Computer simulation of heart-lung bypass

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Abstract

A computer model of the extracorporeal circulation has been developed. The global model takes into account the hydraulic behaviour, the thermal behaviour, and the biochemical one.

An urine output model has finally been derived from clinical data.

The interactive characteristics of the computer model allow to change the main perfusion variables (pump flow rate, gas flow rate and composition, water temperature) and to simulate the administration of drugs (vasodilators or diuretics) in runtime mode and to observe the consequent patient response.

Results are graphically presented on the personal computer monitor.

Such a model is valuable for the training of perfusionists and for testing new devices.

1 Introduction

Interaction mechanisms between the heart-lung machine and the patient are complex. Perfusionists learn by direct clinical experience how to regulate the machine control parameters in order to maintain the patient's vital functions during cardiopulmonary bypass. A mathematical model could be useful in the training period: perfusionists could simulate extracorporeal manoeuvres with no risk to the patient even in the case of particular emergency situations, or in the training period.

The model can also be utilised as a testing tool to study the influences of new technological solutions or machine control modes on the patient.

The extracorporeal circulation model represents the heart-lung machine components (arterial pump, oxygenator, arterial filter, venous reservoir, arterial and venous cannulae, lines) and the patient. Variables of clinical interest are calculated as a function of time and displayed on the computer monitor.

2 Materials and methods

Figure 1 shows a typical extracorporeal circulation circuit with the main components. The represented components have been characterised by relations between pressure drop and blood flow rate. The relations (linear or quadratic) are dependent on the component analysed and, in most cases, are mathematical formulations of the devices performances as presented by the manufacturer.

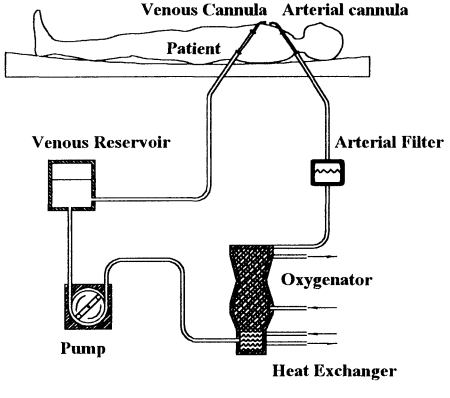
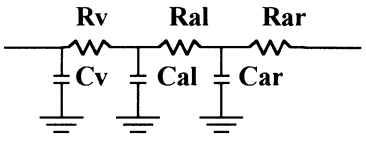


Figure 1: Extracorporeal circulation scheme and the modelled components

Since flow rate in suction pumps is generally low if compared to arterial pump flow rate and venous return flow rate, they are not represented in this model of the extracorporeal circulation. The mathematical representation of the suction lines and pumps complicate the solution of the differential system of equations without any substantial improvement in the global model results.

The patient systemic vascular system is described through a lumped parameters electrical model (Fig. 2). The parameters values are related to patient size and can be modified by drug administration. Three vascular trees have been considered: the arterial tree, the arteriolar tree and the venous tree. The correspondent resistance and compliance values refer to a patient of 70 kg weight in normal conditions.



arterial tree	Rar 0.07 mmHg s/cm3 Car 4 cm3/mmHg
arteriolar tree	Ral 0.6 mmHg s/cm3 Cal 4 cm3/mmHg
venous tree	Rv 0.3 mmHg s/cm3 Cv 4 cm3/mmHg

Figure 2: Electrical analogue for the patient systemic circulation

Heat exchanges during extracorporeal circulation are also modelled in order to calculate the patient temperature in response to variations of the blood perfusion temperature in each different period of the extracorporeal circulation (cooling period, hypothermic period, rewarming period).

Heat dissipation through the extracorporeal devices has been neglected. Arterial blood temperature can be derived from the thermal efficiency of the heat exchanger which is generally given as a function of blood flow rate by oxygenator manufacturers.

The patient temperature has been calculated solving the following energy balance equation:

$$Mc_p \frac{dT_p}{dt} = Q_a \rho_s c_s T_a - Q_v \rho_s c_s T_v$$

In this equation the first term stands for the patient internal energy time variation, where M is patient weight, c_p is patient specific heat coefficient, and T_p is patient temperature. The second term of the above equation is the difference between heat inflow to the patient and heat outflow from the patient, where ρ_s and c_s are blood density and blood specific heat coefficient, Ta and Tv are blood arterious and venous temperatures, and Q_a and Q_v are arterious and venous blood flow rates respectively.

Finally the model calculates O_2 and CO_2 exchanges between the patient and the oxygenator during extracorporeal circulation. Fick's law is used to calculate O_2 and CO_2 concentrations at the outlet from patient (or from oxygenator):

$$[O_2]_{out} = \frac{Q_{in}}{Q_{out}}[O_2]_{in} - \frac{VO_2}{Q_{out}}$$

VO_2 represents patient oxygen consumption (or oxygenator O_2 production). The same equation can be rewritten for the calculation of CO_2 concentration.

Other important variables related to blood oxygenation (pO_2, pCO_2, pH, HCO_3^-, oxyhaemoglobin saturation SO_2) are then calculated from Henry's law, Anderson-Hasselbach's relation [1], and Kelman's equations [2,3].

Patient metabolism is calculated as a function of patient temperature and patient body surface area. Patient oxygen consumption is reduced to 50% at 28°C, to 60% at 25°C, to 70% at 20°C, to 85% at 15 °C [4]. Respiratory ratio is used to calculate patient CO_2 production from patient oxygen consumption.

Finally an oxygenator model has been developed to simulate gas exchanges between venous blood and oxygen. The oxygenator model calculates both oxygen given to blood (oxygenator VO_2) and carbon dioxide removed from blood (oxygenator VCO_2).

The characteristic parameters of the oxygenator model are the blood film thickness and the membrane thickness. It is possible to vary these parameters to reproduce typical oxygenator VO_2 and VCO_2 representative of different commercial oxygenators.

The heart-lung bypass model is implemented on a personal computer and C language is utilised. The user moves through a window menu to set all data and parameters of the extracorporeal circuit and those of the patient and then simulation starts. It is possible to change typical extracorporeal circulation control parameters, e.g. pump flow rate, water temperature for the heat exchanger, gas flow rate and composition for the oxygenator in runtime mode. It is also possible to simulate drug treatments related to vasodilation control or diuresis control. The main model output variables are venous return blood flow rate, arterial and venous pressures, patient temperature, oxyhaemoglobin arterial and venous blood saturation and other related variables (pO_2, pCO_2, pH, HCO_3^-). These variables are graphically shown in real time on the computer monitor. If the value of some of these variables is out of range, then the user can decide to suspend the simulation and to change the control parameters. The simulation then continue from the point in which it was suspended and the user can observe the consequences of the interventions made.

3 Results and discussion

Simulation results are included in this section.

Figure 3 shows simulation results concerning the cooling period. Water temperature is set at 20°C. Patient temperature reaches 26°C in 15 minutes.

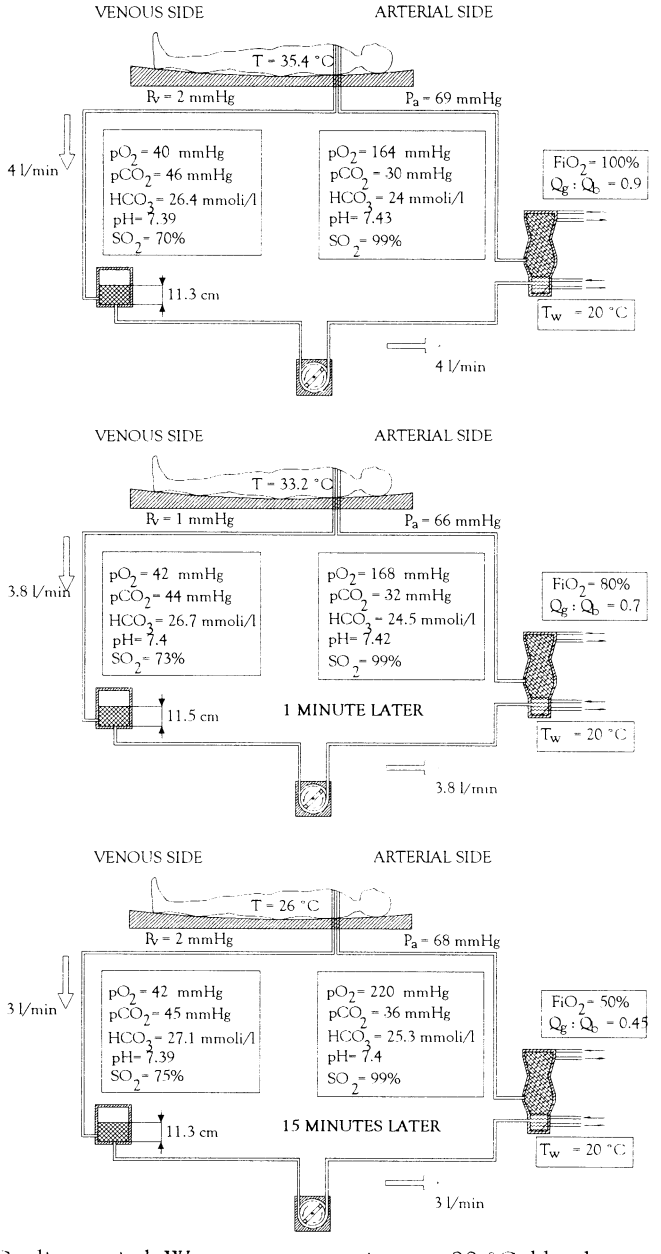


Figure 3: Cooling period. Water temperature is set to 20 °C, blood pump flow rate, gas flow rate and oxygen percentage in the gas mixing are gradually decreased in relation to patient temperature (T). FiO_2: O_2 percentage in the gas mixing. Q_g:Q_b: gas to blood flow rate ratio. T_w: water temperature. P_a and P_v: arterial and venous pressures.

During the cooling period blood pump flow rate and gas flow rate and oxygen percentage in the gas mixing are gradually decreased to match the reduced patient metabolism due to hypothermia.

All parameter and variable values shown in Fig. 3 appear on the computer monitor continuously updated as simulation proceeds; furthermore they are saved in ASCII form for postprocessing, in order to obtain, for example, charts or tables.

Hypertension is a direct consequence of patient vasoconstriction which often occurs during extracorporeal circulation. Vasodilator drugs are generally administered to the patient to correct such a pathologic state. Vasodilator drugs can act mainly on the arterial vascular tree or on the venous vascular tree.

The time course of arterial pressure and that of the blood level in the venous reservoir following the administration of a dose of venous vasodilator drug (3 mg in 20 cc of physiologic solution) are shown in Fig. 4. This drug is generally given to the patient at the end of the extracorporeal circulation with the aim at lowering pressure as well as at lowering venous return to give blood to the patient. The administration of a diuretic drug causes a steep rise in urine flow rate and volume, which are shown in Fig. 5. The drug effect lasts for about 10 minutes, then urine flow rate returns to normal values.

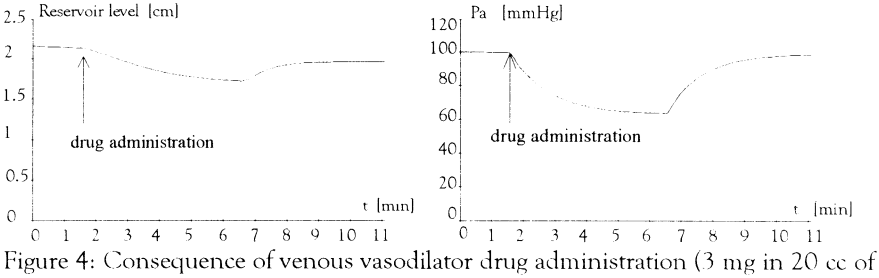


Figure 4: Consequence of venous vasodilator drug administration (3 mg in 20 cc of physiologic solution) on arterial pressure and on blood level in the venous reservoir.

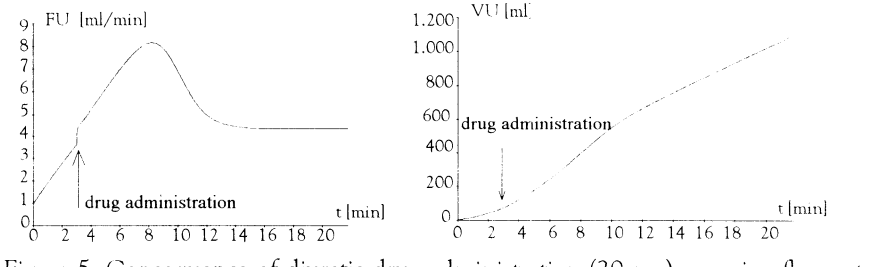


Figure 5: Consequence of diuretic drug administration (20 mg) on urine flow rate and on urine volume.

Blood oxygenation is mainly dependent on blood flow rate and gas composition in the oxygenator, while blood CO_2 content can be modified through gas flow rate in the oxygenator. If blood flow rate is decreased venous oxyhaemoglobin saturation and blood venous pO_2 decrease (Table 1). This situation can lead to tissue hypossia. An increment in gas flow rate causes an excessive CO_2 removal out, low pCO_2, and alkalosis (high pH level) follows, as shown in Table 2.

Table 1. Effects of pump flow rate decrease on model output variables, observed two minutes later.

Pump flow rate [l/min]	4 → 3	
Time [min]	t_0	t_0+ 2
Arterial blood pressure [mmHg]	69	40
Venous blood pressure [mmHg]	2	4
Reservoir blood level [cm]	10.5	11.6
Arterial pO_2 [mmHg]	215	202
Venous pO_2 [mmHg]	42	35
Arterial pCO_2 [mmHg]	35	44
Venous pCO_2 [mmHg]	44	60
Arterial HCO_3^- [mM/l]	25	27
Venous HCO_3^- [mM/l]	27	29
Arterial pH	7.4	7.34
Venous pH	7.34	7.27
Arterial SO_2 %	99	99
Venous SO_2 %	73	59

Table 2. Effects of gas flow rate increase on model output variables, observed two minutes later.

Gas to Blood Flow Rate Ratio	0.6 → 0.9	
Time [min]	t_0	t_0+ 2
Arterial pO_2 [mmHg]	160	156
Venous pO_2 [mmHg]	38	36
Arterial pCO_2 [mmHg]	34	23
Venous pCO_2 [mmHg]	45	30
Arterial HCO_3^- [mM/l]	25	22
Venous HCO_3^- [mM/l]	27	23
Arterial pH	7.41	7.52
Venous pH	7.34	7.35
Arterial SO_2 %	99	99
Venous SO_2 %	70	71

4 Conclusions

A model of heart-lung bypass has been realised and implemented on a personal computer. This model is able to simulate the patient reaction to different artificial perfusion conditions.

The extracorporeal circulation model consists of the patient model and that of the artificial components, which are implemented to study the man-machine interaction. The model describes significant aspects of heart-lung bypass, related to hydraulic, thermal and biochemical arguments.

Model results show the hemodynamic, thermal and biochemical response of the patient to modifications of fundamental control parameters of extracorporeal circulation, such as pump blood flow rate, water temperature in the heat exchanger, gas flow rate and composition in the oxygenator. The model describes the patient response following the administration of vasodilator or diuretic drugs.

Graphic and real time representation of the model output variables allows an immediate comprehension of the results. The user is able to vary the control parameters at any instant during simulation.

Furthermore, the possibility to modify runtime the control parameters of the cardiopulmonary bypass represents a valuable interaction method between the user and the model, and allows a quick training about the extracorporeal circulation.

5 References

1. Roughton F.J.W. Transport of oxygen and carbon dioxide, *Handbook of physiology*. Section 3: Respiration, eds. W.O. Fenn and H. Rahn, vol. I, pp. 767-825, Am. Physiol. Soc., Washington DC, 1964.

2. Kelman G.R. Digital computer subroutine for the conversion of oxygen tension into saturation. *J. Appl. Physiol.*, 1966, 21, 1375-1376.

3. Kelman G.R.: Digital computer procedure for the conversion of pCO_2 into blood CO_2 content. *Respiration Physiology*, 1967, 3, 111-115.

4. Parulkar G.B., Shah H.N., Bahat M.M., Joshi V.M. Oxygen consumption and acid-base changes during cardiopulmonary bypass, *Thirty years of extracorporeal circulation*, eds. S. Hagl, W.P. Klövekorn, N. Mayr, and F. Sebening, pp. 544-551, Gerber editors, München, 1984.