Controlling Perfusion Adequacy:

Continuous pH and Blood Gas Monitoring

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On July 6, 1956, we closed an intra-atrial septal defect using cardio-pulmonary bypass, the DeWall bubble oxygenator system, and finger pumps. We calculated required flow from patient weight. In 1957, we began to utilize a Pemco Disc oxygenator with roller pumps and calculated our flow rates from surface area using DuBois tables for determining surface in M^2, and from height and weight. Our pumps were adjusted to deliver 2.2 liters per square meter body area.

BLOOD GASES

In June, 1960, we began a study of blood gases, both arterial (after oxygenation) and venous return, utilizing Instrumentation Laboratory Equipment then available. We learned that our arterial oxygen tension usually ranged above 300 mmHg while CO^2 would be in the low 20 mmHg range with pH shifted strongly alkaline utilizing flows of 2.2 liters/min. per M^2. These allayed our fears of under-oxygenation and CO^2 retention which were the then "current concerns" of extracorporeal support.

At this time, control of pump flow by blood gas determination was inviting but instability of equipment and the delay time of determinations made this approach too unreliable for routine clinical application. We, however, took this opportunity to investigate the effects of O^2 flow rates through the disc oxygenator, various flow rates of pump output and hypo-thermia from profound 15° C to mild 30-35° C on O^2-CO^2 tension and pH. From these studies we learned to adjust our pump flow, disc rotation, and oxygen flow through the oxygenator with hypothermia. We compared our findings with the flow-rate schedules then recommended by other investigators and found excellent confirmation.

THE 1960's

In the 1960's we, as most others, took extra care, however, to keep our flow rates "safely" high at any temperature believing we could do little injury with excessive oxygenation and low CO^2. A pH of 7.6 was reassuring as were O^2 tensions of 300 mmHg or higher with CO^2 tensions of 10 to 15 mmHg.

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The sixties might be called the period of "compensation" for the bad early times of minimal flow when extracorporeal circulation was beginning. Initially (early fifties), the cumbersome, high prime volume, inefficient oxygenators and traumatic pumps produced such serious damage to the blood with physiological flows that the work of Anthony Andreason and Frank Watson between 1949 and 1953 in England showing that a dog could survive an azygos vein return (10% resting cardiac output) led to extracorporeal perfusion at these volumes with attendant hypoxic, hypercarbic difficulties. With the development of the DeWall bubble oxygenator in 1955, larger pump outputs were possible and by 1960 high flows usually above physiological needs were generally used and extolled.

However, increasing evidence that the cellular elements of the blood area adversely affected by unphysiological concentrations of O^2 and CO^2 in both disc and bubble oxygenators and similar findings reported from the early studies with membrane oxygenators reawakened our interest in continuously monitoring blood gases during extracorporeal circulation. We had also become acquainted with the cerebral effects of hyperventilation in patients suffering chest injuries that resulted in flail chest which required respiratory stabilization by respirator. These patients often develop sufficient traumatic wet lung to interfere with transport of O^2 through the edematous alveolar wall to the capillary.

The resulting arterial hypoxia then becomes the respiratory center stimulant to increase both depth and rate of respiration. If this increased respiratory rate triggers a demand respirator, gross overventilation frequently occurs with CO^2 blow off and pH shift to 7.6-7.8 ranges. Confusion, then loss of consciousness, then loss of muscle tone with flaccid syncope occurs due to constriction of cerebral vessels secondary to severe alkalosis.

This degree of hypocapnia occuring in hyperventilation syndrome is known to produce confusion, loss of consciousness and flaccidity accompanied by high voltage, slow wave electroencephalographic tracings in children, and these same changes were frequently seen in the electroencephalographic tracings of adults while on cardiopulmonary bypass, although adequately perfused with highly oxygenated blood but with low CO^2 tension and marked "respiratory" alkalosis.

MONITORING BLOOD GASES

In an effort to further evaluate these considerations, we began to routinely monitor our pump runs using a Radiometer Flowthrough Cuvette equipped with digital readout.

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We have not felt it wise to return blood from the Cuvette to the perfusion circuit, although we have demonstrated that gas (ethylene oxide) sterlization of the Flowthrough Cuvette is safe bacteriologically and harmless to the Cuvette. However, chemical contamination of the blood can occur in event of electrode membrane rupture. Since the amount of blood loss with this equipment is minimal with virtually continuous monitoring, discard of the sample seems at present the prudent course.

The Radiometer Flowthrough Cuvette and the digital readout is mounted with the cardiopulmonary bypass equipment, and the extracorporeal pump technicians after special training* make the determinations. Check determinations are run about every 30 minutes by the hospital laboratory often on two separate machines and we expect these values to match the pump team's determinations. Fortunately, in skilled hands modern polarographic equipment is stable and reliable and close correlation between the three machines is the rule.

Blood gases and pH, both arterial and central venous (right atrial), are determined after stable anesthesia is established and the central arterial and venous sampling and pressure recording catheters have been placed.

RESULTS

Our studies have shown that if the flow rate of O^2 through the bubble oxygenator is adjusted to give an arterial tension of 100-200 mmHg in the oxygenated blood, and CO^2 is mixed in with the oxygen to give 30-35 mmHg. CO^2T with arterial pH of 7.35-7.45, we can reduce the perfusion flow rate by 25-33% from that calculated by the formula 2.2 L/M^2 body surface and deliver venous blood to the right atrium with PO^2 tensions in the 30 mmHg. range (well above the 25 mmHg tension shown by the studies of Mort et al as representing excellent tissue perfusion), with body temperature 35° C.

We do not attempt to elevate arterial mean pressure by increasing perfusion minute volume if our blood gases and pH values are in normal range. We use Neosynepherine added by slow drip to maintain arterial mean pressure of 100 mgHg., and maintain central mean venous pressure in 8-10 mmHg. range by volume adjustment.

At termination of bypass, blood gases and pH are determined every 15 minutes using the Flowthrough Cuvette equipment for the first hour or until stable in normal range, then every 30 minutes the second hour or until out of the postoperative recovery ward and stabilized in the intensive care unit. Decisions affecting respirator need, continued intratracheal intubation and oxygen breathing mixtures are based on these determinations.

CASE HISTORIES

Data from 14 selected cases is presented below illustrating the reduction in perfusion flow commonly attained by continuous O^2-CO^2 and pH monitoring of both arterial and central venous blood during normothermic bypass with Neosynepherine vasomotor support. (Bubble oxygenator and roller pump):

Aortic to Coronary Bypass

Case #1:
Weight 75 kg.
Height 179 cm.
S.A. 1.95 M^2, length of pump run 3 hours.
Calculated flow (1.95 x 22)—4290/CC/min.
Average flow during run—3700/CC/min.
Difference—590/CC/Min.
Our first VpH was 7.52 with a pCO^2 of 33.
Our last VpH was 7.548 with a pCO^2 of 26.
Mean right atrial O^2 was 43.5 mmHg.
No sodium bicarbonate or tham given.

Aortic to Coronary Bypass

Case #7:
Length of pump run: 1 hour, 40 minutes.
Calculated flow 3800/CC/min.
Average flow during run 3146/CC/min.
Difference 654/CC/min.
Average VpO^2 was 34 mmHg. (right atrial)
First VpH on pump was 7.42 with a pCO^2 of 32.
Last VpH on pump was 7.46 with a pCO^2 of 35.
No sodium bicarbonate or tham given.

Aortic to Coronary Bypass

Case #15:
Pump run: 1 hour, 30 minutes.
Calculated flow 4400/CC/min.
Actual average flow 3612/CC/min.
Difference 778/CC/min.
Average VpO^2 during run 31.8 mmHg.
First VpH on pump was 7.35 with pCO^2 of 49.
Last VpH on pump was 7.45 with pCO^2 of 36.
No sodium bicarbonate or tham given.

Aortic to Coronary Bypass

Case: #23:
Pump run 3 hours.
Calculated flow 4488/CC/min.
Actual average flow 3718/CC/min.
Difference 770/CC/min.
Average VpO^2 during run 36 mmHg.
First VpH was 7.42 with a pCO^2 of 32.
Last VpH was 7.46 with a pCO^2 of 35.
No sodium bicarbonate or tham given.

Aortic to Coronary Bypass

Case #48:
Duration of pump run—3 hours.
Calculated flow 3850/CC/min.
Actual average flow 3500/CC/min.
Difference 350/CC/min.
Average VpO^2 was 31 mmHg.
First pH in pump was 7.53 with pCO^2 of 27.
Last pH in pump was 7.45 with pCO^2 of 33.
No sodium bicarbonate or tham given.

Aortic to Coronary Bypass

Case #54:
Length of pump run, 2 hours, 20 minutes.
Calculated flow 4788/CC/min.
Actual average flow 3520/CC/min.
Difference 1168/CC/min.
Average VpO^2 during run 36.2 mmHg.
First VpH on pump was 7.44 with pCO^2 of 26.
Last VpH on pump was 7.38 with a pCO^2 of 33.
No sodium bicarbonate or tham given.

*Training Seminars of Londen Company, Cleveland, Ohio, U.S. Agents of Radiometer.

Aortic to Coronary Bypass

Case #68:
Duration of pump run—2 hours, 43 minutes.
Calculated flow 4092/CC/min.
Actual average flow 3600/CC/min.
Difference 492/CC/min.
Average pO^2 during run was 39 mmHg.
First VpH was 7.36 with a pCO^2 of 38.
Last VpH was 7.36 with a pCO^2 of 41.

Aortic to Coronary Bypass

Case #69:
Duration of Bypass 1 hour, 40 minutes.
Calculated flow 3806/CC/min.
Average actual flow 3145/CC/min.
Difference 661/CC/min.
Average VpO^2 was 34.
First VpH was 7.42 with a pCO^2 of 32.
Last VpH was 7.46 with a pCO^2 of 35.

Aortic to Coronary Bypass

Case #70:
Duration of bypass, 2 hours, 4 minutes.
Calculated flow 4200/CC/min.
Average actual flow 3600/CC/min.
Difference 600/CC/Min.
Average VpO^2 was 35 mmHg.
First VpH on pump was 7.39 with pCO^2 of 32.
Last VpH on pump was 7.43 with pCO^2 of 31.
No sodium bicarbonate or tham given.

Aortic Valve Replacement

Case #71:
Duration of bypass, 2 hours.
Calculated Flow 3522/CC/min.
Average actual flow 3208/CC/min.
Difference 316/CC/min.
Average pCO^2 was 38.8 mmHg.
First VpH on pump was 7.31 with pCO^2 of 42.
Last VpH on pump was 7.38 with a pCO^2 of 35.
No sodium bicarbonate or tham given.

Aortic to Coronary Bypass

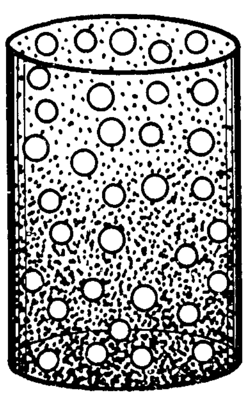
Case #73:
Duration of bypass, 2 hours, 2 minutes
Calculated flow 4300/CC/min.
Average actual flow 3385/CC/min.
Difference 915/CC/min.
Average VpO^2 during pump run 41 mmHg.
First VpH was 7.23 with a pCO^2 of 36.
Last VpH was 7.36 with a pCO^2 of 37.
No sodium bicarbonate or tham given.

Aortic to Coronary Bypass

Case #74:
Duration of bypass, 2 hours and 4 minutes.
Calculated flow 4092/CC/min.
Average actual flow 3390/CC/min.
Difference 702/CC/min.
Average VpO^2 was 34 mmHg.
First VpH was 7.40 with a pCO^2 of 36.
Last VpH was 7.43 with a pCO^2 of 34.
No sodium bicarbonate or tham given.

Case #75:
Duration of bypass, 2 hours and 41 minutes.
Calculated flow 3916/CC/min.
Actual flow 2920/CC/min.
Difference 996/CC/min.
Average $VpCO^2$ was 32 mmHg.
First VpH on pump was 7.36 with a pCO^2 of 30.
Last VpH on pump was 7.25 with a pCO^2 of 41.
One amp of sodium bicarbonate given after pump run adjustment of pH. But patient did very well.

Case #76:
Duration of bypass, 2 hours, 37 minutes.
Calculated flow 4488/CC/min.
Average pump flow 3333/CC/min.
Difference 1155/CC/min.
Average pCO^2 during run was 31.6 mmHg.
First VpH on pump was 7.38 with a pCO^2 of 41.
Last VpH on pump was 7.49 with a pCO^2 of 32.
No sodium bicarbonate or tham given.



COMMENTS

It will be observed from the numbering of the presented cases that only an occasional case is presented from early in the series. This reflects our early hesitation to take full advantage of the potential flow reduction indicated by the blood gas and pH determinations. As we gained confidence in determinations, learned better how to use central venous O^2 and CO^2 and pH as indications of adequate body perfusion, and as we gained surety in blood pressure management with peripheral vasoconstrictors, we began to take full and routine advantage of the method as illustrated in Cases 68-76.

The remaining 62 cases in this series show pump run reduction of 300 cc. or less from the calculated flow using surface area (2.2L x M^2) largely because we did not reduce our pump flow to match and O^2 and CO^2 and pH indications.

Electroencephalographic monitor has been routine and with physiological pH, pCO^2 and pO^2, no abnormalities have been recorded.

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