Programmable Calculators and Cardiopulmonary Bypass

Eric A. Rose, M.D.; Susan M. Haubert, R. N., C.C.P.; and Henry M. Spotnitz*, M.D.

From the Cardiovascular Surgery Research Laboratory, Columbia University College of Physicians and Surgeons, New York, New York

INTRODUCTION

Technical and therapeutic advances have continuously improved the safety and broadened the applications of cardiopulmonary bypass. Coupled with these advances has been an increase in the number and complexity of arithmetic calculations required for clinical extracorporeal circulation.

In most cardiac surgical centers the majority of these critical calculations are done by hand. These calculations increase the workload of operating room personnel. In addition, they increase the likelihood of computational errors which may have serious consequences. Therefore, we have examined incorporation of programmable calculators into the routine of repetitive calculations required for current methods of cardiopulmonary bypass.

All programs to be described for use during cardiac surgery were written on magnetic cards for the Texas Instruments TI-59 programmable calculator equipped with a PC-100A thermal printer (Figure 1.) The device is commercially available for approximately $400.00. Copies of the program can be reproduced on blank magnetic cards by the calculator at a cost of less than $0.50 each. After insertion of the magnetic program cards, the user is prompted to enter the data required for the desired computations in correct sequence. All data entries are printed, allowing immediate confirmation of their accuracy. Results for each computation are printed with labels for the appropriate units within seconds of completion of data entry.

Programs have been developed and clinically applied for calculation of:

1) Body surface area and pump flow for bypass based on patient height and weight.

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Address for reprints: Henry M. Spotnitz, M.D., Department of Surgery, 630 W. 8th Street, New York, New York 10032
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2) Heparin anticoagulation and protamine reversal for cardiopulmonary bypass using the Bull\textsuperscript{1} protocol, based on activated clotting time (ACT).

3) Drip rates and drug dilutions for drugs to be administered by continuous infusion.

**CALCULATION OF BODY SURFACE AREA AND PUMP FLOW**

Body surface area can be calculated from patient body weight and height using the formula:

$$
\log A = 0.425 \log W + 0.725 \log H + 1.8564
$$

where $A$ is body surface area in square meters, $W$ is body weight in kilograms, and $H$ is height in centimeters\textsuperscript{2}. This formula is the basis for standard body surface area nomograms.

Our program (Figure 2) prompts the user to enter body weight and height and calculates and prints body surface area using the above equation. The user may elect to enter body weight in pounds or kilograms and may enter height in centimeters or inches. Regardless of the units of entry of weight or height, body surface area is calculated in units of square meters. In addition, estimated pump flow for cardiopulmonary bypass
is calculated and printed automatically using the formula:

\[ F = A \times 2.3 \]

where \( F \) is pump flow in liters per minute and \( A \) is the previously calculated body surface area in square meters.

**ANTICOAGULATION PROGRAM**

Bull\(^1\) has described a protocol for heparin anticoagulation based on correlation of increases in the activated clotting time (ACT) with sequential heparin doses in individual patients. Unlike most clinical protocols, heparin doses are not based solely on patient body weight or surface area, and supplemental heparin doses for prolonged bypasses are not administered at fixed arbitrary time intervals. Instead, Bull's method compensates for variation between patients in sensitivity to the anticoagulant action of heparin and the duration of action\(^3\). Despite the important theoretical advantages of this protocol, many cardiac surgeons and perfusionists have found it mathematically complicated and time consuming. Execution of the Bull protocol with a programmable calculator, however, makes the technique clinically feasible and efficient.

Insertion of the program cards into the calculator readies it for the protocol. All activated clotting time (ACT) determinations are made by automated technique with the Model 800 Hemochron Blood Coagulation Timer (International Technidyne, Met-
Figure 4. Data base for calculations during bypass, based on linear regression of three data points determined during initial anticoagulation to 480 second ACT. It is assumed that no heparin is metabolized, excreted, or distributed from the intravascular space during initial data acquisition. Review of the printed record prevents errors during perfusion. A correlation coefficient (R) greater than 0.95 between ACT and TCH is our criterion for acceptability of the initial observations.

**DATA BASE**

ENTER BASELINE ACT 119. SEC
ENTER 1ST HEP DOSE (MGS OR MG/SQ.M.) 120.
ENTER ACT AT 5 MIN. 279. SEC
ENTER 2ND HEP DOSE (MGS OR MG/SQ.M.) 150.
ENTER ACT AFTER 2ND HEP DOSE 451. SEC

\[ R = 0.999 \]

Figure 5. Prediction of additional heparin requirements during bypass using the data base illustrated in Figure 4 and linear regression program. 86 mg is the predicted heparin dose to increase the ACT from 374 to 480 seconds, based on the slope of the regression line.

ENTER OBSERVED ACT 451. SEC

**FOR PROT DOSE**

PROT DOSE IS 346.77 (MGS OR MG/SQ.M.)

**FOR DRIP DOSE**

(MCG/KG/MIN)

ENTER PTS. WT. (KG) 63.
ENTER SOLN VOL. (CCS) 250.
ENTER DRUG WT. (MG) 200.
ENTER MICRODROPS /MIN 24.

DRIP DOSE IS 5.08 MCG/KG/MIN

Figure 6. Protamine requirements are calculated from the initial data base and the estimated circulating heparin level based on the ACT at the conclusion of bypass. Protamine in mg = Estimated Total Circulating Heparin x 1.3.

Figure 7. Calculation of rate of drug administration from entry of patient weight, drug weight and dilution volume, and microdrops per minute infusion rate.
uchon, New Jersey). All samples for ACT determinations are drawn from the right atrium prior to bypass and from the venous return line of the pump oxygenator during bypass. Program card insertion and calculator data entry are done by the perfusionist.

After a baseline ACT determination, a test dose of 1–2 mg/kg of heparin is administered intravenously as a bolus. Five minutes are allowed for intravascular mixing and a second ACT determination is made. The calculator determines additional heparin required to raise the ACT to 480 seconds, the desired therapeutic level, from the formula:

\[ H_2 = H_1 \times \frac{(480-\text{ACT1})}{(\text{ACT1}-\text{ACT0})} \]

where \( H_2 \) is the predicted second heparin dose (expressed in any consistently used units), \( H_1 \) is the first heparin dose, \( \text{ACT0} \) is the baseline ACT, and \( \text{ACT1} \) is the ACT measured five minutes following administration of the first heparin dose (Figure 3). The equation is based on the known linear correlation of ACT and circulating heparin levels.

The ACT is determined five minutes after the second heparin dose has been administered, and cardiopulmonary bypass is begun when adequate anticoagulation has been confirmed. The three data points relating ACT and heparin dose are entered as a data base for all subsequent calculations. Review of the printed record allows a check for errors (Figure 4). A linear regression subroutine is called out by the program which finds the line of best fit for the three data points relating heparin dosage to ACT response. The correlation coefficient (R) for the data is printed. R greater than 0.95 is our criterion for acceptability of the data base.

ACT determinations are made every 30 minutes during bypass and entered (Figure

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<table>
<thead>
<tr>
<th>FOR DRIP RATE (MICRODROPS/MIN)</th>
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<tr>
<td>ENTER PTS. WT. (KG)</td>
<td>ENTER PTS. WT. (KG)</td>
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<td>63.</td>
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<tr>
<td>ENTER SOLN VOL. (CCS)</td>
<td>ENTER SOLN VOL. (CCS)</td>
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<tr>
<td>ENTER DRUG WT. (MG)</td>
<td>ENTER DRUG WT. (MG)</td>
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<tr>
<td>ENTER DRIIP DOSE (MCG/KG/MIN)</td>
<td>ENTER DRIP DOSE</td>
</tr>
<tr>
<td>5.</td>
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</tr>
</tbody>
</table>

**Figure 8.** Calculation of desired infusion rate in microdrops per minute, given desired rate of drug administration, patient weight, and composition of drug solution.

**Figure 9.** Calculation of desired drug concentration—drug weight is computed after entry of desired solution volume, patient weight, rate of drug administration, and drip rate.
FOR SOLN VOL (CCS)
ENTER PTS. WT. (KG) 63.
ENTER DRUG WT. (MG) 200.
ENTER MICRODROPS /MIN 24.
ENTER DRIP DOSE (MCG/ KG/ MIN) 5.
SOLN VOL IS 254. CCS

Figure 10. Calculation of desired drug concentration—solution volume is computed after entry of desired drug weight, drip rate, rate of drug administration, and patient weight.

5). The calculator determines the additional dose of heparin required to raise the ACT to 480 seconds if it has fallen out of therapeutic range. At the termination of bypass, the ACT is again determined (Figure 6). The calculator uses the linear regression routine to estimate the amount of protamine required to return the ACT to the control value based on a ratio of 1.3 mg protamine to 1 mg circulating heparin.

PROGRAM FOR ADMINISTRATION OF DRUGS BY CONTINUOUS INFUSION

Catecholamines (e.g. dopamine, dobutamine, epinephrine, isoproterenol), antiarrhythmics (e.g. lidocaine, procaine amide), and antihypertensive drugs (e.g. nitroprusside) have become pharmacologic mainstays in the care of cardiac surgical patients. Because they are rapidly metabolized, these drugs are usually administered by continuous intravenous infusion. Accurate dosage is imperative since the therapeutic range for these agents may be narrow. Inadequate dosage may result in failure to achieve therapeutic goals while excessive dosage may result in significant toxicity. Doses of agents administered by continuous infusion can be calculated using the formula:

\[ D = \left( \frac{R x M}{W x V} \right) \times 16.67 \]

where \( D \) is the drip dose of drug expressed in micrograms/kg/min, \( R \) is the rate of infusion of the drug solution expressed in microdrops/minute (1 microdrop = 1/60 cc), \( M \) is the amount of drug dissolved in solution expressed in mgs, \( W \) is the weight of the patient expressed in kilograms, and \( V \) is the volume of fluid in which the drug is dissolved expressed in mls. If any four of the five variables are known, the value of the fifth can be calculated.

Programs were written to solve for \( D \) (drip dose, Figure 7), \( R \) (drip rate, Figure 8),...
M (drug weight, Figure 9,) and V (solution volume, Figure 10). The calculator prompts the user to enter the data necessary for each computation.

DISCUSSION

The programs described have been routinely applied in clinical and laboratory procedures over a one year period. More than 400 clinical cardiopulmonary perfusions have been conducted with the anticoagulation protocol. Program card insertion into the calculator and all data entries are performed by the perfusionist and require less than 10 minutes time for all three programs per case.

While the calculator has proven simple and efficient, human error in its use is possible. Therefore, close attention to insure correct data entry, verified by review of the printed record, is required for safe clinical application. In addition, meticulous maintenance of equipment is mandatory to avert calculator malfunction. The program cards have required replacement at three month intervals. The calculators have required factory maintenance at six month intervals when used for two cases per day.

REFERENCES