. His course in the operating room appeared uneventful, and he was returned to the recovery room in fair condition 90 minutes after anesthesia was started. At 4:30 P.M., 1 hour after his admission to the recovery room, his respiration became labored, his fingernails became cyanotic, and his rectal temperature was found to be 42.3°C. Cyanosis deepened; resuscitative measures were taken, but his condition worsened and he was pronounced dead at 5 P.M.

*Comment.* Dehydration and heavy surgical drapes may cause hyperthermia during warm weather, especially in children. Continuous observation of rectal temperature with a thermistor probe thermometer would almost certainly have forestalled this unnecessary fatality.

*Case 3.* A well-developed man, age 60 years, was admitted with the complaint of abdominal distension, and cramping abdominal pain of 2 months' duration. Findings on physical exami-

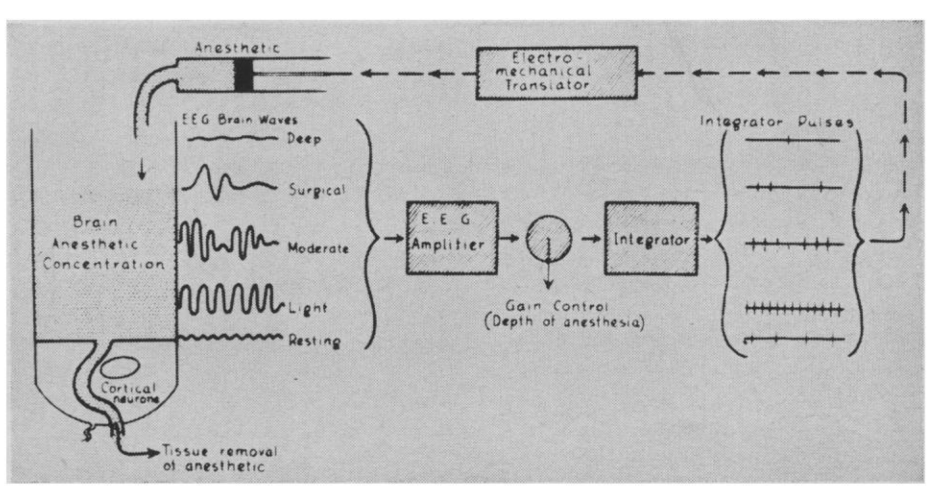


Fig. 2. Schematic diagram of a servo system for controlling depth of anesthesia. [Courtesy Bickford *et al.*]

nation were normal except for abdominal distension. In laboratory analyses of blood and urine constituents and serum electrolytes, the results were within normal limits. The electrocardiogram was normal except for tachycardia. An x-ray examination of the abdomen was compatible with a diagnosis of obstruction of the distal small bowel. A decompression tube was introduced, and the patient was prepared for exploratory laparotomy. Anesthesia was induced with 250 milligrams of thiopental and maintained with ethylene and ether in oxygen. An attempt to introduce an endotracheal catheter failed, but a satisfactory airway was produced with oropharyngeal and nasopharyngeal tubes. During exploration of the abdomen the patient's pulse remained steady, and except for a mild depression of his blood pressure and a moderate increase in respiratory rate, his course was considered to be satisfactory. The bowel was decompressed. Immediately afterward his blood pressure was unobtainable and cyanosis developed. Despite forced infusion of whole blood and artificial respiration with 100-percent oxygen after an emergency trachetomy, he died. A carcinoma of the cecum was found to be responsible for his preoperative symptoms.

*Comment.* The information available does not reveal the immediate cause of death. Rate of respiration is not an adequate measure of adequacy of pulmonary ventilation. The blood pressure and pulse rate may remain stable during wide variations of total-body blood flow. The origin of the heartbeat may become grossly abnormal without this being detectable by palpation of the pulse. It seems probable that in this case valuable time was lost in ascertaining that respiratory exchange was sufficient. It cannot be determined whether a cardiac arrhythmia, appearing in response to strong visceral stimulation, was responsible for failure of the circulation, or whether the failure was due to sudden pooling of blood in the splanchnic vascular system as a result of rapid reduction of intra-abdominal pressure. Answers to these questions might have been provided by a device that could be used to measure respiratory exchange, by an electrocardiograph, and by an instrument sensitive to the oxygen saturation of central venous blood.

This sort of thing happens only a few times each year in most clinics, but even once is too often if it can be prevented. Our ability to predict these occurrences is directly dependent on the extent of our knowledge of what is going on.

**Recent Developments**

The foregoing histories do not give an entirely fair picture of what we can do today. There has been considerable activity among clinical researchers and instrument manufacturers in the last decade to develop devices for regulating more accurately the administration of anesthetic drugs, for controlling respiration, and for providing more reliable information on depth of anesthesia and circulatory status. Described below are a few devices which either have found their way into clinical practice, have shown promise but have required additional engineering, or have served as a basis for clinical studies which have provided new insights into the nature of the state of anesthesia. I make no attempt to present an exhaustive list of the instruments that are available. The examples used for illustration were selected without regard to comparative quality or efficiency of operation.

1) Frumin and Lee (*1*) successfully designed a machine (Fig. 1) which automatically samples exhaled air at the end of expiration, measures its carbon-dioxide tension, and, by means of a servo system, adjusts the inflating pressure of a mechanical lung ventilator to maintain the carbon-dioxide tension at any desired level. The system incorporates a nitrous oxide–oxygen mixing system to provide anesthesia as well.

2) Servo systems have also been used by Bickford and his associates (*2*) and by Bellville and his associates (*3*) for automatically regulating the depth of anesthesia by feeding back information obtained from the electroencephalogram to control the administration of anesthetic drugs. Figure 2 illustrates one scheme for converting monitored information to regulate administration of an anesthetic agent.

3) An explosion-proof, thermostated *p*H probe (Fig. 3) was constructed in the anesthesiology laboratory at Columbia University (*4*), for making serial measurements of the arterial blood during surgical operations. Rendering monitoring equipment safe for

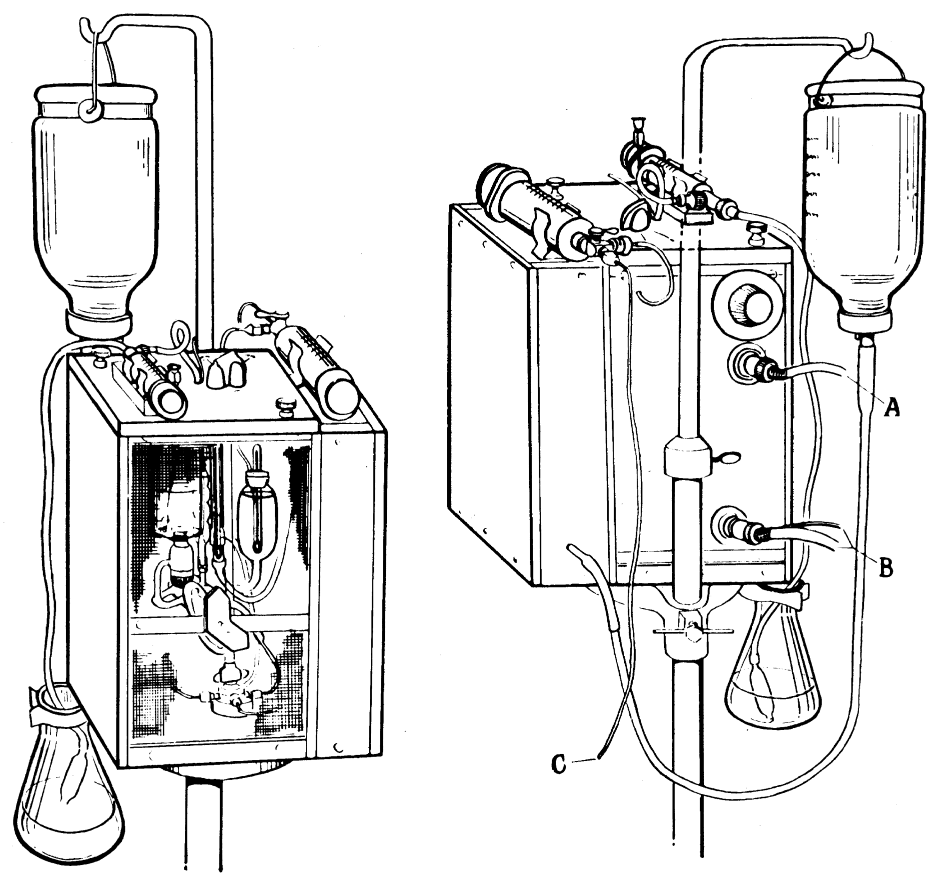


Fig. 3. A thermostated glass electrode probe for rapid, serial measurements of blood *p*H. (Left) Front view, showing position of glass electrode and external controls. (Right) Back view, showing connections: *A*, to power source for heater elements; *B*, to potentiometer; *C*, to arterial cannula.

use in the neighborhood of explosive gas mixtures is important in designing an electrical device for use by anesthetists. This *p*H monitor has been very useful for studying alterations in respiration and metabolic response during anesthesia.

4) Ten or more companies manufacture devices suitable for monitoring the electrocardiogram in the operating room. To my knowledge only two instruments have been approved by the Underwriters' Laboratory as explosion-proof, although several others have been designed to reduce the hazard in the event of an explosion. Figure 4 shows a device, based on the work of Zoll and his associates (*5*), which displays the electrocardiogram and sounds an alarm if the pulse interval falls below a predetermined level, simultaneously beginning to send electric stimuli to the heart to maintain cardiac action. Obviously, this device does not provide for support of the circulation, beyond displaying the abnormal rhythm if ventricular fibrillation is the cause of failure, but it will be helpful in the event of complete heart block or cardiac arrest (*6*).

5) A host of miniaturized pulse monitors, all very similar, have appeared on the market in recent years. These are small, highly portable instruments, usually battery-operated transistor circuits which detect the pulse by means of a microphone strapped or taped to the finger, or by sensing the QRS complex of the electrocardiogram through two needles or plate electrodes. The signal is either a flashing light, a flicking meter needle, or a deflection of the meter movement that indicates average pulse rate. A highly desirable feature of some instruments is the conversion of the pulse to an audible signal—a click, squeak, or chirp—which eliminates the need for looking constantly at the device. The pulse monitor illustrated (Fig. 5) allows for alternate inputs, either a microphone or electrocardiogram electrodes. It is based on a design by Severinghaus (*7*).

6) Automatic, indirect blood-pressure monitors are beginning to appear. These detect the peripheral pulse with a microphone or photoelectric device, automatically inflate a cuff on the finger or arm, and indicate the pressure at which the pulse just disappears (the systolic blood pressure). The monitor illustrated in Fig. 6 employs a variable capacitance microphone on the finger and an adjoining inflatable cuff. Each detected pulse operates a solenoid valve which

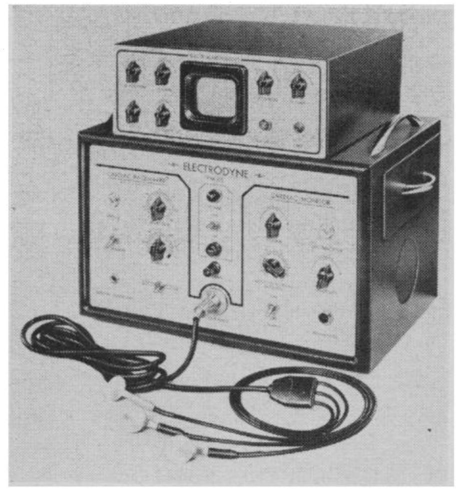


Fig. 4. The Electrodyne cardiac monitor and pacemaker with electrocardioscope.

admits a measured amount of air into the cuff. An adjustable leak in the cuff allows the cuff pressure to hover continuously around the systolic pressure. This pressure is displayed by means of an anaeroid manometer.

7) Oximeters, devices which indicate oxygen saturation of the blood by distinguishing between the color of oxygenated and reduced hemoglobin in the lobe of the ear, have been used in numerous clinics during the last decade to determine the adequacy of gas exchange in the lungs. More recently, polarized platinum or gold electrodes covered with thin plastic films, with current-carrying capacity directly dependent on the partial pressure of oxygen, have been used for the same purpose (*8*, *9*).

8) Infrared analyzers (*10*), specifically sensitized to carbon dioxide or to one of several gaseous or volatile polyatomic anesthetic agents, have been employed to measure exhaled carbon dioxide, as in the Frumin and Lee device (Fig. 1) described above, or to follow the uptake and excretion of anesthetic substances. Gas chromatography has made it possible to measure simultaneously a number of the constituents of a mixed-gas sample. These methods are too cumbersome for routine clinical use, and the cost of the equipment is very high, but much information of value has been obtained through using them in clinical research.

9) Devices for measuring respiration that are somewhat cruder but more practical from the standpoint of the clinician are a group of pneumatic and pneumatic-mechanical devices sensitive to flow of air. These include the Ohio minute volume meter (Fig. 7), which is a simple venturi tube with an associated pneumatic integrator, and which tends to indicate the average level of ventilation; the ventimeter (*11*), which is a rebreathing bellows in a calibrated plastic dome, and which indicates the volume of each respiration; the Wright anemometer, a British invention which is a pneumatic turbine operating a watch-type dial indicator; the Bennett respiration meter, which is a light, wooden cogwheel movement indicating gas flow on a dial.

During open heart operations, when a mechanical pump and oxygenator system is temporarily substituted to perform the functions of the heart and lungs, it is not unusual for eight or ten physiological parameters to be monitored. These might include blood pres-

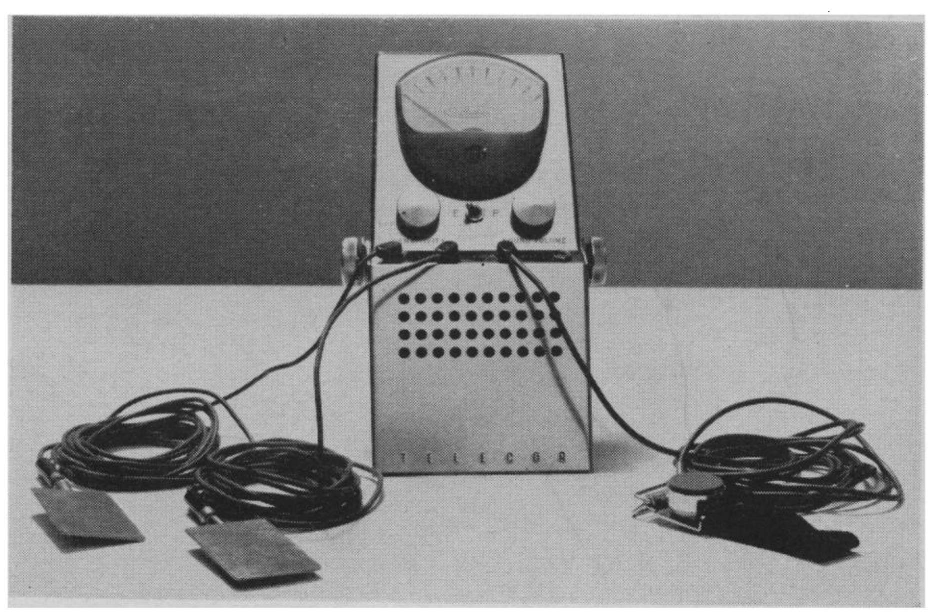


Fig. 5. The Burdick, Inc., Telecor.

sure at two or three sites, total blood flow, oxygen saturation, blood $p$H, carbon-dioxide concentration and hematocrit, blood coagulability, hemolysis, the electrocardiogram, and the electroencephalogram. However, such monitoring requires an electronic technician and at least one other person in the operating room and two or three chemical technicians outside in a laboratory. Obviously this is not practicable as routine procedure in the operating room.

## Shortcomings of Instruments

There appear to be several reasons why these recent developments have not been incorporated into routine practice.

1) All of these devices are portable; hence, setting them up adds to the time required to prepare the patient for anesthesia and surgery. Also, they are not always available; somebody else may be using the instruments, or a part may be missing.

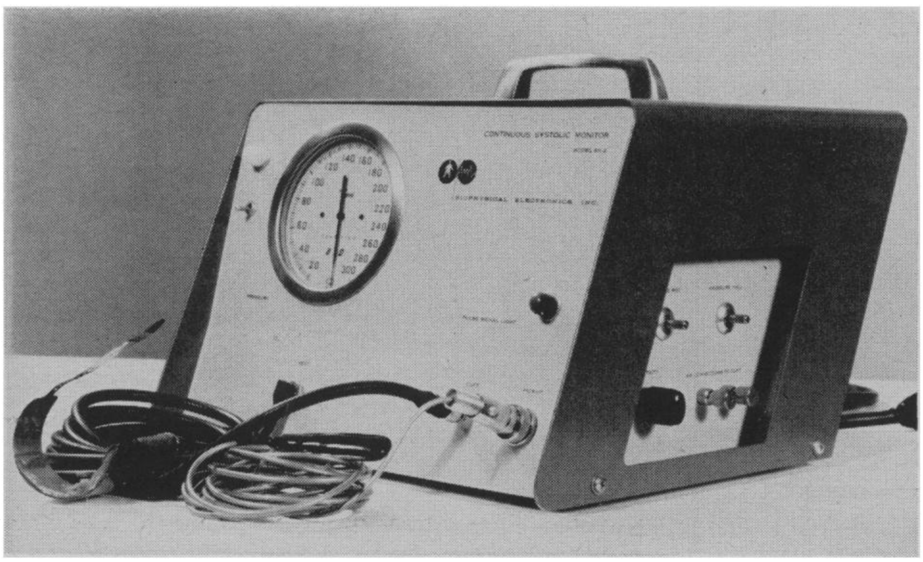

Fig. 6. The continuous systolic monitor.

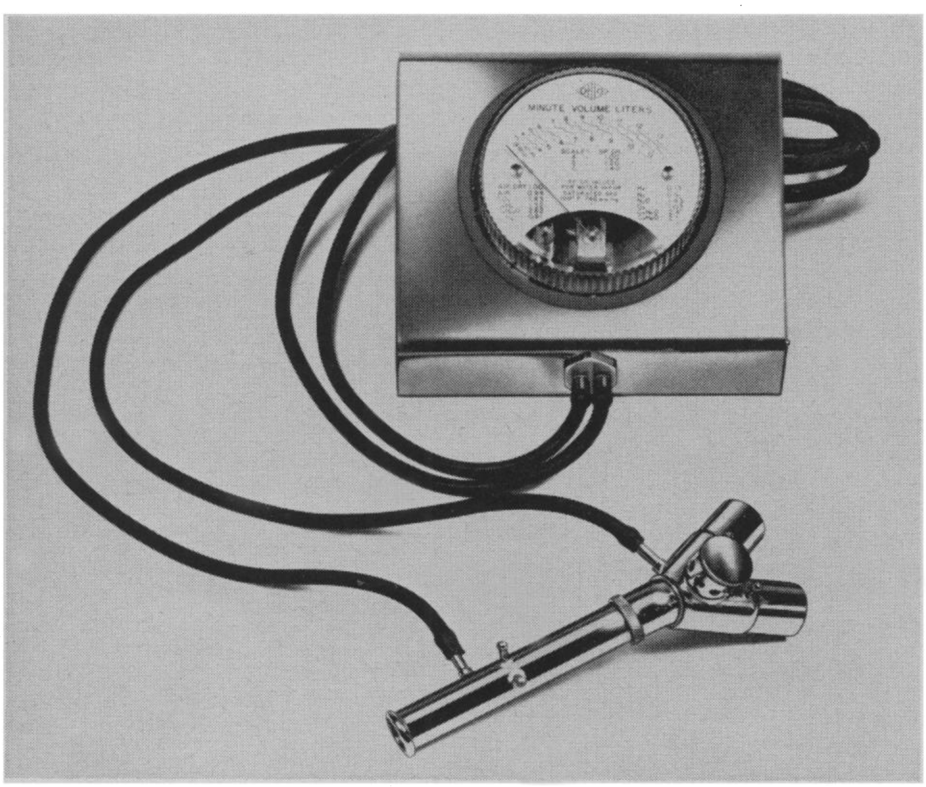


Fig. 7. The Ohio minute volume meter. [Courtesy Ohio Chemical and Surgical Equipment Co.]

2) Interpretation of the information presented by the instruments is sometimes difficult. This results from several factors. The clinician may be unfamiliar with the signals that are being presented. False signals may be generated due to artifacts resulting from movement or from signals generated by other equipment in the area. Equipment failure occurs too frequently, as a result of interference or dislodgment of leads and cables. And finally, the information presented by many of these instruments is not particularly useful or reliable. An example of this is the information given by instruments that monitor the pulse. These devices consist usually of some sort of transducer, attached to the finger tip, which is activated by a change in the volume of the finger tip. Occasionally these instruments fail to detect a pulse signal as a result of purposeful peripheral vasoconstriction when the more vital, central circulation is quite adequate. On the other hand, electrocardiograms have been obtained from patients whose hearts have ceased to have any effective pumping action.

3) Many of these instruments consist of bulky and multiple chassis accompanied by a bale of lines, lead cables, and so forth. Such machines contribute unduly to the general confusion of the operating room. This is disturbing to the anesthetist and is resented by other teams in the operating room.

4) The use and maintenance of this type of equipment is frequently beyond the competence of the anesthesiologist, and hence he views it with suspicion and is reluctant to accept it.

## Possible Solutions

All of these problems are soluble, but investment of time and money is required for further development. In seeking to improve this instrumentation, first, the acceptability of permanent installations in the operating room should be tested. If automatic control systems and monitoring devices were made more readily available, clinicians would use them more often and the development of improved devices would be accelerated. Second, transmission systems should be simplified, as through telemetering. Telemetry is a science that has been developed to a very high degree for the astronautical industry. Surely, only minor modifications should be required to produce a miniaturized transmitter and multiplexer with attached sensing elements which could be plastered unobtrusively to the patient before he is brought to the operating room. Upon his admission to the operating room the necessary intelligence could be picked up by a permanently installed wall receiving-and-display unit. William Thornton has devised a system of this sort, which is being used successfully by the anesthesiologists at the University of North Carolina (*12*). And finally, we should attempt to develop new sensing elements and data-processing systems to provide more positive information. Electrical impedance plethysmography, as conceived by Nyboer (*13*), may furnish evidence of alternations of regional blood flow during anesthesia about which we can do little more than guess at the present time.

Similar challenges exist in practically every phase of medical practice and biological research. Our methods of diagnosis can probably be speeded by application of modern computer techniques for correlating the information obtained from the medical history of the patient, the physical examination, and laboratory data. Zworykin is experimenting in this area in collaboration with physicians at New York Hospital and Mt. Sinai Hospital, New York (*14*). Methods of keeping medical records and recalling information can probably be made more efficient and certain by applying modern data-recording principles such as every other important industry relies upon today. Nursing techniques can be performed by mechano-electrical systems in many instances; for example, thermistor or thermocouple thermometers are wired from each patient's bed to a central display and recording unit in some Scandanavian hospitals. Pulse and respiratory rates could be similarly monitored and transmitted to the nursing station. This would enable us to make better use of our nurses, who are in very short supply today. Machines are being perfected which will scan blood slides and tissue slides for evidence of malignancy and other disorders. These can speed diagnosis and further reduce the number of personnel required to attend each patient (*15*). Routine clincal chemical analyses are now being performed in a number of hospitals more reliably and more rapidly by machines (*16*), designed on principles utilized by the chemical industries for several decades.

These are examples of ideas for improving medical practice through application of instrumentation and automation that have already occurred to workers in this field. A few of these ideas are already being proved practical, but most of our medical institutions continue to ignore them.

Why are we still so far behind? There are too few scientists of the caliber of Zworykin and his associates at the Medical Electronics Center of the Rockefeller Institute and the Radio Corporation of America Laboratories, and of Robert Bowman's group at the Laboratory of Technical Development of the National Heart Institute, who are willing to apply themselves to this work. And there are still too few companies willing to gamble on this undeveloped market. Also to blame are members of the medical profession and hospital administrators who have not learned to appreciate fully the advantages to be derived through abandoning traditional methods. And this brings us to another roadblock.

Physicians, by virtue of their specialized training in the medical sciences, are not equipped to undertake this type of development by themselves. And engineers are equally unable to produce satisfactory solutions because they lack understanding of the physician's problem. There, are two obvious solutions to this dilemma. One is to educate a number of physicians in the engineering sciences. This will undoubtedly become a more common procedure in future years, as instrumentation becomes a more commonplace part of medicine, but at best it will be a slow process. A more immediate solution is to bring engineers into our hospitals and medical research laboratories, where they can become acquainted at first hand with our problems and, even more important, can participate in the field trials which determine whether or not a given line of development is feasible. To meet the long-term need for more engineers interested in biomedical instrumentation, research institutes and training centers will have to be established. The Russians have shown the practicality of such units with their successful Institute of Experimental Surgical Apparatus.

Our scientific societies can play an important part in effecting these changes. The more these problems are talked about, the more urgent will be the demand for their solution. Among the several thousand scientific and technical organizations in the United States there is as yet not one national society devoted exclusively to advancing medical instrumentation. Only one organization has significant representation of regularly active local groups throughout the country—the Institute of Radio Engineers' Professional Group on Biomedical Electronics. Members of the Instrument Society of America have made a few valiant attempts to initiate a national program but have met with frustration as a result of having to compete with too many established interests. Other engineering societies have had similar experiences. The medical and biological societies have failed to advance even this far.

Lastly, advancement will depend also upon the accumulation of a substantial and authoritative literature devoted to medical instrumentation. The *IRE Transactions on Medical Electronics*, the bibliography on medical electronics which is prepared by the Medical Electronics Center of the Rockfeller Institute and published by the Professional Group on Medical Electronics, the proceedings of the new instrumentation division of the New York Academy of Sciences, the digest of technical papers based on the annual Conferences on Electrical Techniques in Medicine and Biology, the annual instrument issue of *Science*, and similar publications represent the sound beginning that has been made in establishing useful library and communications media in this young but promising field of science.


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