
A Technique for Computer Assisted Monitoring in the Management of Total Heart-Lung Bypass

Jeffrey B. Riley B.A., C.C.T.

Emory University Hospital
Atlanta, Georgia 30322

Abstract

A technique for computer assisted data management during bypass is presented. The data entry requirements and example algorithms are included as well as patient examples.

Information flow parallels the heat, oxygen and carbon dioxide transfer system. A hemodynamic program has been developed for bypass application.

Employing a computing system to aid in monitoring during bypass not only offers the capability of rapid data manipulation but adds variable function and time plotting, alternative record keeping and long-term recall from memory for patient group evaluation or device performance comparison.

Background

Figure One presents a schematic of the three transfer systems the perfusionist must control during heart-lung bypass. The maintenance and balancing of the oxygen transfer (\dot{V}_{O_2}), carbon dioxide transfer (\dot{V}_{CO_2}) and heat transfer (\dot{Q}) control the patient acid base status and allow the perfusionist to adequately support tissue respiration during surgical procedures requiring heart-lung bypass. Figure Two lists common bypass acid-base disorders and the primary underlying transfer system imbalances. The removal of tissue heat decreases \dot{V}_{O_2} and \dot{V}_{CO_2} requiring the operator to make artificial ventilation alterations or observe the consequential large changes in blood O_2 and CO_2 content leading to pH alterations and acid base disorder in-

creasing patient morbidity. The addition of kilocalories to patient tissue increases \dot{V}_{O_2} and \dot{V}_{CO_2} requiring an operator increase in the artificial ventilation rate to maintain normal arterial and venous blood O_2 and CO_2 contents.

Current heart-lung bypass monitoring techniques employ the measurement of parameters that are indices of blood O_2 and CO_2 content. The parameters are combined with the perfusionist's knowledge of the patient's physical characteristics, the cardiac output and the O_2 and CO_2 carrying capability of the blood to subjectively estimate the \dot{V}_{O_2} , \dot{V}_{CO_2} , \dot{Q} and situational ventilation requirements. It is not the purpose of this presentation to discuss any single monitoring variable's adequacy as a predictor in the three transfer systems. The greater number of variables the perfusionist is capable of measuring and assimilating, the greater the operator's ability to accurately predict \dot{V}_{O_2} , \dot{V}_{CO_2} and \dot{Q} and respond to patient perfusion requirements to maintain or be able to return to a physiologic homeostasis prior to termination of heart-lung bypass and return of control of the transfer systems to the patient's normal compensatory mechanisms.

It is not the purpose of this presentation to defend the logic of monitoring \dot{V}_{O_2} , \dot{V}_{CO_2} and \dot{Q} , but to present a computer assisted calculating and monitoring scheme to assist the perfusionist in the management of total heart-lung bypass. Figure Three lists computing system capabilities for lending support to data manipulation for total heart-lung bypass. The computer is capable of inputting data, storing data, manipulating data (mathematics) and representing the data in any for-

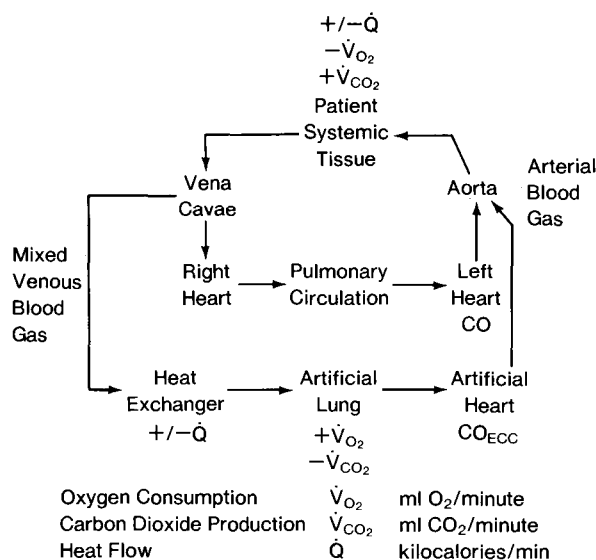


FIGURE 1

mat the programmer chos es and the computing system will allow.

Several hand-held calculator programs have recently been reported and have grown in clinical usage. A large memory computing system with adequate device-user interface components minimizes the user's role in inputting program selection and data values, freeing the perfusionist to attend to the patient support equipment. Figure Four lists the variables entered pump side and in the blood gas laboratory. Sample time is included with every data entry and serves as the referencing address for the data storage matrix in computer memory.

It is not the purpose of this presentation to establish normal values for the monitored and calculated vari-

SYSTEM IMBALANCES

Process	Patient/ECC Imbalance
Respiratory acidosis	patient $\dot{V}_{CO_2} >$ oxygenator \dot{V}_{CO_2} patient $\dot{V}_{O_2} \geq$ ECC delivery of O ₂ or distribution of CO
Metabolic acidosis	ECC delivery of O ₂ or distribution of CO $<$ patient \dot{V}_{O_2} patient $\dot{V}_{CO_2} =$ oxygenator \dot{V}_{CO_2}
Mixed respiratory and metabolic acidosis	patient $\dot{V}_{CO_2} >$ oxygenator \dot{V}_{CO_2} ECC delivery of O ₂ or distribution of CO $<$ patient \dot{V}_{O_2}
Compensated metabolic acidosis	ECC delivery of O ₂ or distribution of CO $<$ patient \dot{V}_{O_2} oxygenator $\dot{V}_{CO_2} >$ patient \dot{V}_{CO_2}

FIGURE 2

1. Variable retrieval and entry
2. Data manipulation and calculation
3. Data presentation and trend plotting or variable function plotting to predict response
4. Alternative record keeping
5. Long term recall from memory for patient group evaluation and device performance comparison

FIGURE 3

ables in various perfusion circumstances, but to present a technique for perfusionists with access to large memory computing systems to employ. Knowledge of additional variables will allow the future formulation and testing of patient management hypotheses.

The mathematical formulae and the subroutines known to exist prior to the development of this computer assisted monitoring technique are referenced.

Method

The following computer program presentation has been implemented on the TRS-80* Micro Computer System. The program currently awaits interpretation for use in the operating room suites on the Hewlett-Packard** 5600A Patient Data Management System for on line patient monitoring during heart-lung bypass.

Hemodynamic Program

The mean arterial pressure (P1) and mean central venous pressure (P2) are entered at each sample time with the roller pump blood blow (Q1). The hemodynamic program employs the nasopharyngeal temperature (T2) and the hematocrit (H1) to predict the blood viscosity (V1) using a mathematical statement based on Rand's measurements.¹ Viscosity is predicted with the following statement:²

$$V1 = 2.718 \uparrow (.02345 * H1 + 2.718 \uparrow (-.0487 * T2 + .9213))$$

Peripheral vascular resistance (P3) in dynes.sec.cm⁻⁵ is calculated as follows;

$$P3 = ((P1 - P2) * 1333) / ((Q1 * 1000) / 60)$$

* Radio Shack, Tandy Corporation, One Tandy Center, Fort Worth, Texas, 76102

** Hewlett-Packard Co., 175 Wyman Street, Waltham, Massachusetts, 02154

DATA ENTRY: PERFUSIONIST AT PUMPSIDE TERMINAL

Temperatures
TE, TR, Tbi, TBo, TWi, TWi

Flow Rates
C.O., H₂O Q, 100% CO₂ Q, 100% O₂ Q, Room Air Q

Pressures
mABP, mCVP, Various circuit pressures

Miscellaneous
Shim pressure values, event code, volume measurements, RBC addition

Initial Computer Entries
Patient age, weight, height,
Immediate pre-bypass values of cardiac output,
Hematocrit, BE, PaCO₂

DATA ENTRY: BLOOD GAS LAB TERMINAL

Arterial and venous blood gases analyzed at 37°C:
PaO₂, PaCO₂, PaH
PvO₂, PvCO₂, PvH

Arterial and venous % O₂ saturation of hemoglobin
SaO₂, SvO₂

Hematocrit and hemoglobin
Hct, [Hb]

Atmospheric pressure
P_{atm}

FIGURE 4

The vascular geometric component (P4) is separated from the vascular resistance by dividing the resistance by the viscosity;²

$$P4 = P3 / (V1 / 100)$$

The cardiac output is reported normalized to body surface area and body weight. The peripheral vascular resistance is normalized to body surface area for individual comparison to a patient population.

Perfusionist knowledge of the blood viscosity, vascular geometry and the vascular resistance will aid in the differential diagnosis of the cause of hypotension due to extreme hemodilution or pure peripheral vasodilation.² Quantitative knowledge of the Cardiac Index and vascular resistance will help document patient arteriovenous shunting, vascular collapse or diffuse vasoconstriction during mechanical vascular support.

Oxygen Transfer Program

The PaO₂ (O3) and PvO₂ (O4) analyzed at 37°C are entered into the program with the values of the arterial (S3) and venous (S4) % O₂ saturation of he-

moglobin measured directly by oximeter. If direct measurements of %O₂ saturation are not available, the saturations are predicted by the following statements employing the current values for arterial (T6) and venous (T5) blood temperature, arterial (H3) and venous (H4) pH and base excess (BE).^{3,4}

$$P = 10^{\uparrow}((\text{LOG}(01) / \text{LOG}(10)) + .48 * (H3 - 7.4) + .024 * (T6 - 37) + .0013 * BE)$$

$$N = 100 * (((P - 67.07) * P + 2121) * P - 8532) * P$$

$$S3 = N / (((P - 67.07) * P + 2396) * P - 31350) * P + 936000$$

The venous sO₂ is predicted by substituting the appropriate sample values in the same statements.

If the patient is not normothermic, the arterial blood pO₂ is temperature corrected to the nasopharyngeal temperature (T2) and reported as the patient PaO₂ (O1) by the following statements;⁵

$$F0 = .0052 + (.0268 * (1 - (2.718^{\uparrow}(-.3 * (100 - S3))))))$$

$$O1 = 03 * 10^{\uparrow}(F0 * (T2 - 37))$$

Similarly, the arterial and venous blood pO₂'s are corrected to the respective blood temperature for use in calculating blood O₂ content and O₂ transfer in the artificial lung. The simple arterial-venous difference in pO₂ and SO₂ is reported when requested by the user.

Arterial blood O₂ content (V6) and venous O₂ content (V7) in O₂ volumes % is calculated to include oxygen carried dissolved in solution by the following statements where H2 is the hemoglobin concentration;

$$V6 = ((01 / 760) * S5) + ((S3 / 100) * H2 * 1.34)$$

$$V7 = ((02 / 760) * S5) + ((S4 / 100) * H2 * 1.34)$$

The O₂ solubility (S5) is predicted by:

$$S5 = (4 * 10^{\uparrow}(-6 * H2 + 3.46 * 10^{\uparrow} - 4) * T5 + (1.3 * 10^{\uparrow} - 4 * H2 + 3.5 * 10^{\uparrow} - 2))$$

The arterial-venous O₂ content difference may be calculated, reported and employed to calculate $\dot{V}_{O_2}(05)$ by:

$$05 = (V6 - V7) * Q1 * 10$$

The value of \dot{V}_{O_2} is reported and normalized to body weight for patient group comparison. Knowledge of the \dot{V}_{O_2} value aids the perfusionist in quantitating patient

metabolic activity, artificial lung function and the systemic distribution of the perfusate during heart-lung bypass.

Oxygen transfer by the artificial lung may further be evaluated by calculating the gas to blood flow ratio (GB) and % O₂ in the ventilating gas inlet (O9) employing the sample time values of the O₂ gas (Q4), CO₂ gas (Q3) and room air (RA) flow rates.

$$GB = (RA + Q4 + Q3)/Q1$$

$$O9 = (Q4 + (.201*RA))/(RA + Q4 + Q3)*100$$

Carbon Dioxide Transfer

The arterial (C3) and venous (C4) pCO₂ analyzed at 37°C are entered into the program. The PaCO₂ is corrected to the nasopharyngeal temperature (T2) if the patient is not normothermic by this statement;⁵

$$C1 = C3*10^{(.019*(T2 - 37))}$$

The arterial blood pCO₂ (C1) and venous blood pCO₂ (C2) are corrected to the current sample value of blood out and blood in temperatures by the same equation for use in CO₂ transfer calculations.

The actual patient, arterial (H3) and venous (H4) pH's are corrected from the laboratory 37°C analysis (H5, H6) employing the current values of nasopharyngeal (T2), blood in and blood out temperatures at sample time;⁵

$$H3 = H5 + .0149*(37 - T2)$$

The corrected pH is used for calculating total blood CO₂ content. Total blood CO₂ content may be predicted from blood gas and pH values by the Singer-Hastings method or may be calculated from CO₂ measurements in the gas phase in this method.^{6,7} If the mass spectrometer measurement of the ventilating gas exit pCO₂ is not available, the $\dot{V}CO_2$ is calculated by predicting arterial (V9) and venous (VO) total CO₂ content with the following BASIC version of Kelman's Fortran algorithm of Singer-Hasting's nomogram to predict CO₂ content from pCO₂ (C1), blood temperature (T6), SO₂ (S3) and pH (H3);⁸

$$P = 7.4 - H3$$

$$PK = 6.086 + 0.42*P + (38 - T6)*(.00472 + .00139*P)$$

$$TP = 37 - T6$$

$$SL = .0307 + .00057*TP + .00002*TP*TP$$

$$DX = .59 + .2913*P - .0938*P*P$$

$$DR = .664 + .2275*P - .0938*P*P$$

$$D = DX + (DR - DX)*(1 - S3/100)$$

$$CP = SL*C1*(1 + 10*(H3 - PK))$$

$$CC = D*CP$$

$$HT = H1*.01$$

$$V9 = (HT*CC + (1 - HT)*CP)*2.22$$

Venous blood CO₂ content (VO) is predicted by substituting the appropriate sample values in the same statements.

Total venous-arterial CO₂ content difference (WO) may be calculated to quantitate $\dot{V}CO_2$ (CO) given the cardiac output (Q1);

$$WO = V9 - VO$$

$$CO = WO*Q1*10$$

When a direct measurement of the ventilating gas exit pCO₂ (P5) by mass spectrometer is available, the percent CO₂ (VO) in the artificial lung ventilating gas exit is calculated using the atmospheric pressure of the day (P6) and the water vapor pressure (P7);

$$VO = (P5/(P6 - P7))*100$$

The 100% humidity water vapor pressure (P7) is adjusted for temperature before use in the above statement by;

$$P7 = 1.891*TV - 23.955$$

where TV is the ventilating gas temperature. The ventilating gas inlet % CO₂ (VI) is calculated from the gas flow meter readings for CO₂ gas (Q3), O₂ gas (Q4) and room air (RA) flow;

$$VI = (Q3/(Q3 + Q4 + RA))*100$$

The $\dot{V}CO_2$ (CO) to the ventilating gas may be calculated;

$$CO = (VO - VI)*(Q3 + Q4 + RA)*10$$

The Respiratory Quotient (RQ) for the artificial lung and perfusion/ventilation circumstance may then be evaluated as the ratio of $\dot{V}CO_2$ (CO) to $\dot{V}O_2$ (O5);

$$RQ = CO/O5$$

Heat Transfer

At sample time, the blood in (T5), blood out (T6),

water in (T7), nasopharyngeal (T2) and rectal (T3) temperatures are entered into the program. Water out temperature (T9) and water flow (Q9) are optional entries for heat exchanger function quantitation. The beginning warm time (TW) is entered to calculate elapsed warm time. The current hematocrit (H1) is used to predict blood specific heat (S1) and density (D1) to calculate heat flow with the following statements;

$$S1 = -.0017 * H1 + .94$$

$$D1 = .0006 * H1 + 1.03$$

The blood out/blood in (E1) and water in/blood in (Dφ) temperature gradients are calculated and used for heat flow and heat exchanger function calculations;

$$E1 = T6 - T5$$

$$DO = T7 - T5$$

The coefficient of heat exchange (C8) is evaluated by;

$$C8 = E1 / Dφ$$

Blood heat flow (Q7) is calculated using blood flow (Q1);⁹

$$Q7 = E1 * S1 * D1 * Q1$$

Water heat flow (Q8) is evaluated with the measured water flow (Q9) and water out/water in temperature gradient;

$$Q8 = (T9 - T7) * Q9$$

The ratio of the heat flow taken up by the blood stream (Q7) to the heat flow given up by the water path (Q8) is a measure of the heat accountability in the heat exchanger.¹⁰

The rate of rise of the nasopharyngeal temperature may be calculated from sample period to sample period. The number of kilocalories (Q1) that are ideally exchanged to warm or cool a patient kilogram body weight (BW) to a certain nasopharyngeal temperature (T2) are calculated;

$$Q1 = (T2_i - T2_o) * BW * .83$$

assuming the specific heat of the body is .83 calories/grams°C.

The actual number of kilocalories exchanged (QA) from one sample time (T1) to another is calculated by multiplying the elapsed time by the blood heat flow (Q7);

$$QA = (T1_i - T1_o) * Q7$$

The percent ideal warming or cooling is calculated by summing the actual number of kilocalories exchanged per sample period and dividing the sum by the ideal kilocalories (Q1) needed to warm or cool the nasopharyngeal temperature difference.

Heat, similar to oxygen, may be used as an indicator of the adequacy of the distribution of the cardiac output during total heart lung bypass. A vasoconstricted, cold patient returning a high venous blood heat content in the face of a large arterial blood to nasopharyngeal temperature gradient is not being peripherally perfused well, especially if other metabolic monitors support the diagnosis.

Data Storage and Presentation

Figure Five outlines the computer data management system's ability to aid the perfusionist during bypass in information display. The measured variables and calculated variable values are stored in a matrix addressed by the sample time. The capability to display the time trend of four variables continuously and list the most recent sample values of the arterial and venous blood gases, and hemodynamic information is available at pump-side. The user may chose from a menu to obtain sample time values of oxygen, carbon dioxide and heat transfer information in addition to the routinely displayed $\dot{V}O_2$, $\dot{V}CO_2$, R.Q. and \dot{Q} normalized to the patient's body weight.

Subroutines are being developed to present one variable plotted as a function of another measured variable (e.g., the PaO₂ as a function of the gas to blood flow ratio). Retrospective study of a large population of perfusion situations allows the generation of a mathematical formula to predict the shape of the artificial oxygenator device function curve. During a stable bypass situation, after obtaining two measured data points, the position of the function curve may be established and the computer may predict the value of

COMPUTER INFORMATION STORAGE AND PRESENTATION

- A. Matrix storage of data entries and variable calculations at sample time
- B. Elapsed time trend plots
- C. Two variable plot, function curve generation
- D. Variable prediction from two points for a known, mathematical model to aid perfusionist decision in patient management during bypass.

FIGURE 5

a control variable (e.g., gas to blood ratio) necessary to yield an optimal monitored variable (i.e., PaO₂).

The computer's ability to sort, define and make logical decisions allows the development of a subroutine to define acid-base disorders presently occurring and sort out the underlying cause by evaluating the monitored and calculated variables in the same logic fashion that the perfusionist would. The computer could be programmed to issue prompting questions and define the presence of an acid-base disorder for educational purposes or to decrease the chance of human error in evaluating monitored parameter.

Conclusion

A technique is presented to employ a large memory, rapid access computer system to calculate variables that quantitate the oxygen, carbon dioxide and heat transfer systems during total heart-lung bypass. A subroutine to aid the perfusionist in interpretation of hemodynamic information is presented.

Quantitation and documentation of monitored and calculated variables stored for retrieval during or after bypass will allow perfusionist to develop a more quantitative approach toward patient management and device comparison during bypass. The calculated

variables will aid validity to intra-operative patient management decisions and allow the generation and substantiation of new patient management hypothesis in retrospective evaluation of large patient groups.

Bibliography

1. Rand, P. W.; Lacombe, E.; Hunt, H. E.; and Austin, W. H., Viscosity of Normal Human Blood Under Normothermic and Hypothermic Conditions, *J. Appl. Physiol.* 19(1):117-122, 1964.
2. Pfaender, L., and Riley, J., Viscosity Induced Resistance Changes During Bypass with Hemodilution and Hypothermia, *J.E.C.T. Proceedings*, 1980, In Press.
3. Thomas, L. J., Jr., Algorithms for Selected Acid Base and Blood Gas Calculations, *J. Appl. Physiol.* 33(1):154-158, 1972.
4. Severinghaus, J. W., Blood Gas Calculator, *J. Appl. Physiol.* 21(3): 1108-1116, 1966.
5. Kelman, G. R., and Nunn, J. R., Nomograms for Correction of Blood pO₂, pCO₂, pH and Base Excess for Time and Temperature, *J. Appl. Physiol.* 21(1):1484-1489, 1966.
6. Singer, R. B., and Hastings, A. B., An Improved Method for the Estimation of Disturbances of the Acid Base Balance of Human Blood, *Medicine (Baltimore)* 27:233, 1948.
7. Riley, J., Prediction of Arterial Blood pCO₂ by Measuring the Ventilating Gas Exit pCO₂ in a Bubble Oxygenator, *J.E.C.T. Proceedings*, 1980, In Press.
8. Kelman, G. R., Digital Computer Procedure for the Conversion of pCO₂ into Blood CO₂ Content, *Resp. Physiol.* 3:111, 1967.
9. Esmond, W. B., et al., Optimization of the Medical Blood Heat Exchanger: Plastic Film Heat Exchanger, *Tran. Amer. Soc. Acty. Int. Org.* IX, 1963.
10. Riley, J., and Winn, B., *In Vitro* Analysis of Extra-corporeal Blood Heat Exchange Devices, *J.E.C.T.* 9(3):34, 1977.