At the 1980 AmSECT Conference in Philadelphia, members and participants were treated to a special presentation by Tom Hankins. The audience was struck by Mr. Hankins' pictures of a Tandy Corporation computer, disc-drive, printer, and keyboard sitting on a plastic shelf above the pump suckers on his heart-lung machine. Imagine the audience response to his slides.

In reading the paper and talking to Mr. Hankins, his objective for this communication was simple, to present "...a more precise controlled method of perfusion" using a pumpside microcomputer system. He randomly selected 70 patients and assigned them to either a conventional perfusion protocol or to a computer-assisted protocol. The computer-assisted group protocol had criteria limits set for the computer-calculated parameters and specific blood flow or pharmacologic responses for the perfusionist based on the calculated values.

While one might argue today that Hankins’ protocol was biased toward more successful perfusion outcomes in the computer-assisted group, we have to remember that in 1980 perfusion by protocol not including calculated parameters like SVR was common. Mr. Hankins demonstrated in 1980 that having computer calculations pumpside and a disciplined protocol for vasoactive drugs and maintaining blood flow could improve markers of adequate perfusion.

It is ironic to read statements in the 1980 JECT like "monitoring critically ill patients with the aid of a computer has been explored for more that a decade". Here we are more than two decades later and we are just starting to get serious as a profession in regard to adopting computer-assisted bypass as a standard of care because of quality and safety national mandates (see AmSECT Today, March 2004, p. 6). Hankins and his coworkers later published a 1998 follow-up article: “Evolution of a cardiovascular information system” (JECT 1998, 30(1): 42–45).

Hankins’ 1980 article is a JECT classic that helped to show us early that we can improve our pump-side decision making with the aid of a computer. Hankins’ 1980 JECT protocol design is a starting place for future studies to test the value of computer-aided perfusion. Perhaps with the advantage of hindsight, as a profession we should have learned more from Hankins’ 1980 communication and others like it?

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Computer Assisted Bypass Management

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Introduction

In order to improve the perfusion during cardiopulmonary bypass from a condition of controlled shock to as normal as possible, there must be a more precisely controlled method of perfusion. Subjective or empirical criteria used as a means of management often places a patient in a condition which, through better perfusion management, could otherwise be avoided. Physiological events occurring within the patient, such as increased resistances, lactic acid production, etc., may also go unnoticed due to lack of sufficient data for objective evaluation.

During cardiopulmonary bypass, patients undergo changes in temperature, depth of anesthesia, blood pressure, blood flow, urine output, hemodilution, and biochemical components. The parameters by which most perfusionists determine adequate perfusion are: 1) mean arterial pressure; 2) arterial blood gases; 3) blood flow; and 4) urine output. These few parameters have long been the standard of perfusion adequacy. The perfusion may be judged adequate by these parameters alone, but is it as optimal as possible? Due to ever changing conditions of the patient, other parameters such as: 1) venous blood gases; 2) resistances; 3) oxygen consumption indices; and 4) lactic acid levels, should also be continuously monitored, evaluated, corrected, and re-evaluated.

In order to properly monitor and evaluate all of these variables quickly and efficiently, a microcomputer system was utilized on-pumpside. The application of a microcomputer for patient management during bypass is particularly advantageous for the perfusionist, in that it permits quick storage and retrieval of large bits of data far beyond the data base of programmable calculators. The computer's ability to analyze large numbers of variables quickly and efficiently and to provide new means for improved decision making and patient management during cardiopulmonary bypass will be described in this paper.

Materials and Methods

The microcomputer system used is a TRS-80 LEVEL II 32K* memory system. The system is comprised of: 1) keyboard or central processing unit (CPU) (Fig. 1); 2) memory interface unit (Fig. 2); 3) cathode ray tube (Fig. 3); 4) magnetic disc drives (Fig. 4); and 5) tractor feed printer (Fig. 5). This system allows for 32,000 bytes of RAM (read and access memory) and each floppy diskette (Fig. 6) has a storage space of about 55,000 bytes of memory. This system affords a total address of about 142,000 bytes of access and storage memory. The computer language used is BASIC. The program utilized was developed by the author.

Sixteen different options of parameter data (Fig. 7) either annotated (Fig. 8), simple calculations (Fig. 9), or trend analysis (Fig. 10) are programmed for selection during bypass. Each of these options can, at the perfusionist's discretion, be selected and repeated.
throughout bypass. They are comprised of the following: 1) PRE-BYPASS DATA (date, name, ID#, sex, age, race, height, weight, body surface area, blood volume, surgeon, assistant, anesthesiologist, perfusionist, assistant, type case, priming solutions, total priming volume, heparin dosage, final dilution hematocrit, sodium, potassium, calcium, glucose); 2) INITIAL BYPASS DATA (maximum flow, minimum flow, mean arterial pressure, mean pulmonary artery pressure, central venous pressure); 3) POST-
BYPASS DATA (time off bypass, cross clamp time, total heparin dose, protamine dose, total urine output, average urine output cc/min, number of grafts, medications, blood given, total fluid to pump, blood loss, patient fluid balance); 4) BLOOD GAS TEMPERATURE CORRECTION; 5) BLOOD GASES-BYPASS (arterial-venous: pH, PO₂, PCO₂, HCO₃⁻, base deficit, O₂ saturation, O₂ content); 6) HEMATOCRIT CORRECTION FACTOR; 7) BLOOD CHEMISTRY AND HEMATOLOGICAL DATA (hemoglobin, hematocrit, sodium, potassium, calcium, glucose, blood urea nitrogen, arterial and venous lactic acid); 8) MEDICATIONS (NaHCO₃, mannitol, albumin, lasix, lidocaine, pancuronium, heparin, plasmalyte 148, potassium, calcium, packed cells, whole blood, total medications); 9) PERIPHERAL RESISTANCE; 10) SYSTEMIC VASCULAR RESISTANCE; 11) OXYGEN INDEX (oxygen consumption, arterial-venous oxygen content difference, tissue oxygen extraction index, red blood cell flow); 12) OXYGEN NEEDS (oxygen need, oxygen factor, optimal flow); 13) CARDIAC INDEX (L/min, cc/min, cc/kg/min, L/min/m²); 14) BLOOD PRESSURES (systolic arterial, mean arterial, diastolic arterial, systolic pulmonary artery, mean pulmonary artery, diastolic pulmonary artery, central venous pressure); 15) TEMPERATURES (esophageal, rectal, myocardial, arterial reservoir, venous reservoir); and 16) URINE OUTPUT (total output cc’s, average output cc’s/min).

In a comparative study of 70 patients randomly selected from a population of those undergoing coronary artery bypass, 35 patients were perfused using conventional parameters and methodology (GROUP I) and 35 patients were perfused using computer assistance (GROUP II). Demographic variables were measured to determine group differences with regard to age, weight, body surface area, number of vessels

**FIGURE 7.** Example of 16 different parameter options available to perfusionist.

**FIGURE 8.** Annotated comments during blood gas data recording making simple suggestions for correcting present condition.

**FIGURE 9.** Simple calculation for peripheral resistance with only three data entries.

**FIGURE 10.** Trend analysis on a 30 minute time basis for evaluation of esophageal temperature pattern.
grafted and bypass time. Statistical analysis was done using Fisher's Omnibus test. This procedure combines the "t"-test and the "F"-test to determine if the groups differed with respect to means and/or variances.

Perfusion in Group I was managed in the following manner: 1) blood flow was decreased as mean arterial pressure increased, in order to maintain an arterial pressure below an empirically set maximum mean pressure of 80 mmHg; 2) gas flow was adjusted accordingly to maintain an arterial PO2 within the range of 200 to 250 mmHg; 3) there was no intervention with vasodilators or vasoconstrictors. Parameter measurements evaluated and recorded for Group I at 10 minute intervals were: 1) temperatures (esophageal, rectal, myocardial, arterial reservoir, venous reservoir); 2) pressures (mean arterial, mean pulmonary artery, central venous pressure); 3) flow (L/min, cc/min, cc/kg/min, L/min/m2); 4) peripheral resistance; and 5) systemic vascular resistance. Parameter measurements at 20 minute intervals were: 1) arterial and venous blood gases (pH, PO2, PCO2, HCO3, base deficit, O2 saturation); 2) oxygen consumption; 3) arterial-venous oxygen content difference; 4) tissue oxygen extraction index; 5) red cell flow; 6) oxygen needs; and 7) electrolytes (sodium and potassium). The computer was used to calculate the monitored parameters.

A crystalloid prime consisting of: 1) 2,000 cc PlasmaLyte 148; and 2) 50 cc Mannitol; 12.5 gm/50 cc was used in both groups. All patients in Groups I and II had blood flow parameters calculated at a minimum of 2.0 L/min/m2 and a maximum of 2.4 L/min/m2. However, Group I had instances where flows were lowered below the minimum flow in order to compensate for increasing mean arterial pressures. Hematocrits for both groups averaged 24 ± 1.7 volumes % and all patients were perfused at 28 C.

Results

Demographic data of Group I and Group II for age, weight, body surface area, number of grafts and bypass time, as seen in Table I, were closely matched and there was no significant difference (p > .05) between the two groups. Resistances during hypothermia were found to start increasing to the point necessary for pharmacological intervention with vasodilators at roughly 20 minutes into bypass for Group II. Mean peripheral resistance for Group II was 40.6% higher than Group II and 16% above the normal range. However, mean resistance in Group II was in the normal range. Statistical difference was p < .0001 (Fig. 11). Mean systemic vascular resistance for Group I was 36.9% higher than Group II and 33.0% above the normal range. Group II was within the normal range. Statistical difference was p < .0001 (Fig. 12).
Mean oxygen consumption index for Group I was 33.1% higher than Group II and averaged 100.5 cc/min/m². Group II averaged 75.5 cc/min/m². Statistical difference was p < .00001 (Fig. 13). Mean tissue oxygen extraction index for Group I was 143.2% higher than Group II and averaged .0793 cc/min/m². Group I mean tissue oxygen extraction index rose more sharply and quickly than Group II during rewarming.

**FIGURE 11.** Peripheral resistance comparison shows Group I averaged 1.28 ± 0.2 units which was 16.0% above the normal range and 46.9% above Group II. Group II averaged 0.91 ± 1 units. The normal range for peripheral resistance is 0.9 ± 1.1 units.

**FIGURE 12.** Systemic vascular resistance comparison shows Group I averaged 3299.97 ± 640.1 dyne-sec/cm²/m², which was 33.1% above the normal range and 36.9% above Group II. Group II averaged 2409.57 ± 235.0 and was only 0.8% above the normal range. The normal range for systemic vascular resistance is 1970.00 ± 2350.00 dyne-sec/cm²/m².

**FIGURE 13.** Oxygen consumption comparison shows Group I averaged 100.5 ± 28.0 cc/min/m² and was 33.1% higher than Group II. Group II averaged 75.5 ± 19.4 cc/min/m². The normal range for oxygen consumption is 142 ± 8 cc/min/m².

**FIGURE 14.** Tissue oxygen extraction index comparison shows Group I averaged .0793 ± .02 cc/min/m² and was 143.2% higher than Group II. Group II averaged .0326 ± .008 cc/min/m². This index, in conjunction with oxygen consumption and arterial-venous oxygen content difference, is felt to be a very integral indicator of the adequacy of perfusion and oxygen debt.
Mean urinary output for Group I was 28.7% lower than Group II and averaged 937.7 cc/patient or 7.3 cc/min. Group II averaged 1315.7 cc/patient or 13.0 cc/min. Statistical difference was p < .0003 (Fig. 16).

Group I mean perfusion blood flows were significantly (p < .0001) lower than the minimum calculated flow due to increased mean arterial pressure. This produced an associated demand and administration of sodium bicarbonate. Group I required an average of 4 mEq/l/hour of sodium bicarbonate, while Group II required no sodium bicarbonate. Our indication for administration of sodium bicarbonate was a base excess greater than -3.0 with an associated low HCO₃ level (20 or below). Group I bicarbonate demand, in conjunction with the overall increases in resistances, oxygen consumption indices and lowered urine output, suggest that pharmacological control rather than mechanical should have been used to lower pressure and maintain as optimal perfusion and oxygen delivery as possible.

Discussion

Monitoring of critically ill patients with the aid of a computer has been explored for more than a decade. The management of critically ill patients in the post-operative period has also been described. Using the computer as a real-time clinical tool, multiple parameters can quickly and efficiently be evaluated and subsequent pharmacological or mechanical intervention instituted. Other computer advantages are: 1) one does not need to keep a handwritten record at the pump; 2) the records are printed on fan-fold paper for easy book binding; 3) the entire case information is stored on the magnetic diskettes; and 4) data retrieval for review and statistical analysis is simple and less time consuming because disc files can be made according to type case, complications, etc. Since implementing the computer for use during cardiopulmonary bypass: 1) flows have not dropped below the minimum calculated flow of 2.4 L/min/m²; 3) peripheral resistances and systemic vascular resistances have remained within or close to the normal range; 4) oxygen consumption has averaged between 70 and 80 cc/min/m²; 5) urine output has increased; 6) use of vasodilators has increased; and 7) most important, no sodium bicarbonate has been required. Most calculations using the computer, including keyboard entry and data storage, take less than 10 seconds before the data appears on the
screen and is simultaneously printed on paper. This is an advantage for the perfusionist, as it diverts attention from the oxygenator for only a few seconds. During a 90 minute bypass procedure, this would amount to an average of 7.5 minutes. This would include keyboard, data retrieval, storage and record printing time or 8% of the total bypass time.

In evaluating the need for a computer for use during cardiopulmonary bypass, an important consideration other than patient and data management is cost. The cost of a microcomputer system for perfusion purposes can run from $1,000 to $25,000 depending on how much data one demands and what type of records are to be kept. The more accessible memory needed, the more expensive the system will be. The system used in this study cost $4,000. In this “age of computers,” a possibility for those seriously considering using a computer, but who are limited in funds, is the hospital’s data processing department computer. It is easy to purchase a reasonably inexpensive “dumb” terminal and interface it with the main computer in data processing. In this manner one can “time share” and have access to a relatively vast memory in comparison to the actual memory needed and without a large outlay of equipment funds. The approach of time sharing is, however, not without its own problems. Often when one time shares, due to heavy demand on the central memory core, the response time from entry to acquisition of data can take up to 90 seconds or more. Also, there is a large amount of down time associated with time sharing systems. Therefore, one must carefully consider these points when taking the time sharing approach.

The single most important consideration and probably the biggest disadvantage to a computer system is software. Software is the language that instructs the computer as to its method of execution. Unless one is capable of writing programs, programming assistance must be utilized. If the aid of a computer programmer is enlisted, one can expect to pay an average of $20 per hour for program development.

Conclusion

After careful review of perfusion methodology, hemodynamic mechanisms and pharmacological support, it is our firm belief that computer evaluated data rather than subjective or empirical criteria can best be utilized for the maximum physiological management of patients. Computer assistance allows accurate, quantitative evaluation of the patients as well as decision making regarding treatment either by pharmacological or mechanical intervention during cardiopulmonary bypass.

References


