Estimating allowable blood loss with correction for variations in blood volume

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All the theoretical relationships between blood loss and change in haematocrit used for calculating the allowable pre-transfusion blood loss assume a strictly normovolaemic situation. In this study a formula was derived in which account was taken of the variation in blood volume. The formula was based on clinical data. Measurements of the blood loss, the blood haemoglobin concentration and the haematocrit (HCT) were performed on 230 occasions in the course of 35 transurethral prostatic resections. The change in blood volume was estimated by the haemoglobin dilution method and the value so obtained was compared to both the measured haematocrit and the theoretical value that would presumably have been recorded if there had been no change in blood volume. The relationship established from these comparisons was: blood loss = preoperative blood volume \times [\text{In preop HCT} - \text{In postop HCT} (1 + 0.15 \times \text{blood volume change})]

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In recent years increasing attention has been focused on the cost and risks of replacing blood loss with bank blood. In many situations of surgical bleeding it seems more rational to maintain normovolaemia by deliberate haemodilution with colloid and/or crystalloid solutions. This practice is limited primarily by the decrease in the systemic oxygen transport that occurs when the haematocrit (HCT) falls below 30\% (1–3). To avoid the risk of tissue hypoxia at lower HCT levels, theoretical formulae (4, 5) or nomograms (6) are commonly used to estimate the blood loss that can be accepted before transfusion of erythrocytes becomes advisable. However, these guides to safe haemodilution all apply to a strictly normovolaemic situation.

The aim of this study was to derive a formula describing the relationship between blood loss and haematocrit that is valid outside the normovolaemia situation. The blood loss, the haematocrit and the blood volume – estimated by the haemoglobin dilution method (7) – were measured over 10-min periods during 35 transurethral prostatic resections, and the results were then compared to Bourke & Smith’s theoretical formula for normovolaemic haemodilution (4).

PATIENTS AND METHODS

The material for the study consisted of 35 elderly men (mean age 70 years, s.d. 7) with benign hyper trophy of the prostate gland, who underwent transurethral resection. Appropriate patient and institutional approval was obtained for the study. Epidural anaesthesia was used in all cases; 8–13 ml of mepivacaine 2\% with adrenaline (Carbocain*-adrenaline, Astra, Sweden) was administered through an indwelling catheter. Acetated Ringer solution (Ringerdex, Pharmacia, Sweden), 10–12 ml·kg\(^{-1}\), was given as an intravenous fluid supplement during induction of anaesthesia, and subsequently at a rate twice the normal rate for 5 min. An infusion of 500 ml of 6\% dextran 70 (Macrodex*, Pharmacia, Sweden) was given to 7 patients. Erythocytes transfusion was given to 6 of the patients; however, measurements performed during and after this transfusion were not included in the statistical analysis.

Blood samples

A blood sample (5–10 ml) for measuring the blood haemoglobin (B-Hb) concentration and the haematocrit was drawn on the week-day before surgery and at the following times during the day on which the operation was performed: before and after anaesthesia had been induced, every 10 min during surgery, and, in 15 of the patients, 1 and 2 h after the operation had been completed. These analyses were performed on a Coulter Counter S plus (Coulter Electronics, Florida, USA) where the haematocrit is obtained as the product of the mean erythrocyte corpuscular volume and the red blood cell count. The coefficient of variation in these measurements was about 1\%.

Blood loss

Glycine 2.2\% in water was used for urinary bladder irrigation. The irrigant used was collected in buckets, to each of which was added about 1000 IE of heparin to prevent coagulation of the dispersed blood. Every 10 min during the resection the bucket was replaced and the blood content of the irrigant was measured with the Leo HemoCue® system (Leo Diagnostics, Sweden). To obtain the volume of blood lost, the haemoglobin content was compared to the B-Hb value recorded at the end of the 10-min period (8). The mean accuracy of the blood loss determination was 100\% (s.d. 5), as checked by dispersing various amounts of bank blood in the irrigating fluid.

Calculations

The preoperative blood volume, \(BV_{op}\) was calculated from the formula of Allen and co-workers (0.417 \times \text{cube of height (m)} + 0.045 \times \text{body weight (kg)} - 0.03) (9).
The formula derived by Bourke & Smith (4) was used as a basic model for normovolaemic haemodilution; here, the relationship between blood loss (BL), BV, preoperative haematocrit (HCT), and the next haematocrit measurement (HCT) is described by the equation:

\[ BL = BV_e (\ln HCT - \ln HCT) \]  

(Eqn. 1)

The changes in blood volume during surgery were calculated by the haemoglobin dilution method (HDM) (7). The preoperative total body haemoglobin content (T-Hb) was then calculated from the B-Hb concentration and BV by applying the expression:

\[ T-Hb = 0.91 B-Hb \cdot BV \]  

(Eqn. II)

The blood volume at the end of the next 10-min period, BV, was calculated by subtracting from T-Hb the haemoglobin loss (including the blood sample volume drawn for the preoperative measurement) and by including the B-Hb concentration (B-Hb) at the end of the 10-min period, as shown in Eqn. 1. Thus:

\[ BV_a = T-Hb - Hb_{sample} (0.91 B-Hb) \]  

(Eqn. III)

The methods of statistical evaluation were linear regression analysis and the paired t-test.

RESULTS

The measured haematocrit (HCT) just before induction of anaesthesia was significantly lower than on the day before surgery (means 43.5 and 40.8%, s.d. 4.2 and 4.2, respectively; \( P < 0.01 \)).

During the operations 230 measurements of B-Hb, HCT, and blood loss (BL) were performed. From the estimates of the blood volume by the haemoglobin dilution method, the mean deviation from normovolaemia at each measurement was found to be 0.09 l (s.d. 0.34, range -0.77 to +1.12). The theoretical haematocrit that would have been obtained if normovolaemia had been maintained (HCT) was calculated according to Eqn. I for each one of these observations. The distribution of HCT (normovolaemia) versus HCT (not normovolaemia) is shown in Fig. 1.

The median total blood loss during the 35 transurethral resections was 0.65 l (range 0.05–1.62). There was a significant inverse relationship between the cumulative blood loss and the change in blood volume to the end of each 10-min period of surgery (Fig. 2).

The relationships between HCT, HCT, and the blood volume are illustrated in Fig. 3 and Fig. 4. Linear regression analysis of the data presented in Fig. 3 yielded the following equation:

\[ BV = (HCT_n - HCT_m) / 5.5 \]  

(Eqn. IV)

This equation thus expresses the relationship between the change in blood volume from just before induction of anaesthesia to the end of a given 10-min period during surgery (BV) and the difference between the two haematocrit values HCT, and HCT. The scatter around the regression line in Fig. 3 represents a standard error of an estimate of the difference between HCT, and HCT, of 1.00 HCT per cent.

Linear regression analysis of BV and the quotient of HCT by HCT, as illustrated in Fig. 4 yielded the following equation:

\[ BV = 1 + 0.15 (HCT/HCT_m) \]  

(Eqn. V)

The standard error of an estimate of the quotient of HCT by HCT, from this equation was 0.006, which is about 1/4 of that recorded for Eqn. IV.

By eliminating HCT between Eqns. IV and V and

\[ y = 3.9 + 0.87 x \]

\[ n = 195; \ r = 0.91 \]

Fig. 1. The measured haematocrit (HCT) versus the haematocrit that would probably have been recorded if normovolaemia had been maintained (HCT), as calculated from the relationship between blood loss and change in haematocrit (Eqn. I), in 35 patients undergoing transurethral prostatic surgery. The scatter about the regression line represents the aggregate error in the measurements of haematocrit and blood loss and all deviations from strict normovolaemia.

Fig. 2. The change in blood volume estimated by the haemoglobin dilution method (HDM) versus the cumulative blood loss as measured over 10-min periods during 35 transurethral prostatic resections.
Blood volume change by HDM (I)

Fig. 3. The differences between the theoretical haematocrit (HCT,) that would apply at normovolaemia (according to Eqn. I) and the measured haematocrit (HCT_m) versus the change in blood volume as calculated by the haemoglobin dilution method (HDM).

substituting for HCT_n in Eqn. I, we have:

\[ BL_n = BV_0 [\ln HCT_0 - \ln (HCT_m + 5.5BV_0)] \]  
(Eqn. VI)

and

\[ BL_n = BV_0 [\ln HCT_0 - \ln HCT_m (1 + 0.15BV_n)] \]  
(Eqn. VII)

DISCUSSION

Deliberate haemodilution with non-cellular expanders can be used to minimize the need to replace surgical haemorrhage with bank blood (1). Normovolaemia is then maintained by infusion of colloid and/or crystalloid solutions in volumes matched to the blood loss, a process that will ultimately lead to acute anaemia. However, a moderate degree of anaemia is compensated for by an increase in cardiac stroke volume (2, 3) or oxygen extraction from the blood (10) and does not lead to hypoxia. A haematocrit of 30% seems to be well tolerated by the acutely ill surgical patient in otherwise perfect physical condition, although the target haematocrit for the haemodilution must probably be higher in the presence of coronary heart disease (1). It is difficult during surgery to follow the degree of anaemia, by repeated haematocrit measurements. Instead, a number of rules of thumb and guides have been evolved to insure an adequate haematocrit for oxygen transport. To avoid an underestimation of the anaemia, it is important to take into account that any increment in bleeding during surgery is followed by a proportional drop in the haematocrit (4–6). Therefore, guides to safe haemodilution are commonly based on relationships between blood loss and haematocrit that prevail during normovolaemia. The blood volume must then be assumed to remain unchanged at any moment during the operation. When using deliberate haemodilution in clinical practice, however, a strict normovolaemia can hardly be achieved.

Equations VI and VII in the present study were derived from a clinical material consisting of 35 operations during which the deviation from normovolaemia varied between −0.7 and +1.1. Therefore, these regression equations share the advantage of applying not only to the strictly normovolaemic situation but also to a range of variation in blood volume often encountered during routine surgery. Technically, the formulae were based on 195 paired comparisons between Bourke & Smith’s formula for normovolaemic haemodilution (Eqn. I) and the haemoglobin dilution method for calculating variations in blood volume (7) performed during 10-min periods throughout the surgical operations. The fact that Eqn. I was satisfied—that is to say, HCT_n and HCT_m assumed identical values—whenever the blood volume was the same as before induction of anaesthesia (Fig. 3 and 4), shows that these methods for calculating the relationships between haematocrit and blood loss may indeed be used interchangeably. Thus, Bourke & Smith’s formula seems to be valid also when there is variation in the blood volume of the magnitude encountered in this study. On the other hand, it is still essential for accurate results that normovolaemia prevails at the particular moment when their formula is being used.

The equations for safe haemodilution derived in the present study may prove to be useful in situations where a constant blood volume is not the ideal; to
take an example, when the operation is performed under spinal or epidural anaesthesia, constant slight hypervolaemia is often desired to compensate for the decreased venous return. Suppose that a patient with an estimated blood volume of 5 l has an initial haematocrit of 42. The anaesthesiologist decides that he could tolerate a haematocrit of 32. From Eqn. I the blood loss that may be allowed before transfusion is prescribed is obtained as $5 \left(\ln 42 - \ln 32\right) = 1.36$ l. However, as the operation is performed under epidural anaesthesia, it is considered that hypervolaemia of 0.5 l would be desirable in order to maintain stable circulation. In this situation Eqn. VII can be used to calculate the allowed pre-transfusion blood loss; it yields $5 \left(\ln 42 - \ln 32 \left(1 + 0.15 \times 0.5\right)\right) = 0.99$ l. Naturally, as the crystalloid and/or colloid solution used to produce the hypervolaemia of 0.5 l exerts a dilutive influence on the blood, for any constant rate of bleeding the target haematocrit of 32% will be reached more rapidly in the hypervolaemic than in the normovolaemic patient. On the other hand, the difference between the two calculations is not equal to the degree of hypervolaemia of 0.5 l, as might be expected. This is due to the logarithmic relationship between blood loss and haematocrit; for each increment in bleeding the haematocrit will decrease somewhat less when beginning from a lower haematocrit (in hypervolaemia) than from a higher (in normovolaemia).

Equations for estimating allowable blood loss have certain limitations. All of them are dependent on the accuracy of a number of measurements, calculations and assumptions. In studies of haemodilution during surgery, the degree of blood loss is usually obtained from combinations of a visual estimate, weighing of absorption swabs and a summation of the blood found in the surgical field, on sponges and dressings, and in suction tubes and bottles. In the present study, haemorrhage usually resulted in a decrease in blood volume (Fig. 2), which indicates that our visual estimate of the bleeding was on the low side. However, as all the blood lost during the operations was dispersed in the irrigating fluid, the amount of haemoglobin lost could be measured with a haemophotometer. This study as well as others (11, 12) have demonstrated that the haemoglobin loss can be measured quite accurately during transurethral prostatic resection. Furthermore, to obtain the volume of blood lost, repeated determination of the B-Hb level was performed to compensate for changes in the haematocrit level (8). It seems that this technique of measuring blood loss over discrete time intervals used in the present study would probably be more accurate than those used in previous studies of allowable pre-transfusion blood loss.

The preoperative blood volume was predicted according to Allen et al. (9), who compiled results from six different studies and found that the blood volume in 321 adult males was most strongly correlated to the body weight and the cube of height. Allen's formula gave similar results to measurement of the blood volume with the $^{131}$I-RISA technique in 10 patients scheduled for transurethral resection of the prostate (7).

The variations in blood volume were estimated by the haemoglobin dilution method (HDM) (Eqn. II and III). This is based on calculation of the patient's preoperative total haemoglobin content, from which losses are subtracted. The B-Hb level is used as the indicator of dilution. No radioactive label is used. In a study of the total change in blood volume during transurethral resection of the prostate, the HDM yielded similar results to those obtained by the $^{131}$I-RISA technique (7). The concept of a stable total haemoglobin content in the circulation in the HDM is supported by the lack of evidence of erythrocyte mobilization from non-circulating reservoirs in connection with moderate bleeding (13). A further prerequisite for accurate results is a stable ratio between the haematocrit values for central and peripheral blood, expressed as the haematocrit factor of 0.91. Although this factor is lower in pregnant women and infants, a number of studies show that it varies very little in normal man (14). The haematocrit factor has been found to be constant over a haematocrit range from 9 to 82% (15), and seems to be unaltered by spinal anaesthesia (16) and bleeding of between 10 to 20% of the blood volume (17).

When the HDM is applied several times during an operation, as in this study, a uniform distribution of the haemoglobin molecules in the circulation is a further prerequisite for obtaining accurate blood volume estimations. As, however, identical assumptions apply to Bourke & Smith's formula (Eqn. I), this theoretical consideration cancels out in the 195 paired comparisons between their formula and the HDM. That occasional disturbances in the distribution of haemoglobin in the circulation are of limited importance is further suggested by the fact that with the HDM errors only in the measurement of haemoglobin loss but not in the B-Hb level can be carried over to the next blood volume estimation (7).

The fact that the haematocrit recorded immediately before induction of anaesthesia was lower than on the weekday prior to surgery may be ascribed to change of posture (6, 7); on the day before surgery our patients were ambulatory, whereas during the day of the operation they were kept recumbent. It is advisable to exclude this effect of the body posture on the peroper-
ative change in blood volume when this is assessed, by using the formulae presented in this paper or those pertaining to the haemoglobin dilution method. The effect of body posture can be excluded by measuring the HCT₀ with the patient in the same body position as that in which surgery is to be performed – ideally, immediately before the operation.

REFERENCES