A Computer Simulation of Cardiopulmonary Bypass: Version Two

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Abstract

The second and more complete version of a computer simulation of CPB is presented. Version Two simulates oxygen transfer, carbon dioxide transfer, and heat transfer.

BASIC computer statements were created to mimic the clinical function of the hollow fiber membrane oxygenator. The oxygenator function curves were created from over 400 clinical oxygenation and carbon dioxide measurements from four institutions. Heat transfer and normal physiological relationships were simultated in computer statements written from well-documented sources. The educational computer program reproduces each step of the heat, oxygen, and carbon dioxide transfer, as well as acid/base and vasomotor status change. The input parameters for the simulation are blood flow, FiO_2, $FiCO_2$, gas sweep rate, mean arterial pressure, hematocrit, and water temperature and are introduced into the computer with control rheostats.

Version Two simulates pathophysiologic events and the effect of an individual control parameter. The simulation provides a cost effective means of providing vital information for medical, allied health, and industrial training and product design.

Introduction

An interactive computer simulation of normothermic total heart-lung bypass for basic education was first presented in 1977.[1] A major re-write of the simulation with substantial improvements in reproducing pathophysiologic events and the effect of individual CPB control parameters is now available.

Version One has proven to be a cost-effective means of providing vital information for perfusionists, allied health professionals, manufacturing salespersons, and cardiovascular product developers. Version One has been improved to better mock clinical situations in regard to oxygen, carbon dioxide, and heat transfer, as well as hemodynamic changes during cardiopulmonary bypass. The simulation has been improved to accurately mock oxygenator performance in response to varying patient demand.

Version Two of the simulation has not been developed to replace the experience gained by doing, but rather as an adjunct to pre-clinical educational preparation of students in extracorporeal technology.[1] The computer simulation of bypass has proven to be a cost and time saving adjunct to perfusion education curricula.

The significant improvements in Version Two fall into two categories, hardware and software. A simulator control box has been developed to allow the hands-on adjustment of bypass control parameters such as blood flow, gas sweep rate, FiO_2, $FiCO_2$, hematocrit, mean arterial pressure, and water temperature. The analog signals from the simulator control box are automatically monitored by the computer system and the computer software responds to the rheostat change. Version Two software accurately simulates each mechanical and physiologic step of heat, oxygen, and CO_2 transfer. The effect of changing systemic vascular resistance on oxygen consumption is available in Version Two.

Method

Figures 1 through 3 depict the CPB simulation logic flow. This simulator oxygen transfer logic mimics the exact physiologic steps for the process of oxygen transfer in artificial blood oxygenators and

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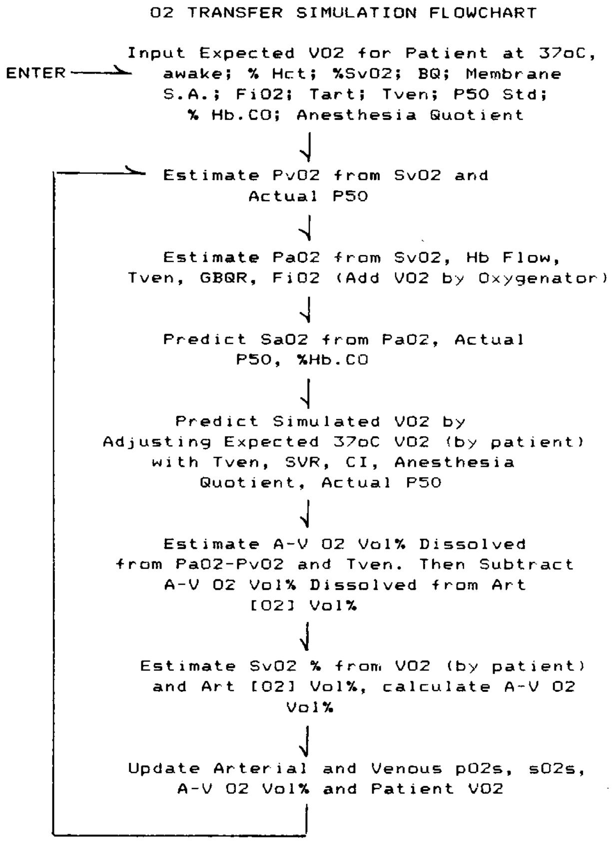

Figure 1: The CPB Simulator logic flowchart for the mechanical and physiologic steps of tissue and artificial lung oxygen transfer.

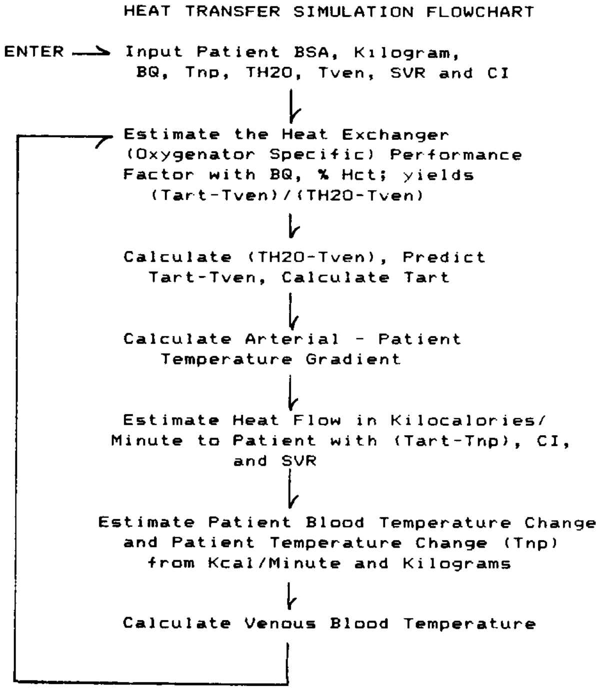

Figure 2: The CPB Simulator logic flowchart for the mechanical and physiologic steps of tissue and heat exchanger heat transfer.

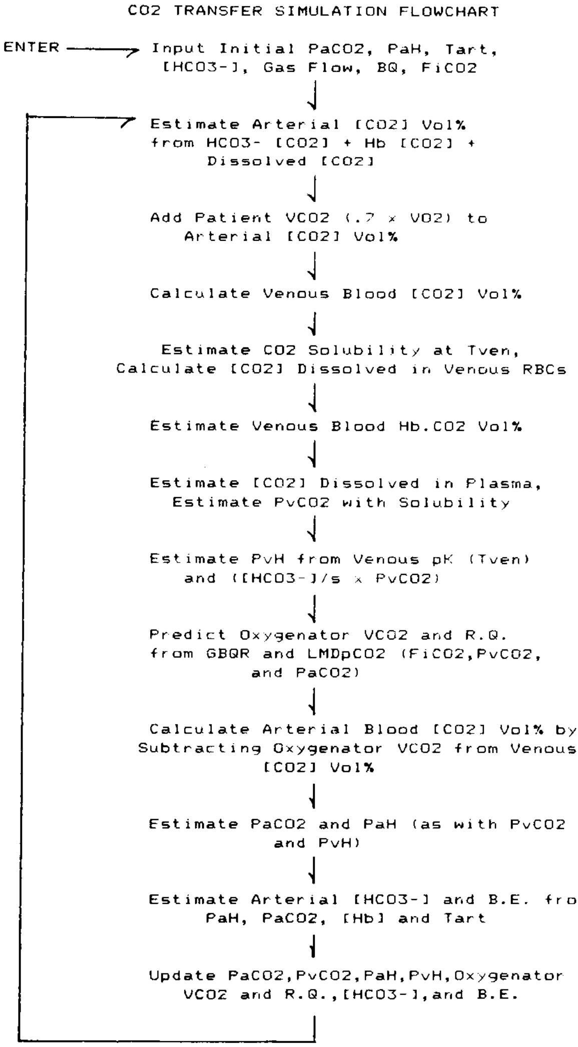

Figure 3: The CPB Simulator logic flowchart for the mechanical and physiologic steps of tissue and artificial blood oxygenator carbon dioxide transfer.

at the tissue level. This simulator accounts for the effects of changes in hemoglobin P_{50}, patient temperature, systemic vascular resistance, cardiac index, and anesthesia neuromuscular blockade levels.[1,3,4,6] Any artificial blood oxygenator may be simulated. Equations to reproduce a specific oxygenator's function are employed to estimate the arterial pO_2 from the venous saturation, hemoglobin flow, temperature and gas to blood flow ratio or FiO_2.[2,5] The arterial saturation is then predicted from the resulting oxygenator PaO_2 employing the actual hemoglobin P_{50} and percentage Hb•CO.[4]

The specific device heat exchanger performance and its interaction with a specific CPB patient may be simulated. The CPB simulation employs an ECC heat exchanger performance factor to predict the change in blood temperature as it traverses the heat exchanger for a given water-blood temperature gradient. The resulting arterial blood temperature is predicted. The heat flow to the simulated patient is estimated employing the blood tissue temperature gradient, cardiac index, and systemic vascular resistance.[10] The heat transfer to the patient is subtracted from the heat in the blood and the patient exit blood temperature is estimated to re-enter the heat exchanger. Obviously, the simulation handles heat flow to or from the heat exchanger.

Simulating carbon dioxide transfer during cardiopulmonary bypass is an extreme technical and theoretical challenge. To accurately simulate CO_2 transfer, the simulation must account for at least three of the four forms in which carbon dioxide is carried in the blood.[7,8]

This simulation predicts changes in blood pCO_2 and pH by quantitating total blood carbon dioxide content and artificial blood oxygenator $\dot{V}CO_2$.[9,11] The patient's tissue $\dot{V}CO_2$ is estimated from the patient $\dot{V}O_2$. Change in arterial and venous pCO_2 and pH are simulated as the student attempts to match the artificial blood oxygenator $\dot{V}CO_2$ to the $\dot{V}CO_2$ of the patient tissue and the carbon dioxide exchange necessary to compensate for change in CO_2 solubility as the blood temperature changes.[11] The effect of cardiac index and systemic vascular resistance on available blood buffers (B.E.) is simulated.

Table 1 lists the CPB simulation initiation inquiry. The parameter values necessary to simulate CO_2 transfer, O_2 transfer, and heat transfer are initially entered into the simulation to mimic a unique patient and artificial blood oxygenator, heat exchanger situation. Aberration in the patient's standard hemoglobin P_{50} and acid/base status prior to bypass may be simulated. Patient CO_2 retention and oxygen debt prior to bypass may be simulated.[11,13]

Table 1

The CPB Simulator initial inquiry of the user to establish the simulated patient's perfusion requirements.

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          CPB SIMULATION INITIALIZATION


Enter the patient B.S.A. in M2?

Enter the patient's VO2 at 37oC in ml/minute?

Enter the HFMO surface area in square meters?

Enter the patient's standard P50 in mmHg?

Enter the patient's %Hb.CO ?

Enter the immediate prebypass PaCO2 and PaH?

Enter the immediate prebypass % SvO2?
```

The CPB simulation is currently implemented on a portable micro-computer with disk drives.[a] A simulator control box[b] has been designed to allow the introduction of varying control parameter values. Table 2 lists the CPB simulator control parameters, the limits and unit of measure that the simulator software will accommodate. As the rheostats are turned, an analog signal is introduced into the portable computer via a uniquely designed analog to digital multiplexing system.[b] Eight CPB control parameters may be singly or simultaneously altered to study the effects on a specific CPB patient.

Table 2

The CPB Simulator control box rheostat parameter labels, limits and units of measure.

CPB SIMULATOR BOX CONTROL RHEOSTATS

PARAMETER	LIMITS	UNIT OF MEASURE
Blood Flow	0 - 7	liters / minute
Gas Sweep Rate	0 - 20.	liters / minute
Water Temperature	5 - 45.	oC
FiO2	20 - 100	Fraction
FiCO2	0 - 20	Fraction
mABP	0 - 150	mmHg
Anes/Muscle Block	1 - 10	Arbitrary Unit
Hematocrit	10 - 40	%

Results

A series of the portable computer monitor displays and subsequent update displays are presented in the text. The example displays are referenced to simulated CPB elapsed time (E.T.). The CPB simulation example displays include arterial and venous blood gases and pH, arterial and venous percent saturation of hemoglobin, arterial bicarbonate concentration and base excess, and hematocrit. The patient's actual Hemoglobin P_{50} is estimated and displayed. Various blood, water, and patient temperatures are displayed. Hemodynamic information, ventilation control parameters, and gas transfer estimates are presented. Systemic vascular resistance (SVR) has the units dynes × seconds × centimeters^{-5}/m^2. A.Q. is an arbitrary anesthesia quotient where 1 is extremely anesthetically light with very little neuromuscular blockade in the simulated patient. R.Q. is the oxygenator respiratory quotient; $\dot{V}CO_2$ divided by

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a. Otrona Advanced Systems Corp., Boulder, CO 80301
b. Extracorporeal Technologies, Inc., Indianapolis, IN 46268

$\dot{V}O_2$. The arterio-venous O_2 volumes percent is also presented at the display.

The example display updates found herein are for a patient that is 2.1 m^2, has an initial $\dot{V}O_2$ at 37° C equal to 275 ml O_2/min, and an immediate pre-bypass $PaCO_2$ equal to 39, PaH equal to 7.38 mixed venous O_2 saturation of hemoglobin equal to 65%, and a standard P_{50} equal to 26mmHg. To scan the example displays, the student operating the simulation initiated bypass with a water temperature at 36° C and decreased the water temperature to 25° C between 5 and 7 minutes E.T. The simulation estimates the effect of rapid cooling and the simulator operator has chosen not to alter gas flow, blood flow, FiO_2, $FiCO_2$ or mean arterial blood pressure. The software accurately simulates the usual respiratory alkalosis that accompanies maintaining a constant oxygenator ventilation rate during rapid cooling. The arterial blood pO_2 rises and the arterial blood pCO_2 decreases as the patient's oxygen uptake decreases with decreasing temperature. The perfusionist continues to employ an euthermic ventilation rate with resulting high oxygenator $\dot{V}CO_2$s. The result is loss of blood CO_2 content and declining arterial blood pCO_2 at 20 minutes E.T. Between 20 and 30 minutes E.T., the perfusionist decreases oxygenator gas to blood flow ratio and FiO_2. The water temperature is changed to 28° C. The result is a lower $\dot{V}CO_2$ and a stabilization of the arterial blood pCO_2. Blood flow was increased in response to the low venous pO_2 and loss of bicarbonate.

The simulation depicts the left shift of the oxyhemoglobin curve (decreasing hemoglobin P_{50} as hypothermia and respiratory alkalosis progress. The simulated hemoglobin P_{50} dropped from 24.5 mmHg at 36° C to 10.7 mmHg at 28° C.

Water temperature is increased to 38° C between 30 and 45 minutes E.T. In the next 21 minutes of simulated bypass, the patient temperature returns to 36.2° C. The arterial blood pCO_2 rises rapidly to 45 mmHg, the base excess rebounds to low normal values, and the patient's oxygen consumption increases. The arterial blood pCO_2 rises rapidly eventhough the oxygenator respiratory quotient is close to 1. The pCO_2 increase is an example of the effect of decreasing carbon dioxide solubility as the blood is warmed, though the oxygenator $\dot{V}CO_2$ simulated is similar to the $\dot{V}O_2$.

Discussion

Version Two of the cardiopulmonary bypass computer simulation is more effective than Version One in simulating physiologic CPB events as well as pathophysiologic situations. Aberrations in hemoglobin P_{50} the effect of changing SVR on oxygen transfer, the effect of acid/base changes on hemoglobin P_{50} and the effect of hemoglobin P_{50} in oxygen transport may all be simulated in Version Two software. Additionally, anesthesia neuromuscular blockade effect on oxygen transfer may be simulated.

Version Two of the CPB simulation has proven to be a valuable adjunct to perfusion technology student training. The hardware and software minimizes the expense of hands-on consistent ECC training experience. The simulator box and software allows a student to study the total effect of simultaneous or single variable changes.

Additionally, the simulation may aid cardiovascular device manufacturers in industrial training and product design. Manufacturer representatives may reproduce clinical situations. Finally, theoretical questions such as, "How much hollow fiber membrane surface area is just enough for a certain patient?", may be addressed with this software. Device modifications that result in measurable performance change may be theoretically tested to establish the feasibility of beginning animal or human trials.

```
        ARTERIAL                        VENOUS
PaO2=212                        PvO2=40
SaO2=99.3                       SvO2=74.4
PaCO2=37                        PvCO2=44
PaH=7.36                        B.E.=-4.4
|HCO3-|=21.2                    P50=24.6
Hct %=24

       Temperatures:
Arterial=35.5                   Venous=35.3
Water=36.0                      Patient=35.0

     Related Information:
Blood Flow=4.7                  Cardiac Index=2.24
Gas Flow=3.0                    G:BQR=.64
FiO2=88                         FiCO2=0
mABP=77                         mCVP=0
A.Q.=3                          SVR=624
VO2=158.5                       VCO2=265
R.Q.=1.67                       A-V 02=3.37
```

CPB SIMULATION DISPLAY UPDATE
E.T.=3 Minutes

```
       ARTERIAL                VENOUS
PaO2=186                 PvO2=36
SaO2=99.2                SvO2=73.2
PaCO2=33                 PvCO2=37
PaH=7.38                 B.E.=−5.2
|HCO3−|=19.9             P50=24.0
Hct %=24

     Temperatures:
Arterial=35.7            Venous=35.5
Water=36.0               Patient=35.2

   Related Information:
Blood Flow=4.7           Cardiac Index=2.24
Gas Flow=3.0             G:BQR=.64
FiO2=88                  FiCO2=0
mABP=77                  mCVP=0
A.Q.=3                   SVR=624
VO2=161.2                VCO2=233
R.Q.=1.44                A-V O2=3.4

        CPB SIMULATION DISPLAY UPDATE
              E.T.=5 Minutes
```

```
       ARTERIAL                VENOUS
PaO2=203                 PvO2=29
SaO2=99.5                SvO2=82.0
PaCO2=28                 PvCO2=31
PaH=7.42                 B.E.=−5.9
|HCO3−|=18.8             P50=17.6

     Temperatures:
Arterial=27.8            Venous=30.4
Water=25.0               Patient=32.9

   Related Information:
Blood Flow=4.7           Cardiac Index=2.24
Gas Flow=3.0             G:BQR=.64
FiO2=88                  FiCO2=0
mABP=77                  mCVP=0
A.Q.=3                   SVR=624
VO2=120.2                VCO2=221
R.Q.=1.84                A-V O2=2.56

        CPB SIMULATION DISPLAY UPDATE
              E.T.=7 Minutes
```

```
       ARTERIAL                VENOUS
PaO2=254                 PvO2=30
SaO2=99.5                SvO2=90.3
PaCO2=23                 PvCO2=25
PaH=7.47                 B.E.=−6.5
|HCO3−|=24

     Temperatures:
Arterial=27.1            Venous=29.1
Water=25.0               Patient=31.0

   Related Information:
Blood Flow=4.7           Cardiac Index=2.24
Gas Flow=3.0             G:BQR=.64
FiO2=88                  FiCO2=0
mABP=77                  mCVP=0
A.Q.=3                   SVR=624
VO2=85.7                 VCO2=228
R.Q.=2.66                A-V O2=1.82

        CPB SIMULATION DISPLAY UPDATE
              E.T.=9 Minutes
```

```
       ARTERIAL                VENOUS
PaO2=298                 PvO2=32
SaO2=99.6                SvO2=95.6
PaCO2=19                 PvCO2=22
PaH=7.52                 B.E.=−6.8
|HCO3−|=17.5             P50=11.0
Hct %=24

     Temperatures:
Arterial=26.6            Venous=28.1
Water=25.0               Patient=29.6

   Related Information:
Blood Flow=4.7           Cardiac Index=2.24
Gas Flow=3.0             G:BQR=.64
FiO2=88                  FiCO2=0
mABP=77                  mCVP=0
A.Q.=3                   SVR=624
VO2=63.1                 VCO2=190
R.Q.=3.01                A-V O2=1.34

        CPB SIMULATION DISPLAY UPDATE
              E.T.=11 Minutes
```

```
       ARTERIAL                     VENOUS
PaO2=199                    PvO2=30
SaO2=99.6                   SvO2=93.9
PaCO2=22                    PvCO2=23
PaH=7.48                    B.E.=-7.0
|HCO3-|=18.0                P50=10.7

     Temperatures:
Arterial=26.4               Venous=27.5
Water=25.0                  Patient=28.4

   Related Information:
Blood Flow=5.0              Cardiac Index=2.38
Gas Flow=1.4                G:BQR=.28
FiO2=60                     FiCO2=0
mABP=60                     mCVP=0
A.Q.=3                      SVR=457
VO2=63.3                    VCO2=90.8
R.Q.=1.43                   A-V O2=1.27
```

CPB SIMULATION DISPLAY UPDATE
E.T.=20 Minutes

```
       ARTERIAL                     VENOUS
PaO2=162                    PvO2=34
SaO2=99.6                   SvO2=92.0
PaCO2=26                    PvCO2=28
PaH=7.42                    B.E.=-7.8
|HCO3-|=18.7                P50=13.3
Hct %=24

     Temperatures:
Arterial=28.1               Venous=28.1
Water=28.0                  Patient=28.1

   Related Information:
Blood Flow=5.0              Cardiac Index=2.38
Gas Flow=1.4                G:BQR=.28
FiO2=50                     FiCO2=0
mABP=50                     mCVP=0
A.Q.=3                      SVR=381
VO2=67.7                    VCO2=60.0
R.Q.=.89                    A-V O2=1.33
```

CPB SIMULATION DISPLAY UPDATE
E.T.=30 Minutes

```
       ARTERIAL                     VENOUS
PaO2=153                    PvO2=41
SaO2=99.3                   SvO2=85.7
PaCO2=34                    PvCO2=35
PaH=7.40                    B.E.=-4.1
|HCO3-|=22.1                P50=19.2
Hct %=24

     Temperatures:
Arterial=34.5               Venous=32.4
Water=38.0                  Patient=30.6

   Related Information:
Blood Flow=5.0              Cardiac Index=2.38
Gas Flow=1.4                G:BQR=.28
FiO2=50                     FiCO2=0
mABP=50                     mCVP=0
A.Q.=3                      SVR=381
VO2=97.6                    VCO2=90.9
R.Q.=.93                    A-V O2=1.95
```

CPB SIMULATION DISPLAY UPDATE
E.T.=45 Minutes

```
       ARTERIAL                     VENOUS
PaO2=121                    PvO2=42
SaO2=98.3                   SvO2=74.8
PaCO2=44                    PvCO2=45
PaH=7.31                    B.E.=-4.6
|HCO3-|=22.1                P50=25.8
Hct %=24

     Temperatures:
Arterial=37.3               Venous=35.1
Water=40.0                  Patient=33.5

   Related Information:
Blood Flow=5.0              Cardiac Index=2.38
Gas Flow=1.4                G:BQR=.28
FiO2=50                     FiCO2=0
mABP=50                     mCVP=0
A.Q.=3                      SVR=381
VO2=147                     VCO2=150.2
R.Q.=1.02                   A-V O2=2.94
```

CPB SIMULATION DISPLAY UPDATE
E.T.=56 Minutes

ARTERIAL	VENOUS
PaO2=130	PvO2=38
SaO2=98.3	SvO2=65.8
PaCO2=45	PvCO2=47
PaH=7.33	B.E.=−2.5
[HCO3−]=23.9	P50=25.8
Hct %=24	
Temperatures:	
Arterial=38.4	Venous=37.1
Water=40.0	Patient=36.2
Related Information:	
Blood Flow=5.0	Cardiac Index=2.38
Gas Flow=4.0	G:BQR=.80
FiO2=75	FiCO2=0
mABP=50	mCVP=0
A.Q.=5	SVR=381
VO2=198.9	VCO2=267.2
R.Q.=1.34	A-V O2=3.98

CPB SIMULATION DISPLAY UPDATE
E.T.=66 Minutes

References

1. Riley, J.B. and O'Kane, K.C.: A computer simulation of maintaining total heart lung bypass for basic education. *JECT*, Proceedings, 1977, p. 42-49.
2. Riley, J.B., Jallad, M.S., Winn, B.A., and Hurdle, M.B.: Recommended ventilation technique for the microporous hollow fiber membrane blood oxygenator. *Proceedings, American Academy of Cardiovascular Perfusion*, January 22, 1984, New Orleans, LA.
3. Riley, J.B. and Palmer-Steele, C.L.: Hemoglobin P50 dynamics during hypothermic cardiopulmonary bypass. *JECT*, 15: 167-170, 1983.
4. Severinghaus, J.W.: Simple accurate equations for human blood O_2 dissociation computations. *J. Appl Physiol.* 34: 599, 1979.
5. Riley, J.B. Walker, C.T., Kauffman, J.N., Rigatti, R.L., Young, M.R., and Daly, W.L.: Prediction of minimal ventilation requirements for oxygenation in a bubble and membrane blood oxygenator during cardiopulmonary bypass. *JECT*, 13: 256, 1981.
6. Riley, J.B., Heineman, O., and Cavanaugh, D.S.: Technique to give relevance to calculated oxygen transfer during cardiopulmonary bypass. *JECT*, 15: 35-40, 1983.
7. "In vivo and In Vitro Carbon Dioxide Dissociation" found in *Respiration and Circulation*, Ed. Altman, P.L. and Dittmer, D.S., F.A.S.E.B., Bethesda, MD, 210-226, 1971.
8. Davenport, H.W.: *The ABC of Acid-Base Chemistry*, 6th Edition, Chicago and London: University of Chicago Press, 1974, pp. 22-49.
9. Snider, M.T., Richardson, P.D., Friedman, L.T., Galletti, P.M.: Carbon dioxide transfer in artificial lungs. *J. Appl. Physiol.* 36: 233-239, 1979.
10. Riley, J.B. and Winn, B.A.: In Vitro analysis of extracorporeal blood heat exchange devices. *JECT*, 9: 134, 1977.
11. Riley, J.B., Justison, G.A.: Alpha-Stat and pH-Stat Management, Techniques in Artificial Blood Oxygenators. *JECT*, 16: 77-78, 1984.
12. Personal communication Richard Crowley, "High dose versus low dose fentanyl, SVR effect on VO_2." January 15, 1984.
13. Riley, J.B., Young, M.R., Rigatti, R.L., and Kauffman, J.N.: Reversal of inconsequential low arterial blood pO_2 at the initiation of hypothermic cardiopulmonary bypass. 7th Annual Meeting of the Scandinavian Society for Extracorporeal Technology, November 11, 1982, Copenhagen, Denmark.