PROGRAMMABLE CALCULATOR: A PROGRAM FOR USE IN THE INTENSIVE CARE UNIT

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SUMMARY
A program has been prepared for use in a small programmable calculator to allow the rapid and accurate determination of derived data. Changes in oxygen availability, deadspace and shunt fraction can be obtained in a few seconds and therapy altered accordingly. $F_{iO_2}$ required to produce a desired $P_{aO_2}$ can be obtained using the iso-shunt concept.

The introduction of pocket-sized programmable calculators has allowed complex calculations to be made rapidly and accurately at the bedside. In this way, information obtained from monitoring systems can be computed and used to determine immediate alterations in therapy. For example, obtaining the shunt fraction with a standard calculator would be tedious and time-consuming, but with a programmable calculator the data obtained from the patient is merely entered and the calculations are performed automatically.

The attainment of the best positive end-expiratory pressure (PEEP) for any patient is a further example of the use of the calculator in the intensive care unit. The most suitable PEEP can be found by calculating the oxygen availability for the patient at different values of PEEP (Suter, Fairley and Isenberg, 1975). The oxygen availability is obtained from the product of the arterial oxygen content and the cardiac output. These calculations can be computed within a few seconds of entering the $P_{aO_2}$, haemoglobin concentration and cardiac output, thus allowing rapid adjustment of PEEP to the optimum value.

The Texas TI59 calculator has been available in the U.K. for several months and costs about £160. It has a storage capacity of 479 program steps with 59 spaces available for storage of data, but this can be rearranged to give from 960 program steps and no data registers to 160 program steps with 100 data stores as required. The calculator has a rechargeable battery pack which gives 2-3 h of continuous use when fully charged.

The programs are recorded on small magnetic cards (7.5 mm x 1.5 mm) which are entered into a slot in the calculator and pulled through by an integral drive motor. Data to be entered are typed into the display and entered into the specific part of the program by pressing the appropriate key. One further advantage of this particular model is the availability of modules which fit into the back of the calculator. A statistics module is available which allows $t$ values, $P$ values, mean, standard deviations and standard errors to be calculated in a few seconds.

Program design
Data entered as shown in table I allow the calculation of the values shown outlined by dotted lines in table I.

A program has been prepared to calculate the values shown in table I. While designed and entered as a complete unit, the program has the advantage that it can be run in separate sections depending on the patient information available.

$V_D/V_T$
The ratio of deadspace to tidal volume is calculated from $P_{aCO_2}$ and $P_{E CO_2}$ using the formula:

$$V_D/V_T = \frac{P_{aCO_2} - P_{E CO_2}}{P_{aCO_2}}$$

$C_aO_2$
Entry of pH and $P_{aCO_2}$ before $P_{aO_2}$ allows the correction of $Po_2$ using the formula (Astrup et al., 1965):

$$P_{aO_2\text{corr}} = P_{aO_2} \times 10^{0.48 (pH - 7.4) + 0.08 (log 5.22 - log P_{aCO_2})}$$

Temperature correction is performed for all blood-gas values by the Radiometer ABL2 blood-gas analyser used in our intensive care unit, but could be included in the program if required.

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TABLE I. Data which are entered and the values which can be calculated, using the programmable calculator

<table>
<thead>
<tr>
<th>Data entered</th>
<th>Calculated values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{BM}$</td>
<td></td>
</tr>
<tr>
<td>$P_{aCO_2}$</td>
<td></td>
</tr>
<tr>
<td>$P_{EaCO_2}$</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td></td>
</tr>
<tr>
<td>$P_{aO_2}$</td>
<td></td>
</tr>
<tr>
<td>$F_{Io_2}$</td>
<td></td>
</tr>
<tr>
<td>$P_{aO_2}$ desired</td>
<td></td>
</tr>
<tr>
<td>$P_{EaO_2}$</td>
<td></td>
</tr>
</tbody>
</table>

Cardiac output

The haemoglobin saturation is obtained by substituting the corrected $P_{aO_2}$ value in the Kelman equation as modified by Thomas (Kelman, 1966; Thomas, 1972):

$$\text{Saturation} = \frac{n^4 + An^3 + Bn^2 + Cn}{n^4 + An^3 + Dn^2 + En + F}$$

where $n = P_{aO_2}corr$; $A = 15$; $B = 2.045 \times 10^3$; $C = -2 \times 10^3$; $D = 2.4 \times 10^3$; $E = 3.11 \times 10^4$; $F = 2.4 \times 10^8$.

Using this algorithm, any deviation of saturation from the standard Severinghaus oxyhaemoglobin dissociation curve is less than 1% (Severinghaus, 1966).

Haemoglobin concentration (g dl$^{-1}$) is entered in the final calculation to obtain the arterial oxygen content. The oxygen combining factor for haemoglobin is taken as 0.06 (Foëx et al., 1970).

$$CaO_2 = \text{saturation} \times Hb (g \text{ dl}^{-1}) \times 0.06 + (0.01 \text{ mmol litre}^{-1} \times P_{aO_2}corr)$$

The calculation of the oxygen content of a blood sample from the oxygen tension is used repeatedly in the program, and it is written as a separate “$O_2$ content subroutine”.

$(P_{aO_2} - P_{aO_2})$; “virtual shunt”

$(P_{aO_2} - P_{aO_2})$ can be used an estimate of the degree of pulmonary dysfunction, and it has been recommended that the value must be less than 39.9–59.9 kPa before a patient is liable to be successfully weaned from a ventilator (Feeley and Hedley-Whyte, 1975). Entry of the barometric pressure and $Fi_{O_2}$ allows the calculation of $P_{aO_2}$ from the conventional alveolar air equation:

$$P_{aO_2} = (P_{Bar} - 47) F_{Io_2} - P_{aCO_2} \left(F_{Io_2} + \frac{1-F_{Io_2}}{0.8}\right)$$

However, this assumes that the patient is in a steady state and that the oxygen concentration and the inert gas content of the inspired mixture have not been altered recently.

Where these conditions are not fulfilled an inaccurate assessment of the $P_{aO_2}$ will be obtained using the standard equation. If the mixed expired gas can be sampled, an alternative form of the equation may be used (Filley, MacIntosh and Wright, 1954; Nunn, 1963):

$$P_{aO_2} = (P_{Bar} - 47) F_{Io_2} - P_{aCO_2} \left(F_{Io_2} - P_{EaO_2} \frac{P_{Io_2}-P_{EaO_2}}{P_{EaCO_2}}\right)$$
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No assumption is made in this equation that the inert gases present in the lungs are in equilibrium with those in the inspired mixture. This form of the equation can therefore be used either during anaesthesia or during the subsequent period of elimination of the anaesthetic.

The value for \((P_{A_{O_2}} - P_{A_{O_2}})\) is displayed, and the program can be halted at this point or can be allowed to continue, in which case the "virtual shunt" is calculated and displayed (Benatar, Hewlett and Nunn, 1973). This assumes \((P_{A_{O_2}} - P_{V_{O_2}})\) of 5 ml dl\(^{-1}\) blood and calculates the shunt fraction using the formula:

\[
P_{A_{O_2}} = \frac{C_{c}^{O_2} - C_{a}^{O_2}}{C_{c}^{O_2} - (C_{a}^{O_2} - (P_{A_{O_2}} - P_{V_{O_2}}))}
\]

If the arterial \(P_{O_2}\) is not acceptable, \(F_{I_{O_2}}\) which is required to achieve an acceptable \(P_{A_{O_2}}\) can be obtained using the iso-shunt concept. The formula used to calculate the "virtual shunt" can be re-arranged to give:

\[
C_{c}^{O_2} - C_{a}^{O_2} = \frac{(Q_{s}/Q_{l}) (P_{A_{O_2}} - P_{V_{O_2}})}{1 - Q_{s}/Q_{l}}
\]

If it is assumed that changing \(F_{I_{O_2}}\) will not change the value:

\[
(Q_{s}/Q_{l}) (P_{A_{O_2}} - P_{V_{O_2}})
\]

then \(C_{c}^{O_2} - C_{a}^{O_2}\) old = \((C_{c}^{O_2} - C_{a}^{O_2})\) new and \(C_{c}^{O_2}\) new = \(C_{c}^{O_2}\) old + \(C_{a}^{O_2}\) new.

Entry into the program of \(P_{A_{O_2}}\) new, which it is wished to achieve, allows calculation, using the oxygen content subroutine described earlier, of \(C_{c}^{O_2}\) new. The values for \(C_{c}^{O_2}\) old and \(C_{a}^{O_2}\) old have already been obtained from previous calculations and are held in data stores.

It is not possible to derive \(P_{c}^{O_2}\) directly from \(C_{c}^{O_2}\) and a "trial and error" or iterative method has to be used to obtain a \(P_{O_2}\) which, when entered into the oxygen content subroutine, yields a value for oxygen content which is acceptably close to the \(C_{c}^{O_2}\) new being sought.

When the oxygen content obtained using the test \(P_{O_2}\) varies by less than 0.02 ml dl\(^{-1}\) of blood from the required \(C_{c}^{O_2}\), the test \(P_{O_2}\) is accepted and \(F_{I_{O_2}}\) calculated from that value using the standard alveolar air equation, since it is assumed that the patient will be in a steady state before any alteration in ventilation is considered:

\[
F_{I_{O_2}} = \frac{P_{A_{O_2}} - (P_{C_{CO_2}}/0.8)}{P_{B_{A_{CO_2}}}-P_{A_{CO_2}}-(P_{C_{CO_2}}/0.8)}
\]

\(Q_{s}/Q_{l}\); \((P_{O_2} - P_{V_{O_2}})\)

If \(P_{O_2}\) of a mixed venous sample is entered to the program, \(C_{v}^{O_2}\) is displayed. The true shunt fraction is calculated and displayed when \(F_{I_{O_2}}\) is entered. The program then displays \((P_{A_{O_2}} - P_{V_{O_2}})\).

Oxygen availability; oxygen consumption per min; calories required for 24 h

Entry of cardiac output (litre min\(^{-1}\)) allows the calculation of the oxygen availability (ml min\(^{-1}\)) and this can be compared with the calculated oxygen consumption. The energy output for a patient at rest oxidizing an "average" diet is 4.83 Cal for every litre of oxygen consumed. The energy–oxygen ratios for the different categories of food do not differ greatly from this value: carbohydrates are within +5%, proteins within −8%, lipids within −2% and ethanol within +1% of the figure (Brown and Brengelman, 1965). Calculating the appropriate oxygen consumption in litre per day allows the energy output per day for that patient to be derived and the caloric intake to be matched accordingly.

The program has been used to monitor the changes in shunt fraction, oxygen availability and oxygen consumption in a number of patients in the intensive care unit, from arterial samples and from mixed venous samples and cardiac output measurements obtained using triple lumen thermodilution catheters. This has allowed the rapid adjustment of PEEP to provide the optimum value for the individual patient by monitoring the changes in oxygen availability. Suter, Fairley and Isenberg (1975) showed that, in normovolaemic patients, the optimum value for PEEP as determined by the oxygen availability for the patient, was correlated with \(P_{V_{O_2}}\). However, variations in arterio–venous shunting or alterations in the peripheral circulation could alter \(P_{V_{O_2}}\) and possibly provide an inaccurate assessment of the optimum PEEP. The use of the programmable calculator allows easy and rapid measurement of the oxygen availability which reflects more directly the benefits and disadvantages of PEEP on the cardiovascular system. The values of PEEP required have varied from 5 to 15 cm H\(_2\)O and could not have been obtained so simply without the use of the programmable calculator. The use of the iso-shunt
concept to predict $F_{1O_2}$ required to obtain a desired $P_{A0_2}$ has been shown to be reasonably accurate in the majority of patients (Benatar, Hewlett and Nunn, 1973; Lawler and Hewlett, 1978). This part of the program can be used with knowledge only of the $F_{1O_2}$ and arterial blood-gas tensions.

The program has also been used for teaching to demonstrate the effects of changes in cardiac output, haemoglobin concentration and arterial $P_{0_2}$ in determining the delivery of oxygen to a patient. Entry of the program uses nearly all the available stores in the calculator memory, and so more complex programs cannot be run on this machine. Also, the speed of calculation is relatively slow compared with larger, desk-top machines. This only becomes troublesome when iterative loops are run as, for example, when predicting $F_{1O_2}$ required to obtain a specified $P_{A0_2}$. However, taking into consideration the relatively low cost and the portability of the calculator, it would appear to justify a place in the intensive care unit, especially if no other computational facilities are available.

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REFERENCES


