The Heart-Lung Pump/Human Interface: A Real Time Microcomputer-Based Simulation

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Abstract

A microcomputer based simulation of the important processes which occur during cardiopulmonary bypass has been developed for preclinical practice for perfusion technologist trainees. The interface to the computer is through a custom designed electronic console with controls for five pump heads, heat exchanger water temperature, gas flow and content, oxygenator and cardiotomy reservoir heights, clamp detection for flow control and variable venous clamping. A keypad is provided for menu driven entry of patient characteristics, timer control, data requests, drug and fluid administration and perfusion system data.

The system operates in real time with waveform and digital data displays of information typically available to the perfusion technologist clinically. The timing and accuracy of the presented information is controlled by the program and patient responses calculated with randomly selected deviations.

Major components of the simulation have been compared to clinical data. Mean error for oxygen content was 0.67%, for CO_2 transfer -0.014ml/l/min and for heat exchanger performance -0.018°C. The simulation has been used for preclinical student training and found to be effective for both practice and student evaluation.

Introduction

The value of computer simulations of some of the important processes that occur during cardiopulmonary bypass have been documented (1, 2). Particularly for perfusion technology students, computer simulations reinforce thought processes that can be dangerous to practice in the clinical setting and impractical to present in written form. The goals of the proposed computer model to carry the simulation of cardiopulmonary bypass to the next level are as follows:

1. Simulate as many of the processes that occur during a procedure as is practical.
2. Present only the data which is normally available in the clinical setting with a presentation similar to the clinical setting.
3. Present the data dynamically so that the timing is consistent with the clinical setting.
4. Represent not only the typical performance but also the normal variability of performance.
5. Allow direct control of only those parameters which are under direct control of the perfusionists clinically.
6. Make it adaptable to a variety of perfusion components.
7. Operate on hardware affordable to teaching and clinical departments.

The purpose of simulating as many of the processes as possible is not just to practice the individual skills. It also forces the student to deal with the interaction of many processes and keep track of all of them simultaneously as would occur clinically. Because the model must compute them in order to operate, many of the parameters either not available or only periodically sampled clinically could be presented. Although they might be presented in a "teaching mode" of the model, they are not presented during the simulation as they promote an artificial decision process not available clinically. The timing of the simulation is important to accurately portray as the rapid rate at which decisions are required and the rates at which the patients respond to changes are critical for students to understand. Since there are no "ideal" patients, the model varies many of the parameters on a random basis to convey the range of variability to be encountered as well as the frequency with which extreme variation is encountered. Having multiple perfusion components extends the model's usefulness, and operating on a personal computer extends its practicality.

Materials and Methods

The model is implemented in compiled BASIC on an 8 MHz IBM compatible microcomputer interconnected with a custom perfusion console. The console provides adjustable controls for five pump heads, oxygenator and cardiotomy reservoir heights, FIO_2, gas flow, heater cooler water temperature, and venous clamping (See Figure 1). It also detects whether the fluid administration line for the cardiotomy reservoir, tubing between the cardiotomy and oxygenator reservoirs, and arterial line are clamped. Menu choices and required data input are performed on a 16 key keypad on the console so computer keyboard interaction is not required. The

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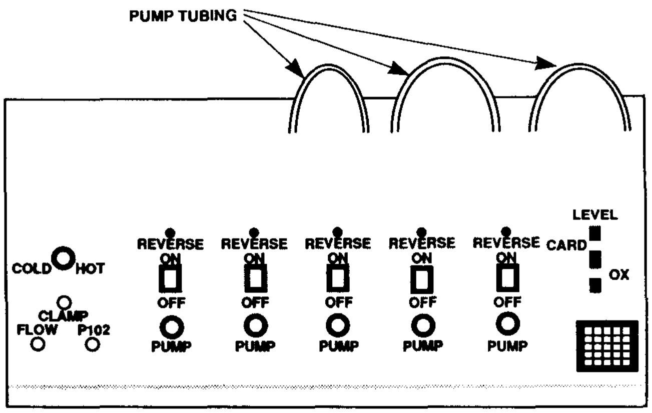
FIGURE 1



eleven adjustable parameters and three clamp status inputs are input to the computer after processing in the console through a MetraBytea Dash-8 Analog-to-Digital board. The keypad is input after conditioning in the console to the serial port of the computer.

The hemodynamic components of the model incorporate the patient's cardiovascular system as well as the bypass, sump, sucker, and cardioplegia circuits (See Figure 2). Resistances, compliances, inertance, and valves are diagrammed as their electrical analogs as has been commonly done (3, 4). The pressure, volume and flow for each compartment representing the major components of the circulatory system are derived 68 times per second using the following equations:

$$\text{Pressure}_n = \frac{\text{Volume}_n}{\text{Compliance}_n}$$

$$\text{Volume}_n = (\text{Flow}_n - \text{Flow}_n{+}1)^* \blacktriangle \text{Time} + \text{Volume}_{no}$$

For all compartments except arterial:

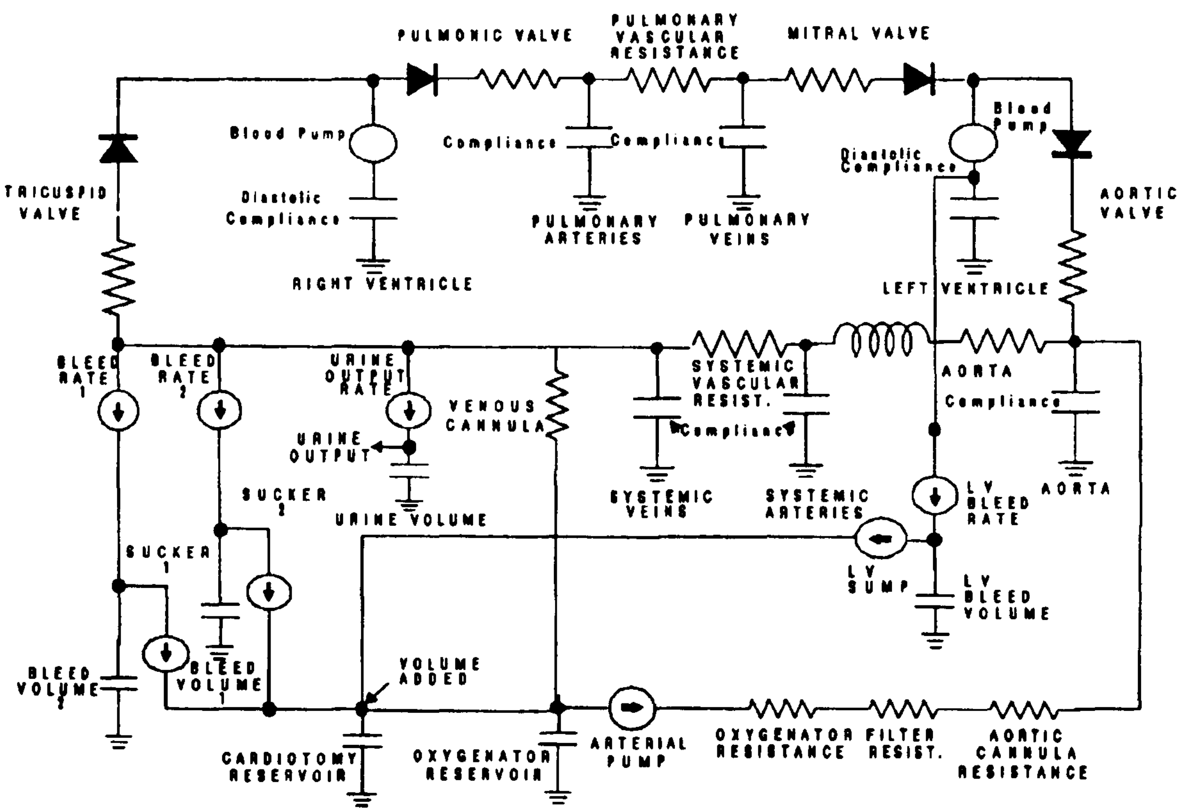
$$\text{Flow}_n = \frac{\text{Pressure}_{n-1} - \text{Pressure}_n}{\text{Resistance}_n}$$

For arterial compartment due to high inertance in aorta:

$$\text{Flow}_{art\cdot} = \frac{\text{Press.}_{aorta} - \text{Press}_{art} + \dfrac{\text{Inertance}_{art\cdot}{}^* \text{Flow}_{art}}{\blacktriangle\text{Time}}}{\text{Resistance}_{art\cdot} + \dfrac{\text{Inertance}_{art\cdot}}{\blacktriangle \text{Time}}}$$

where n is the compartment of interest, n-1 the proximal compartment and n+1 the distal compartment. Continuously solving these equations by iteratively sequencing through the

FIGURE 2



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a MetaByte Inc., Taunton, MA 02780

compartments, the model derives highly accurate values and waveforms throughout the cardiovascular system for these parameters. These, in turn, are acted upon by the perfusion components. The right and left ventricular ejections are based on the contractility index Emax (5). Emax is the slope of the linear relationship between end systolic pressure and end systolic volume. The model uses Emax to predict the stroke volume for a given end diastolic volume preload. The result is contractility and volume sensitive ventricular performance that accurately reflects the transition on and off bypass.

The model allows for menu based input of patient and perfusion set-up characteristics (See Table 1). The menu choices alter the value of the parameters in the model to reflect the characteristics of the patient and circuit selected by the student. In general, arterial and ventricular parameters are scaled to the calculated body surface area, and venous parameters scaled to blood volume calculated from body size (See Table 2). The systemic and pulmonary vascular resistances also are randomly varied around their scaled values. A file of random samples from a Standard Normal Distribution is used to randomly select the number of standard deviations above or below the mean of the parameter. This is also used to select the urine output rate, which is pressure dependent below 80 mmHg. The blood flow rates to the two suckers, and the left ventricular sump are randomly varied each minute, and the student must keep up with the changes or be warned by the surgeon. The blood flow is shown to the student as a bar graph of the percentage of the pump head flow rate. A randomly selected irrecoverable blood loss can require response with packed cells or crystalloid hung by menu choice and administered through control of one of the tubing clamps. The hematocrit is calculated based on all volume-altering factors and is reported after a blood gas is requested.

TABLE 1: Perfusion Case Set-Up Choices

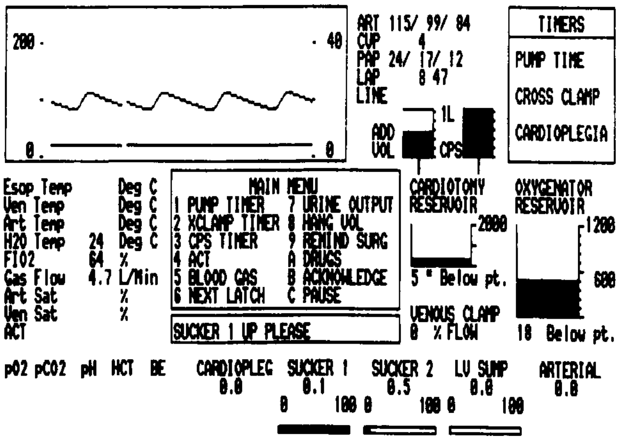
Patient Height
Patient Weight
Patient Age
Patient Gender
Oxygenator Type
Filter Type
Cardiotomy Type
Aortic Cannula Size
Venous Cannula Size
Priming Volume
Prime Components
Arterial Tubing Size Length
Venous Tubing Size and Length
Sucker Tubing Size
LV Sump Tubing Size
Blood Gas Delay
Pump Time (approximate)

TABLE 2: Hemodynamic Model Parameters

Location	Initial Volume (ml)	Compliance (ml/mmHg)	Resistance (mmHg/ml/sec)
Left Ventricle	70*BSA	8*BSA	0.019/BSA
Aorta	40*BSA	0.22*BSA	0.095/BSA
Arteries	40*BSA	0.9*BSA	1.7±0.08/BSA
Veins	0.54*BV	0.18*BV	0.014/BSA
Right Ventricle	70*BSA	17.5*B	0.014/BSA
Pulmonary Arteries	3.2*BSA	2.8*BSA	0.20±0.03/BSA
Pulmonary Veins	0.135*BV	0.017*BV	0.014/BSA

The patient data is shown on the computer display along with the menus and messages from the surgeon (See Figure 3). Pressure data is shown as it might be on a physiological monitor. Volumes are shown dynamically as animated icons of their clinical counterpart. Control of the timing of the pump run is through randomly selected delays, based on a 20-patient data base at Ohio State University Hospitals, which cause messages to be issued to the student for the major milestones (eg. "600 cc's cardioplegia please," "start rewarming, please"). Once on pump, the additional parameters available to the perfusionist are also displayed on the simulator (See Figure 4). ACT's and blood gases can be requested, but the student must wait for the ACT to count up to the value and the blood gas to return from the lab a set delay later. Digital filtering to delay response and programmed errors representing realistic accuracy make the student realize the limitations of the on-line blood gas monitor.

FIGURE 3



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200 .                                  . 40   ART 115/ 99/ 84      TIMERS
                                              CUP      4           PUMP TIME
                                              PAP 24/ 17/ 12       CROSS CLAMP
                                              LAP      8 47        CARDIOPLEGIA
                                              LINE
                                                          1L
0 .                                    . 0    ADD
                                              VOL           CPS

Esop Temp        Deg C   MAIN MENU                      CARDIOTOMY     OXYGENATOR
Ven Temp         Deg C   1 PUMP TIMER   7 URINE OUTPUT  RESERVOIR      RESERVOIR
Art Temp         Deg C   2 XCLAMP TIMER 8 HANG VOL                2000           1200
H20 Temp     24  Deg C   3 CPS TIMER    9 REMIND SURG
FI02         64  %       4 ACT          A DRUGS
Gas Flow     4.7 L/Min   5 BLOOD GAS    B ACKNOWLEDGE   5 " Below pt.            600
Art Sat          %       6 NEXT LATCH   C PAUSE
Ven Sat          %                                      VENOUS CLAMP
ACT                      SUCKER 1 UP PLEASE             0  % FLOW      18  Below pt.

p02 pC02  pH  HCT  BE    CARDIOPLEG  SUCKER 1   SUCKER 2   LV SUMP    ARTERIAL
                            0.0        0.1        0.5        0.0        0.0
                                    0      100 0      100 0      100
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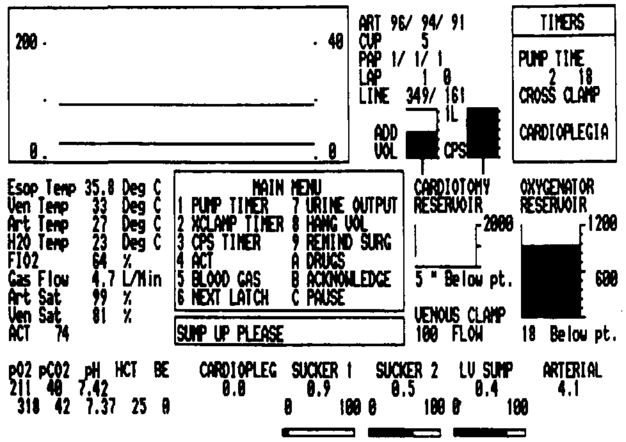
FIGURE 4



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200 .                                  . 40   ART 96/ 94/ 91       TIMERS
                                              CUP     5            PUMP TIME
                                              PAP 1/ 1/ 1             2   18
                                              LAP     1  0         CROSS CLAMP
     .                                 .      LINE  349/ 161
                                                          1L       CARDIOPLEGIA
0 .                                    . 0    ADD
                                              VOL           CPS

Esop Temp 35.0 Deg C   MAIN MENU                      CARDIOTOMY     OXYGENATOR
Ven Temp   33  Deg C   1 PUMP TIMER   7 URINE OUTPUT  RESERVOIR      RESERVOIR
Art Temp   27  Deg C   2 XCLAMP TIMER 8 HANG VOL                2000           1200
H20 Temp   23  Deg C   3 CPS TIMER    9 REMIND SURG
FI02       64  %       4 ACT          A DRUGS
Gas Flow   4.7 L/Min   5 BLOOD GAS    B ACKNOWLEDGE   5 " Below pt.            600
Art Sat    99  %       6 NEXT LATCH   C PAUSE
Ven Sat    81  %                                      VENOUS CLAMP
ACT   74               SUMP UP PLEASE                 100  FLOW      18  Below pt.

p02 pC02  pH  HCT  BE    CARDIOPLEG  SUCKER 1   SUCKER 2   LV SUMP    ARTERIAL
211  40  7.42               0.0        0.9        0.5        0.4        4.1
 310  42  7.37  25  0               0      100 0      100 0      100
```

The blood gases are computed by a ten compartment, partial pressure gradient sensitive model of gas exchange. This very non-linear process requires an iterative approach to approximate gas transfer, calculate error, and improve the approximation until the transfer converges on the correct amount. Appropriate corrections for water vapor pressure,

b. American Bentley, Irvine, CA 92714

temperature and pH are applied to pO_2 as are temperature and O_2 content to CO_2. Body stores of O_2 and CO_2 are computed to reflect the appropriate dynamics as delivery/removal and consumption/production of oxygen and CO_2 go out of balance. Temperature and body size dependent O_2 consumption is calculated with a randomly selected depth of anesthesia.

The patient temperature is also computed based on heat exchanger performance and thermal mass of the patient. Eight sets of one minute resolution temperature curves were used to derive means and standard deviations for the fraction of body mass in a well perfused core and the time constants for redistribution of heat to esophageal and bladder measurement sites.

Because of the random nature of the model, some patients will not be able to be managed by mechanical changes alone. Representative examples of a vasoconstrictor, vasodilator, and diuretic are provided under menu control (See Table 3). Their mean and standard deviation for their respective responses were also derived from the 20 patient data base and incorporated into the model with the random selection of standard deviation. Response to heparin and starting ACT were similarly measured on the data base and implemented with random variation. Rates of removal of the drugs are implemented digitally based on published time constants.

FIGURE 5

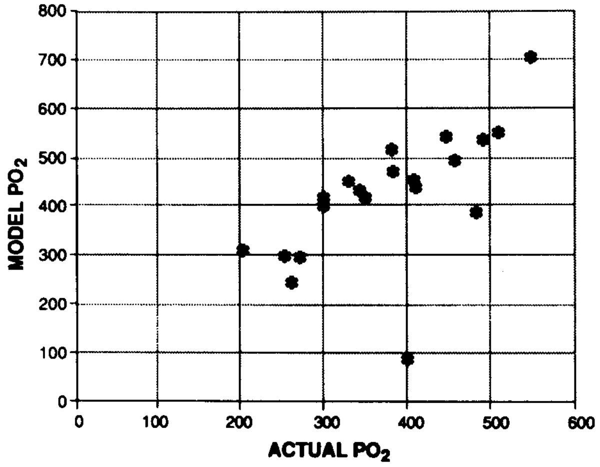


FIGURE 6

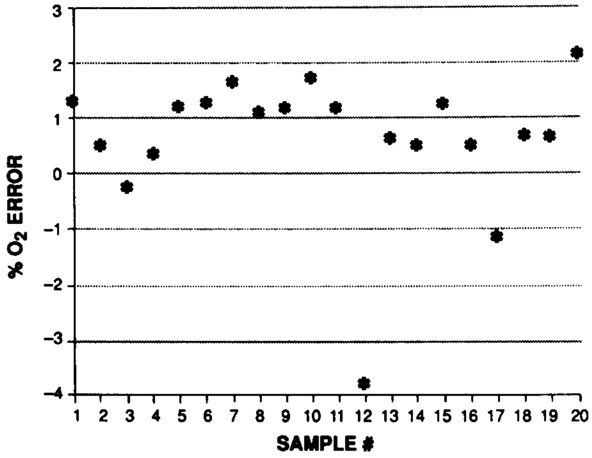


TABLE 3: Pharmacologic Intervention

Phenylephrine
Isoflurane
Heparin
Protamine
Sodium Bicarbonate

Protamine reversal of heparin is set at a ratio of 0.8:1 for the calculated amount of remaining heparin. Sodium bicarbonate may be administered to negate base deficits accumulated during periods of hypoperfusion.

Results

Most of the outputs of the model are simply statistically-based implementations of results from the patient data base or regression equations published in the literature. The accuracy is limited only by that of the source of the data. The performance of the oxygenator and heat exchanger, however, is based on assumptions behind a computer model and

FIGURE 7

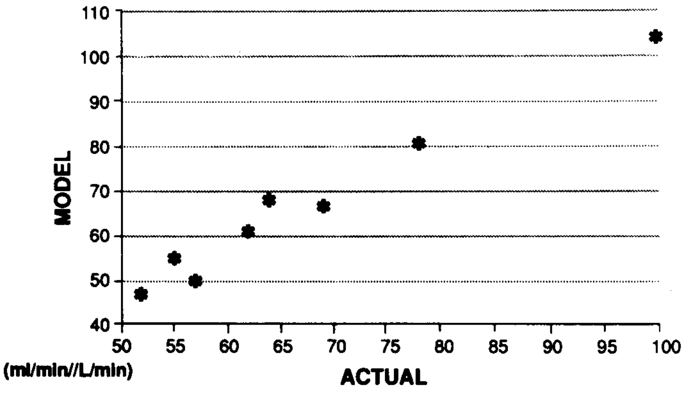
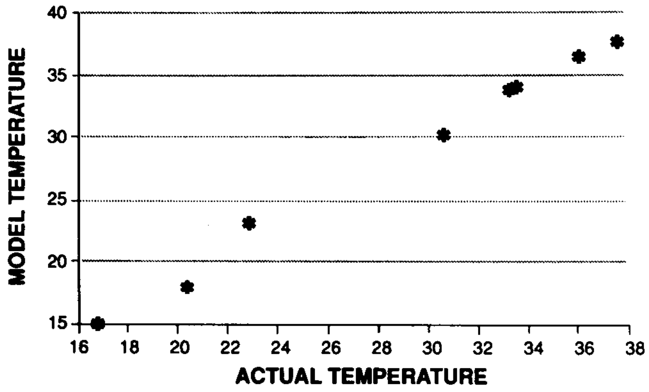


FIGURE 8



could be subject to significant error. To assess the performance of the model of the oxygenator in transferring oxygen, venous saturation, pCO_2, blood flow, gas flow, FIO_2 and temperature were recorded from the 20 patient data base for the American Bentley BOS-CM50 (b). These parameters were directly entered into the model and the pO_2 calculated. This is plotted against the actual patient pO_2 (See Figure 5). The same data was used to calculate the error of O_2 content (See Figure 6). The agreement was generally very good. For flows greater than 5 l/min and saturations less than 65%, the model consistently underestimates the O_2 transfer. There has been insufficient data meeting these criteria to implement a correction. The CO_2 transfer rate was compared to data published by American Bentley (6) as clinical data was unavailable (See Figure 7). The agreement was very good and no corrections are planned. The heat exchanger was evaluated by recording clinical data for cooling and rewarming on venous temperature, heater cooler water temperature, and blood flow. The model calculation of the arterial blood temperature is plotted against the clinical data with exceptionally good results (See Figure 8). The statistical analysis of the relationships can be seen in Table 4.

TABLE 4: Model Performance Summary

Oxygenation:

$pO_{2_{model}} = 86 + 0.90 * pO_{2_{actual}}$ $r = 0.67$ $(p<.01)$

mean O_2 content error = 0.67%

Carbon Dioxide (ml/L/min):

$CO_{2_{model}} = -1.34 + 1.19 * CO_{2_{actual}}$ $r = 0.987$ $(p<.00001)$

mean O_2 content error = -0.014

Temperature:

$TEMP_{model} = -3.5 + 1.11 * TEMP_{actual}$ $r = 0.997$ $(p<.0001)$

mean TEMP error = 0.18°C

The simulation has been used for preclinical practice by eighteen perfusion students. Students had completed 10 weeks of in vivo laboratory experiences before using the simulator. All reported the experience to be realistic in both data presentation and responses and that the experience was beneficial. For nine of the students, the simulator was used for preclinical evaluation of their perfusion skills. It was judged by the evaluator to be an effective tool to create conditions under which student's knowledge and decision making ability could be tested.

Discussion

Many of the processes in which the perfusionist interacts with during surgery can be integrated together into a single comprehensive computer simulation. In addition to the obvious application of student practice and evaluation, the simulator has applications in demonstrating new perfusion components or techniques to experienced perfusionists as well. Advantages of a computer simulation include:

1. Low cost per use
2. Great flexibility in when and where it is used
3. No patient risk
4. No sacrificing of animals
5. The sequence of the simulation can be completely controlled
6. Operation of the simulator can be taken to and beyond lethal limits to learn better responses
7. With sufficient data, virtually any perfusion component can be incorporated for practice

Further development of this simulator will include implementation of a pediatric simulation. Clinical experiences are not available in sufficient numbers to meet the training needs for perfusion students and preclinical practice is more important than for adult cases. An automated perfusion record will be developed with both graphical and tabular results of both monitored and non-monitored parameters to aid both in self assessment and teacher evaluation of students. Data on more types of perfusion components is needed to expand menu choices. Continued development of personal computer processing power, data storage devices, and display technology will greatly expand the potential for subsequent generations of simulators to provide functional non-clinical perfusion experience.

References

1. Riley JB, Winn BA and Hurdle MB. A computer simulation of cardiopulmonary bypass: Version two, *JECT.* 1984; 16: 130-136.
2. Leonard RJ. A total heart/lung bypass simulator. *Trans Am Soc Artil Intern Organs.* 1988; 34: 739-742.
3. Rideout VC. Cardiovascular system simulation in biomedical engineering education. *IEEE Transactions on Biomedical Engineering.* 1972; 3(19): 101-107.
4. McLeod J. Computer simulation of the hydrodynamics of the cardiovascular system. *5th International Conference on Medical Electronics,* Leige, Belgium, July, 1963.
5. Yang SS, Bentivoglio LG, Maranhao V, Goldberg H. *From Cardiac Catheterization to Hemodynamic Parameters.* 1988; 222-225.
6. In-Vitro, Ex-Vivo and In-Vivo Performance Characteristics of the Bentley BOS CM40 and BOS CM50 Capillary Fiber Membrane Oxygenators, American Bentley, 1984.