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Continuous blood gas and pH measurement by the Beckman Chemistry Monitor Model 400 (BCM-400)

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MAINTENANCE of adequate respiratory function is of great importance in the critically ill patient.[1, 2] The patient's respiratory state is determined best from the blood gas values, which also are the basis for definitive treatment and the assessment of the effects of that treatment. Clinical trials in regard to the continuous measurement of blood gas have been reported,[3-6] but from the viewpoint of the stability of the measured values, and of the long-term usage of the measuring device, the results are not entirely satisfactory.

Recently Beckman Instruments‡ developed a continuous blood-gas monitoring device which has been reported to have considerable reliability in the continuous measurement of blood gas.[7-9] We undertook a study of the Beckman Chemistry Monitor, and our report describes the device and presents the results of experiments with the monitor during the last 14 months, together with our conclusions in regard to its use.

Materials and methods

The Beckman Chemistry Monitor Model 400 (BCM-400) is a continuous measuring and recording device for pH, pCO_2 and pO_2 values in blood both in vitro and in vivo (*Fig. 1*). It consists of four meters that display pH, pCO_2, pO_2, and temperature continuously as measured at the sensor block (*Fig. 2*). The values of the parameters are printed every 12 sec by a point recorder installed in the main part of the machine.

When continuous blood gas monitoring is to be performed, an arteriovenous loop must be created in the subject. To do this for an emergency case, two indwelling intravenous catheters (such as the Rochester type Jelco or Abbocath I. V. catheters) are inserted into the artery and vein. A cutdown is not invariably required. The sensor block is then placed in the loop.

In the past, long-term monitoring has been inaccurate because the con-

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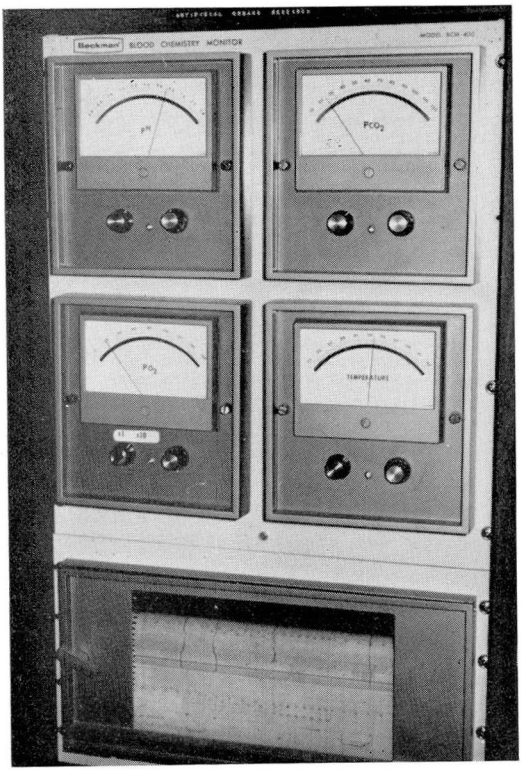


Fig. 1. Photograph of the Beckman Chemistry Monitor (BCM-400).

stant blood flow easily produced a protein buildup on the glass electrodes. In the BCM-400, such buildup cannot occur because each electrode is separated from the blood flow in the sensor block by membranes. All electrode sensors installed in the block have had an electrolyte gel applied to the tips. The tips are then pressed to the appropriate membranes to form a liquid interface between H^+ ions, CO_2 and O_2 molecules and their sensors.

The pH is measured by means of two electrodes, a reference electrode with a silver-silver chloride inner element and an outer plastic body filled with saturated potassium chloride solution, and a glass electrode that measures the changes in H^+ ion concentration in the liquid bridge made through the dialysis cellophane membrane and the electrolyte gel.

The pCO_2 is measured in a similar manner by one electrode that has a pH-sensitive glass electrode surrounded by a silver-silver chloride rim. The reaction in the electrode gel caused by diffusion of CO_2 through the Silastic membrane is as follows:

$$H_2O + CO_2 \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-.$$

pO_2 is measured by oxygen molecules diffusing from the flowing blood

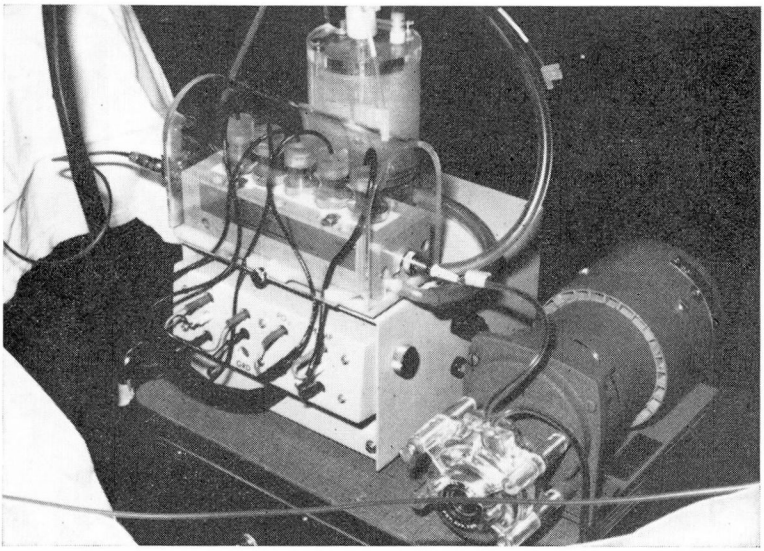


Fig. 2. Photograph of the sensor block of the BCM-400.

through a Teflon membrane and being reduced by the cathode of the sensor which is in the center. The anode is a silver ring around the edge of the sensor. The reactions that occur in the electrode gel are: at the cathode

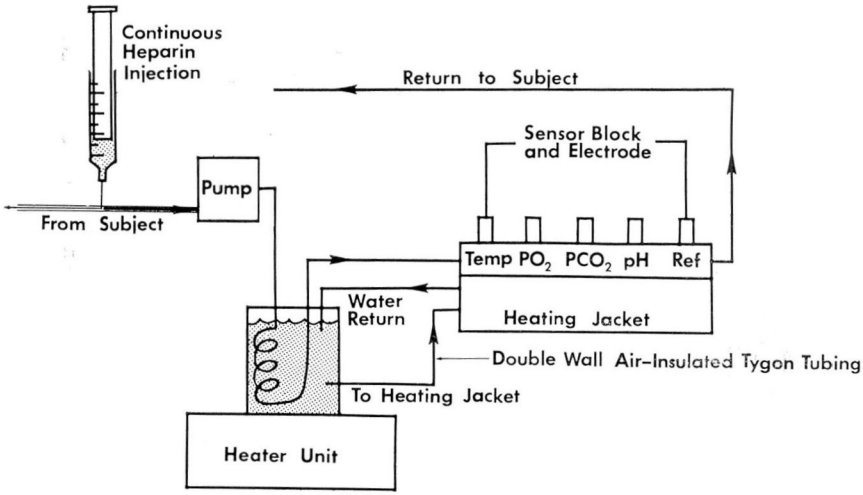
$$O_2 + 2H_2O + 4e \rightarrow 4OH,$$

and at the silver anode

$$4Ag + 4Cl \rightarrow 4AgCl + 4e.$$

The temperature electrode has a pair of thermistors at the tip of the sensor, and they are pressed against a Silastic membrane in the sensor block. From the thermistors a signal is sent to each of the other three meters and compensates each for the temperature coefficient of its sensor. The temperature-maintenance mechanism is related solely to the temperature of the sensor block and not to the temperature of the subject. At any specific temperature the sensor block accurately records the actual reading on the main part of the machine. To avoid direct contact with the electrode, the blood flowing through the sensor block has contact only with Teflon, silicone rubber, and cellophane membrane.

Figure 3 is a schematic diagram of the course of blood flow through the device. The continuous blood flow from the subject is pumped through the sensor block and back into the subject. Constant blood flow through the sensor block is quite important to obtain accurate pH and blood gas measurements. A small blood pump to regulate the blood flow is placed in the loop. In our study we used a flow rate in the range of 10 to 12 ml per minute through the sensor block, the range in which the rate of hemolysis is negli-



HEPARIN INJECTION SYSTEM, FLOW DIAGRAM OF PREHEATER UNIT AND EXTRACORPOREAL LOOP

Fig. 3. Schematic diagram of the blood circulation in the BCM-400.

gible. The blood gas values are displayed on large dials on the monitoring device and are directly recorded on the chart.

To avoid clot formation in the line, heparinization, particularly regional heparinization, is essential. Since the sensor block is directly attached to the monitoring unit by a long connecting cable and is not large, there is no obstruction of the operative field. One of the main points in the handling procedure is assembly of the sensor block. When required, the main body of the monitoring device can be placed in another room and the monitoring can be remote from the subject. The lower half of the main body is a storage cabinet on casters, which may be used for storing spare parts and equipment, or to save space, it may be removed if necessary.

We used the Beckman Chemistry Monitor in 43 experiments with calves, 18 of which involved implanting artificial hearts; 13 in evaluation of new types of oxygenators such as the Landé-Edwards, the G. E.-Peirce membrane oxygenator, and a fluorocarbon liquid-liquid oxygenator; six concerned pulmonary experimentation; four concerned standard extracorporeal circulation; and two involved implantation of the left heart bypass pump.

Results

The problems that we encountered in the practical use of the equipment are summarized in *Table 1*. Of a total of 43 experiments, problems arose in nine. Among 35 cases monitored up to 10 hours, clotting in the line occurred

Table 1.—Problems encountered during continuous blood chemistry monitoring

Hours of monitoring	Problem	Cases	
		Number	Total
0–10	Clotting	6 (17.1%)	35
11–20	Leaking	1 (20.0%)	5
> 20	Clotting	2 (66.6%)	3
Total		9 (20.9%)	43

in six. Among five cases monitored for 11 to 20 hours, leaking interfered with continuous monitoring in one case. Three cases were monitored for more than 20 hours; in two instances clotting in the lines occurred which required flushing.

Clotting seemed to be one of the most serious problems in the continuous monitoring. In our earlier experiments, most of the clotting was caused by the size and design of the catheter that was used for the arteriovenous loop. Several kinds of catheters were tried to maintain continuous slow infusion of heparin and also for collecting blood. A number 10-12 French, approximately 20-inch, plastic catheter was inserted into the femoral artery of each animal in the initial experiments. Subsequently a commercially available double-lumen catheter* was used for sustaining the uninterrupted blood flow and continuous injection of heparin. We found, however, that type of catheter was not large enough and we are now using a much larger, shorter catheter with a simple Y-connector.

Figure 4 shows a representative recording of the Beckman Chemistry Monitor during and after a total heart implantation in a calf. Anesthesia was maintained with nitrous oxide, oxygen, and halothane by means of a semiclosed technic. The animal was ventilated at a rate of 15 breaths per minute. A Bennett respirator Model BA-4 produced a tidal volume of 1,000 ml; the inspiratory-expiratory ratio was 1:1, while the natural-rubber wave-pulsating total heart was implanted. Before the start of extracorporeal circulation, a remarkably low pO_2, which probably was caused by operative manipulation, was observed; the pCO_2 was within normal range. After the commencement of total bypass circulation, the pO_2 level increased significantly, as would be expected. After the start of artificial heart pumping an unstable fluctuation occurred in the levels of pO_2, pCO_2, and pH. Corrections of the blood gas values were made once, 10 hours after the start of recording. After that the blood gas levels appeared to be quite well stabilized.

Figure 5 shows another recording of the Beckman blood gas monitor from an experiment of total heart implantation in a calf. Postoperatively, con-

* *U.S. Catheters and Instrument Co., Glens Falls, New York 12801.*

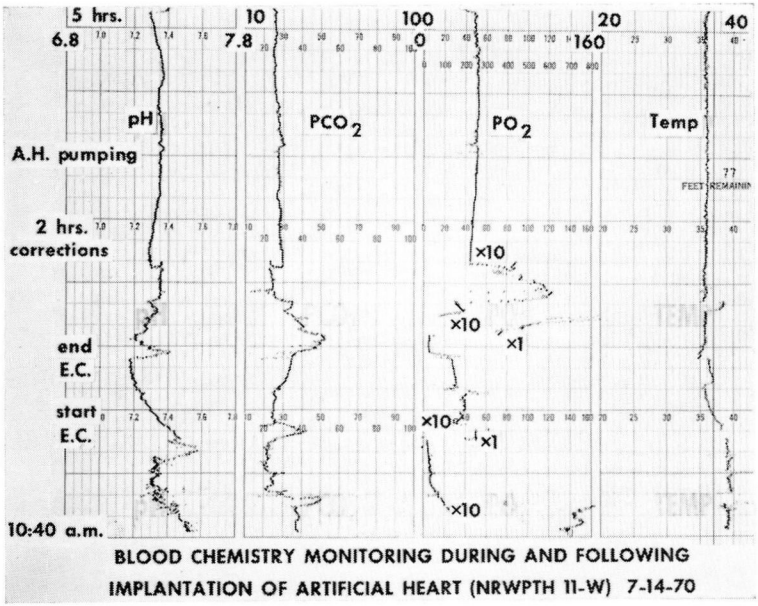


Fig. 4. Representative recording of continuous blood gas measurement in a calf during and after total heart implantation.

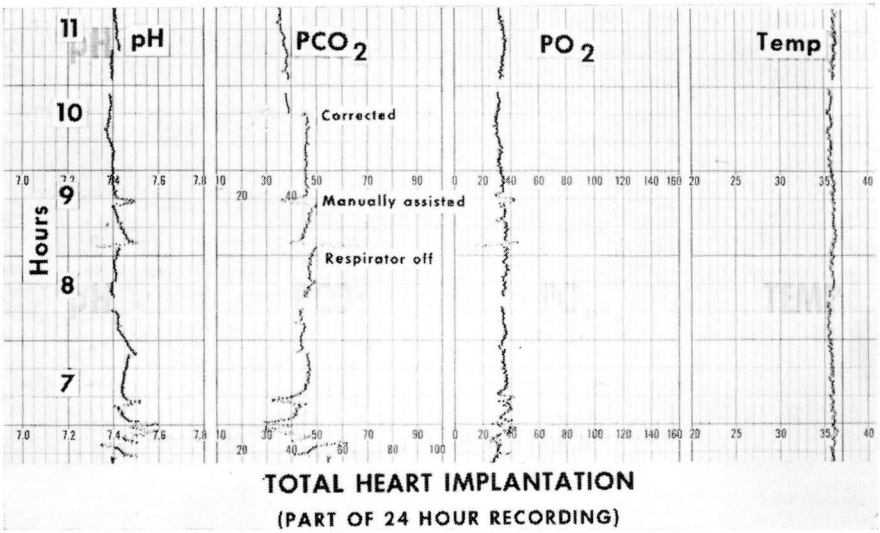


Fig. 5. Another representative recording of continuous blood gas measurement in a calf during and after total heart implantation.

trolled ventilation was maintained with a mechanical ventilator. Seven hours after the start of recording, stable levels were observed in every electrode until we interrupted mechanical ventilation temporarily at 8-½ hr, at which time an increase in pCO_2 was observed along with a decrease in pH and pO_2 levels. One-half hour later, the animal was ventilated manually. At that time, a temporary increase in pO_2 and pH with a decrease in pCO_2 was observed, as was expected. After this manipulation, mechanically controlled ventilation was continued as previously described, and stable values in blood constituents were maintained. Correction of the blood gas value was made once, only in pCO_2, during this 11-hour monitoring. In these two cases, we found that the BCM-400 responded instantly to the changes in pH and blood gas values. Measurement by the conventional methods would have taken at least 5 minutes to determine what had already occurred in the body. The clinical implication is clear: such prompt reaction to the changes in blood gas values would be extremely useful in the management of a patient in a critical condition.

Comments

Based upon our experience with the BCM-400, there are four points to be specially noted when it is used.

(1) *Careful assembly and preparation for use of the device.* The Beckman Chemistry Monitor must be meticulously assembled. At this time the mode of placing the membranes into the five sensor wells of the sensor block is important. Each membrane is color coded to insure use of the correct membrane. The thin membranes or spacers are picked up in turn with tweezers tipped with Teflon and are inserted into the appropriate well. Care must be taken that the inserted membranes are centered at the bottom of the well and are not punctured. If incomplete sealing or the puncture of a membrane occurs, blood will leak into the sensor well. An O-ring supports the seal, so that after the retainer is inserted it is not necessary to turn the retainer nut too tightly or mechanical damage by excessive tightening might occur in the Teflon block. Despite the precaution we used in inserting the membranes, in one case we experienced blood leaking into the sensor block, as described above.

(2) *Sterilization of the sensor block.* It is reported that the sensor block assembly can be sterilized with ethylene oxide. In our experiments, however, all areas of the sensor block where the blood passes were filled with benzalkonium chloride (1:750) solution and left overnight. Before usage a thorough flushing with sterilized heparinized saline solution was performed. This caused no interference with the operation.

(3) *Calibration of blood gas values.* Before the sensor block is connected with the arteriovenous loop, a pump is used and the sensor block is sufficiently flushed out with a sterilized normal saline solution, and sodium bicarbonate is added to a concentration of 24 mEq per liter equilibrated with

a known gas mixture of oxygen and carbon dioxide. This establishes the initial calibration. Next, the sensor is connected with the arteriovenous loop and the blood is allowed to flow and actual recordings commence.

After the blood gas readings become stabilized, blood samples are taken from the outflow of the sensor block (the reading of the BCM-400 at the time of sampling is written down), and the blood gas of the sample is measured using a bench type pH blood gas analyzer (Instrumentation Laboratory Inc.* Blood Gas Analyzer Model 313 was used in our study). If there is a difference between the two values, and the difference is such that an adjustment should be made, the BCM-400 must be reset. It is said that this process should be repeated sometime during the experiment to make the necessary adjustments when required. In our experience in both in vivo and in vitro experiments at a maximal 27-hr continuous blood gas measurement, blood samples were taken at one and one-half to two hour intervals. The differences were noted in short-term monitoring up to three hours. Practically no discrepancy was seen, indicating the reliability of the values recorded by the BCM-400. However, in 17 of 43 cases in which continuous blood gas measurements were made, adjustments against actual measurements with the I. L. pH blood gas analyzer were required. Among the 17 cases in which adjustment was required during operation, eight cases were caused by clotting in the line, and in one case a small leak into the sensor block was due to inadequate preparation. Provided that due care is exercised in the assembly, and technical errors are kept to a minimum, it is not necessary to conduct frequent calibrations with a bench type pH blood gas analyzer. In some of our experiments, accuracy in pH, pCO_2, and pO_2 values was obtained during 10 hours of recording. Thus it may be possible to obtain reliable recording for 10 hours or longer without any recalibration, when the equipment has been properly assembled, calibrated, and maintained by a skilled operator.

(4) *Regional heparinization.* From our experience, we conclude that the clotting problems that occurred in the BCM-400 system can be avoided by systemic heparinization. However, in order to minimize blood loss during and after operation, and in experiments where blood gas measurement is of prime importance, it is necessary to avoid unwarranted administration of heparin. Thus, regional heparinization was considered necessary. As indicated in *Figure 3,* a continuous injection apparatus was attached into the arterial catheter through which normal saline solution containing heparin was administered. The apparatus we used was a Sage† continuous infusion pump Model 240. The problem of clotting in the sensor block, though, has not completely disappeared. Until now we have been giving heparin at a dosage of 4 mg per hour, but we plan to increase this significantly to avoid the clotting problems.

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Summary and conclusion

The Beckman Chemistry Monitor Model 400, developed in order to meet the various clinical requirements for continuous monitoring of blood gas values, showed almost entirely satisfactory performance up to 27 hours of continuous blood gas measurement. Despite several problems encountered in 43 experiments, the device is unquestionably useful for continuous blood gas measurement, and we believe that it may have clinical application.

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