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Presidential Address

Computerized monitoring of seriously ill patients

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When Harvey Cushing introduced the anesthetist's chart to record the temperature, blood pressure, and pulse of patients during operation, he recognized the need for maintaining accurate records on patients during surgical procedures. He did not know that in time physiological changes would be measured accurately by a computer-based system. Our present computerized monitoring system has been developed with the IBM Corporation, which has worked side by side with us for the past 8 years. The direction and advances we have made are largely due to my associates, John J. Osborn, James Beaumont, Kay Martz, and many others in the Heart Research Institute. They represent the multidiscipline approach which is vital in this field.

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Tremendous advances of technology have been made in the past 15 to 20 years. Refinements in sensing devices and electronic gear have made available to the medical profession a large number of excellent products. Another basic change in the picture was brought about by the realization that biochemists, physicists, engineers, and others in basic sciences could be enlisted in a team approach to improve methods of treating seriously ill patients. Many of these applied scientists have found a rich source of new exploration for their abilities. Years ago, it was only a beginning notion to ask for financial support for scientists who had no medical training but who did have skills that might be applied to the sick. Among the very first to do this were the biochemists, who were an enormous help to the physicians in the interpretation of physiological changes occurring during illness. I believe our unit was the first to obtain an American Heart Association Fellowship for an engineer, Mr. M. L. Bramson, who has since made many worthy contributions to cardiovascular instrumentation.

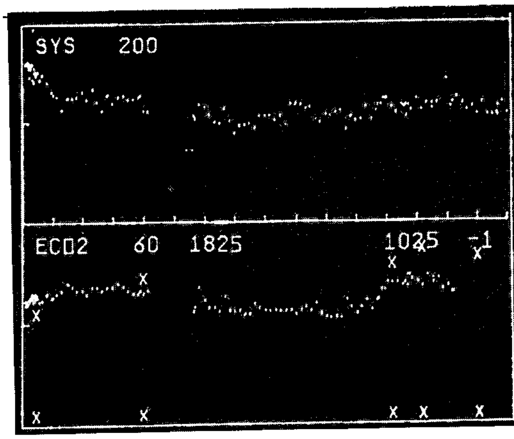

Fig. 1. Systolic pressure (*SYS*) and end-expiratory Pco_2 (*ECO2*) over the last 16 hours. *X's* show arterial Pco_2 plotted on same scale (lower row of *X's* are for location purposes only).

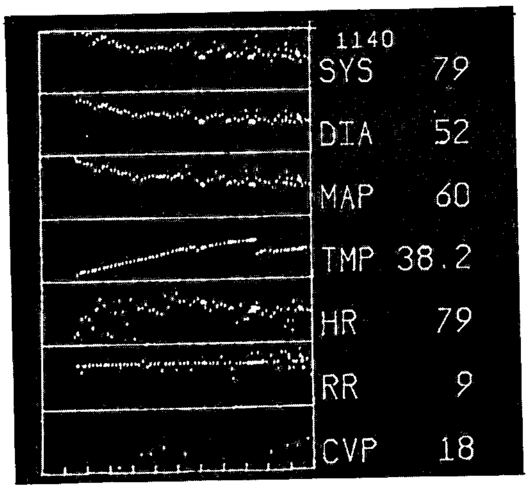

Fig. 2. A 12 hour trend display for the cardiovascular variables; systolic (*SYS*), diastolic (*DIA*), and mean arterial pressures (*MAP*); temperature (*TMP*); heart rate; respiratory rate (*RR*); and central venous pressure (*CVP*). Measurements are made every 10 minutes

Twenty years ago the surgeon had an assistant, one or two trainees, a nurse, an anesthesiologist, and not much else. Now, the skilled cardiovascular surgeon is additionally supported by many nonmedical experts. They come from schools of engineering or physics with advanced degrees and quickly understand the physiological problems involved with the management of seriously ill patients. It is refreshing and essen-

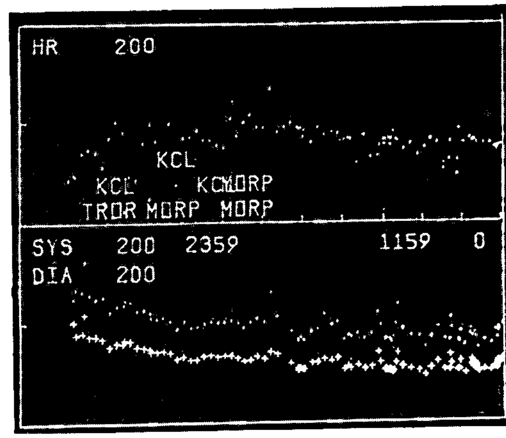

Fig. 3. A 12 hour display of heart rate, systolic and diastolic pressure. Drugs given are shown b abbreviation, with the first letter at the time o administration.

tial that they be there and that they be a the bedside. They are not there to dictat therapy, or even to make a diagnosis, bu to ensure that data are accurate and tha we are actually measuring what we thin we are measuring. It is amazing how quick ly they learn to interpret and to make diagnosis, even, embarrassingly enoug sometimes before the physician himself.

What is it that makes the use of th computer both demanding and attractiv In order for us to use its great capabilit the information given it must be accurat for it only gives back what it has been to to store. For this reason alone, those wh have begun to use computers have bee required to develop and use only the mo sophisticated techniques and instrument Actually, we are in a position at the mome of having our technology for quantitati measurement at a far more developed sta than our ability, at times, to interpret t information the system can give us.

Present capabilities include compute controlled actions, that is, the automa performance of a function to provide effic ency and to conserve money or skill labor. Included in this category are aut mated notes formerly provided by nurs vital sign recording, and control of fl balance. We have not, as yet, conclud that we should "close the loop" and rely computer measurements to regulate treatment in this way. Our approach has been to use accurate measurements of cardiac and respiratory performance to provide a more intelligent insight into the physiological changes occurring in seriously ill patients. The direct measurements upon which our calculations are based are often less valuable than the computerized calculations made from these values.

Our computer system collects and sorts a large number of measurements. Systolic, diastolic, and mean blood pressure are constantly recorded by strain gauge from an in-dwelling arterial catheter usually placed in the femoral artery. A catheter is also placed in the right atrium to measure central venous pressure via the external jugular vein. Pulmonary artery or pulmonary wedge pressures are usually established during the postoperative period, depending upon the necessity. Routinely, the pulse rate, central temperature by rectal thermistor probe, skin temperature by toe and/or thigh thermistor probes, respiratory flow, airway pressures, and inspired and expired oxygen and carbon dioxide concentrations are recorded automatically (Figs. 1 to 3). These airway measurements are quite accurate and follow those obtained by blood analysis. From these values it is possible to make a number of very useful and informative computations with the aid of an IBM computer. The sensing system for respiratory measurements is a pneumotachograph placed in the respiratory line near the patient's tracheal tube. All pressure tubes are connected to solenoid valves and to specialized plumbing under control of the computer. They are frequently flushed with warm air between measurements to prevent condensation.

Such variables as pulmonary compliance and resistance, arterial-alveolar differences for oxygen and carbon dioxide, and end-expiratory carbon dioxide concentration are measured. Oxygen uptake, carbon dioxide output, respiratory quotient, and a number of other pulmonary measurements are also available. In fact, it is entirely feasible to usc mathematical calculations and obtain many sophisticated values which heretofore have not been possible. These data are displayed on request on a screen at the patient's bedside. The measurements are routinely made every 10 minutes for all instrumental beds. It is possible to recall this information for any period of time during the previous 24 hours. Various other data, such as blood chemistries, are entered into the electronic record by the central laboratory. The data in Tables I to III are available routinely on any patient in our Cardiopulmonary Intensive Care Unit. These are the usual parameters observed during the course of observation on seriously ill patients, whether after operation or after trauma. This would seem to be a rather large mass of information to be accumulating mostly on a 10 minute schedule for an individual patient, but it is only the beginning of what is possible with the use of a computer and these other systems.

One point worthy of re-emphasis is that making simultaneous on-line measurements

Table I. *Direct measurements*

Arterial pressure
Central venous pressure
Pulmonary artery pressure
Electrocardiogram
Temperature
Airway pressure
Airway P_{CO_2}
Airway P_{O_2}
Airway flow

Table II. *Computations made by special call or requiring blood samples*

Time-course inspiratory compliance
Full lung mechanics
Ventilation-distribution index
Cardiac output by Fick principle
Cardiac output by dye-dilution curve
Thermodilution cardiac output
Correlations between variables
Lung pressure-volume plots
Acid-base balance
Physiological dead space (Vd/Vt)
Pulmonary shunt ($\dot{Q}s/\dot{Q}t$)
Alveolar-arterial carbon dioxide gradient

Table III. *Simple, automatically computed measurements*

Arterial dp/dt	
Mean arterial pressure	
Heart rate	
Pulse rate	
Per cent premature contractions	
Tidal volume	$\int_0^t$ flow
Minute volume	$2 \times \int_0^{30\ sec.}$ (expired flow)
End-expiratory Pco_2 (mean of highest Pco_2 of all breaths in 30 sec.)	
End-inspiratory Po_2 (highest end Po_2 during inspiration)	
End-expiratory Po_2 (lowest Po_2 during expiration)	
Lung compliance	mean least squares best fit to formula $P = \frac{V}{C} + FR$ over each inspiration in 30 sec.*
Lung nonelastic resistance	
Oxygen uptake	$\int_0^t \underset{\text{inspiration}}{(\text{flow})\ (Po_2)} - \int_0^t \underset{\text{expiration}}{(\text{flow})\ (Po_2)}$
Carbon dioxide output	$\int_0^t \underset{\text{inspiration}}{(\text{flow})\ (Pco_2)} - \int_0^t \underset{\text{expiration}}{(\text{flow})\ (Pco_2)}$
Work of inspiration	$\int_0^t F \times P$

*P, Airway pressure. V, Volume of inspiration. C, Compliance. F, Airway flow. R, Airway resistance.

of physiological events in separate organ systems brings into light relationships which were not recognized when isolated measurements were made. Again, accuracy must be emphasized, but another essential aspect is that the measurements be made regularly and automatically. The data displays of these measurements must be simple and easily understood by those in charge of taking care of the patient. This usually means a nurse initially, and, frequently thereafter, a Fellow or house officer.

To a new nurse a first look at these data is somewhat bewildering, but a good nurse can be taught to manage and interpret them in a week. However, full understanding, particularly of the measurements of respiratory function, requires a number of months. Does this add to or decrease the number of nursing hours? In our unit, it has been possible most often to utilize one nurse for two patients on this system, whereas previously we were obliged to have "one-to-one" nu ing. From the nurses point of view ma hours of tedious charting have been eli nated, for, when the standard observatio are being made automatically, the nurse free to perform more essential things t keeping notes. Intensive care nursing w this system becomes a much more intellig and interesting profession. She can regu therapy and know when a clinical cours normal or abnormal.

What can we follow with greatest be fit at the present time? Undoubtedly resp tory observations have been the most va able. We can diagnose hypo- or hyperve lation by respiratory measurements al even though we are also making frequ automatic Pco_2 determinations. We measure minute and tidal volume, l compliance and resistance, and some ments of the distribution of ventilat When the blood-gas determinations are u with a computer, they become much more useful because they can be combined with other information in calculations to follow parameters such as pulmonary shunting or changes in dead space. These determinations are displayed as dotted lines or graphs. They have become essential in following the trend of a seriously ill patient on a respirator.

Experience with the use of this information has shown us quite clearly that respirators sometimes do not live up to their expectations, failing in subtle ways which are not ordinarily discovered with standard observation. A frequent finding is arrhythmias caused by unrecognized respiratory difficulties which can be detected through the use of the computer. Deterioration of pulmonary and cardiac function is frequently made apparent by analyzing a number of physiological variables, long before clinical diagnoses can be made. This is important, because the decision for altering the treatment can be made earlier, before secondary organ deterioration takes place.

With continuous respiratory measurement, the trends of the patient become evident almost immediately. If he is too weak to ventilate himself properly, it will show up in a very few breaths. If his respiratory drive drops in response to overenthusiastic sedation, it will become apparent quite soon.

A recent example of the computer being right and the clinician wrong was illustrated by the following: Dr. Osborn was showing the unit to a director of an intensive care ward—a very good clinician. He had admired what we were doing and then made the usual comment: "This is really very nice, if you can afford it, but on our ward we don't really need it, because we are able to keep very close clinical watch on our patients, so we pick up any respiratory changes early anyway."

Just at that time, the nurse came up and asked, "Dr. Osborn, the computer says that the P_{CO_2} has been rising for the last hour, and it is now almost 60, but the patient looks all right. Do you think the computer is broken?" The visitor and he then looked over the patient and the respirator very carefully. Ventilation was adequate; tidal and minute volume were unchanged; there was no evidence of anything wrong. "You see," said the visitor. "This is just what I mean. Here the computer is misleading you. The patient is obviously doing fine."

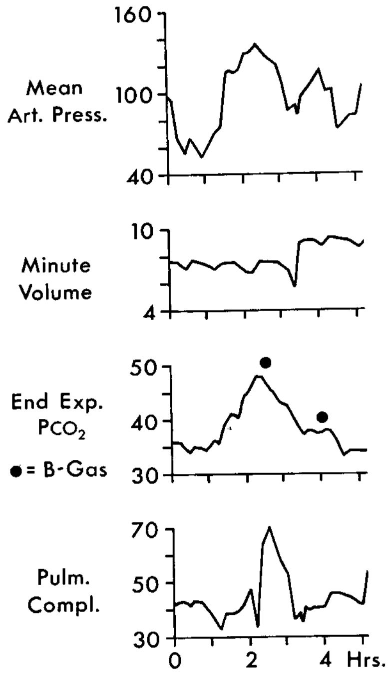

Fig. 4. Coordinated plots of four simultaneous measurements on a patient who was inadequately ventilated due to a defective humidifier in the respirator.

A blood-gas sample was drawn, to check the computer, and while waiting for it, the nurse changed the humidifier system. It was a new type, and she had wondered if it was giving trouble. Immediately the P_{CO_2} began to fall and soon was back to normal. On further checking, a defective system had been bypassing expiration and recirculating part of the expired gas. An interesting confirmation of the patient's problems was that, just about the time we found and began to fix the difficulty, the patient's wife, who had been visiting, said, "I just wanted to ask you, Doctor, if things are all right. When I first came in this afternoon my husband was fully alert, and in the last hour he has become less responsive."

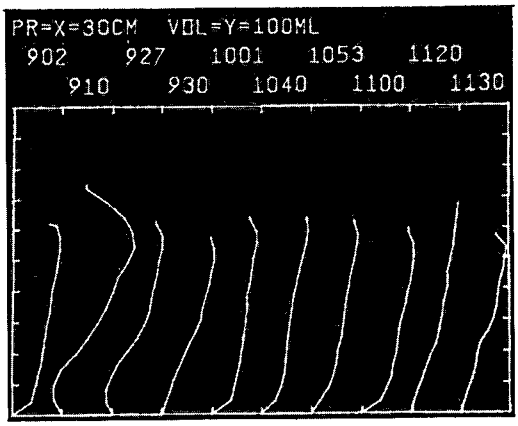

Fig. 5. Pressure-volume plots of inspiration. Time each measurement was made is shown at top. Volume on vertical scale. Note that the patient is "out of phase with respirator" at the time of the second breath. *PR,* Pressure. *VOL,* Volume.

These events are illustrated in Fig. 4. Note on the trace of mean blood pressure that the patient shows a strong "stress response" and a rise in blood pressure, presumably due to the respiratory acidosis, which the graph tracks directly. Notice also that the patient's lung compliance apparently rises. This is an artifact due to voluntary movement of respiratory muscles as he becomes acidotic. He is "sucking" somewhat on the respirator, but so slightly that we cannot see it clinically. It is apparent only as a lung which is easier for the respirator to inflate.

This is a good example of the value of quantitative measurements. They showed changes which were not apparent to a good clinician. The blood-gas analysis gave the diagnosis, just as did the computer, but the only reason the blood-gas sample was drawn was that the computer had alerted the staff that things were wrong. In the normal course of events, the blood gas was not due to be drawn again for another 3 hours, or unless the patient was in difficulty. The "difficulty" was not recognizable by clinical signs.

Measurements of lung compliance make it possible to follow lung mechanics accurately and even to prognosticate events as they are developing. Fig. 5 shows an example of loss of lung compliance caused by accumulation of secretions.

It has been apparent for some time that there is a strong relationship between respiratory inadequacy and cardiac arrest or fibrillation. The most useful guide in this respect is the end-expiratory P_{CO_2}.

Has computer based monitoring decreased morbidity and mortality rates in our unit? This is difficult to answer precisely. Certainly the patients are getting well faster and a greater percentage of the more seriously ill are surviving, but there are many factors involved with morbidity and death. It is certain that our intensive care staff rely on the data furnished by the system in their continuous care and find themselves to be unsure when they do not have these data.

The fact that we are monitoring a large number of measurements makes it easy to generate a display for following trends and to detect abnormalities before they become serious problems. There are some disadvantages in making 10 minute measurements; there are times when minute observation would be more desirable. As mentioned previously, monitoring of the expiratory carbon dioxide level is the most valuable observation in assessing the stability of a patient on a respirator. Pressure-volume curves also permit more intelligent management of patients on respirators. The use of positive end-expiratory pressure is valuable in managing severe respiratory problems, but it can also cause serious complications such as decreased cardiac output and pneumothorax. It is essential to select the proper positive end-expiratory pressure, besides monitoring pressure-volume curves, P_{CO_2}, blood pressure, and other parameters.

Our present alarm system tends to combine two functions which are logically quite distinct—catastrophic alarm and early warning indication. The catastrophic alarms are usually simple functions of a single signal, e.g., asystole or ventricular fibrillation from the electrocardiogram or respirator disconnect from airway pressure. These alarms require immediate attention and, consequently, must be in continuous operation. They are more apt to provide assistance to the nurse than to the doctor.

The warning indications are usually based on trends or combinations of variables or on derived parameters (such as compliance). These represent more slowly changing variables and call for action in the near future but not necessarily immediately. They are usually of more assitance to the doctor than the nurse and may be on an intermittent basis. For the future we see the alarm function being taken over by some combination of special purpose "black boxes" at the bedside.

The financial aspect of using the computer in this way is of primary consideration. An IBM 1800 computer is capable of servicing forty to fifty beds. This means that the central facility can service several hospitals; at present we are utilizing our systems in two satellite institutions in San Francisco. The patient interface equipment for these beds probably costs $1,000,000. However, if one evaluates the total cost, the computer contributes probably less than 10 per cent of the cost of computer-based monitoring. Furthermore, the price-to-performance ratio of computers is dropping so rapidly that the same capability will be available for $20,000 in ten years. This means that the financial determinants will probably be the "front line" or interface-sensing devices, plus the increasing labor costs for maintenance and operation, rather than the computer costs. Disregarding research costs, which have been substantial, we roughly estimate that our current monitoring system costs about $25.00 per patient day more than conventional monitoring.

Currently, our system processes data to give us derived parameters, such as work of respiration and compliance. In the future, it will use the information and trends to present logical physiological implications and predictions based upon these values. We are engaged in a joint project with Dr. John Siegel and the IBM-Watson Research Center to study the cluster analysis of multivariate measurements and trends in making predictions about the clinical course of patients and to use a large data base to anticipate the effect of various forms of therapeutic intervention. It may be possible in the future to observe the trajectory of a patient's status in time and to anticipate, for example, that he is heading toward sepsis or high-risk cardiac failure. To reach this position, we will have to evaluate a mass of physiological data in order to identify which specific measurements are most important. These studies may lead to a form of computerized diagnosis and prognosis based upon the potential effect of various types of therapy. Actually, what we are doing here with the computer is what we have been doing with our own memory bank and human logic. Only time will tell whether the computer will be more reliable than our own brain in this respect.

Conclusions

1. Cardiovascular surgery has been benefited substantially by our enlisting the aid of many nonmedical scientists.

2. Intensive cardiorespiratory care with this system becomes a much more intelligent and interesting profession for nurses and physicians.

3. On-line simultaneous physiological measurements have demonstrated relationships between organ dysfunction which were hitherto unrecognized with conventional observations.

4. Our present system processes data to give us derived parameters such as work of respiration and compliance. In the future it will use the information to provide logical physiological implications and predictions.

5. The research costs for developing this system of monitoring seriously ill patients have been substantial and could not have been borne without the generous scientific cooperation of the IBM Corporation and grants from the National Heart and Lung Institute.

6. The seriously ill patient has many labile physiological abnormalities which need to be monitored simultaneously and frequently in order to guide his treatment intelligently.

It is our belief that this is best supplied by an on-line computerized system. One has to have and use many instruments to fly a complicated airplane through a storm at night.

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