REVIEW ARTICLE

Total joint replacement and blood loss: what is the best equation?

Emmanuel Gibon · Jean-Pierre Courpied · Moussa Hamadouche

Abstract With the population aging, total joint replacements which are an effective method to restore patient's mobility are an increasing necessity. However, such operations are known to entail serious blood loss, which may have dramatic consequences in patients with chronic diseases or when the prosthesis is revised, a situation where the blood loss is even higher. Therefore, formulas to better estimate the blood loss are available. These formulas may also be used for clinical studies to compare blood loss between different joint replacement techniques. The aim of this review is to provide a clear understanding of the formulas and to help physicians to further improve their blood loss estimation. Moreover, surgeons will then be able to choose the most accurate and user-friendly formula for more comparable data between clinical studies.

Introduction

It is now well established that the frequency of total hip arthroplasties (THA) and especially total knee arthroplasties (TKA) will increase over the next 25 years [1]. Such operations are known to have a high volume of blood loss. Thus, blood loss for primary conventional TKA ranges from 726 to 1,768 ml [2–6]. Likewise, for primary conventional THA, blood loss ranges from 1,188 to 1,651 ml [7–10]. However, it is hard to compare those rates given the fact that many different equations are used to calculate the blood loss. An accurate method to calculate the blood loss for total joint replacement is critical for better perioperative management. Indeed, to avoid allogeneic transfusions after such procedures, patients are often asked for a preoperative autologous blood donation. However, 50 % of this blood is not transfused [11, 12] due to the difficulty in predicting how much blood will be required for each patient. Therefore, we present a review of different ways to estimate blood loss in total joint replacement. Moreover, such formulas can also be used for clinical research in orthopaedic surgery to compare blood loss between different surgical techniques. Most of these formulas require an estimation of the total blood volume. With different features, some are more accurate and others more cumbersome. Thus, they can be better suited either for autologous blood donation estimation or for clinical studies. Formulas are listed and described based on the lab test used and are summarised in Table 1.

Methods based on the haematocrit

Mercuriali's formula [13]

This formula is based on the preoperative haematocrit (Hct_{preop}) and fifth post-operative day haematocrit ($Hct_{day\ 5\ postop}$). The haematocrits must be written as decimal fractions. This formula requires the patient's blood volume (BV) calculated through the Nadler formula [14] (in millilitres of blood) and requires the volume of red blood cells (RBC) transfused as well. Therefore, this estimation using the

E. Gibon (✉) · J.-P. Courpied · M. Hamadouche
Department of Orthopaedic and Reconstructive Surgery, Clinical Orthopaedic Research Centre, Service A, Cochin Teaching Hospital, Paris School of Medicine, 27 rue du Faubourg Saint Jacques, 75014 Paris, France
e-mail: emmanuel.gibon@gmail.com

J.-P. Courpied
e-mail: jean-pierre.courpied@cch.ap-hop-paris.fr

M. Hamadouche
e-mail: moussa.hamadouche@cch.aphp.fr

Table 1 Summary of formulas and respective studies

Authors	Formula	Unit	Studies	Reference
Mercuriali	$BV \times (Hct_{preop} - Hct_{day\ 5\ postoperative}) + ml$ of transfused RBC	ml of RBC	K	[4, 10, 25]
Bourke	$BV \times (Hct_0 - Hct_t) \times (3 - Hct_{mean})$	ml of blood	K, H&K	[8, 26, 27]
Ward	$BV \times \ln(Hct_f/Hct_i)$	ml of blood	E	[16]
Gross	$BV \times [(Hct_0 - Hct_f)/Hct_{AV}]$	ml of blood	K, H	[3, 6, 28–30]
Brecher	3 phase formula	ml of RBC	P, H	[9, 19]
Lisander	$(BV \times Hct_i \times 0.01) + V_t + V_a - (BV \times Hct_e \times 0.01)$	ml of RBC	K, H	[20, 31]
Meunier	$BV \times [(Hb_i - Hb_e)/Hb_e]$	ml of blood	K	[32]
–	Weight swabs, drapes and drainage bottle volumes	ml of blood	K, H&K	[7, 22, 23, 33–36]

K knee, *H* hip, *H&K* hip and knee, *E* experimental, *P* prostatectomy

Mercuriali formula is expressed in millilitres of RBC:

Estimated blood loss $=$ blood volume

$$\times \left(Hct_{preop} - Hct_{day\ 5\ postoperative}\right)$$

$$+\ ml\ of\ transfused\ RBC$$

The volume of RBC transfused is based on the number of RBC in one blood unit pack. This number is different from one institution to another.

Bourke's formula [15]

Bourke and Smith first described the blood loss as the natural logarithm of the ratio of initial to final haematocrit. Thus, to make it easily memorable for use in the operating room, Bourke and Smith rearranged the equation to obtain a "simplified" equation:

Estimated blood loss $= BV \times (\ln\ Hct_0 \div \ln\ Hct_t)$

rewritten to obtain:

Estimated blood loss $= BV \times (Hct_0 - Hct_t)$

$$\times (3 - Hct_{mean})$$

where BV is calculated using Moore's formula and haematocrits are written as decimal fractions. Hct_0 represents the value of the haematocrit in initial conditions and Hct_t is the value of the haematocrit at t time. The time when the blood sample must be taken for Hct_t is not clear. Hct_{mean} is the average between the initial and final haematocrits. The estimated blood loss using Bourke's formula is therefore expressed in millilitres of blood.

Ward's formula [16]

Ward et al. based their formula on works of Furman et al. [17] in paediatric surgery. The aim of the work of Ward et al. was to create a formula which fits a relevant clinical situation: slow blood loss and volume replacement with colloid/crystalloid, therefore maintaining the intravascular volume near normal. Ward et al. tested the following formula in dogs and humans:

$$\text{Estimated blood loss} = EBV \times \ln\frac{Hct_f}{Hct_i}$$

where Hct_f is the final haematocrit value drawn before transfusion or at the end of the surgery and Hct_i is the initial haematocrit before surgery. The estimated blood loss using Ward's formula is therefore expressed in millilitres of blood.

Gross' formula [18]

Gross designed a new formula to make the blood loss estimation easier than using the Bourke or Ward formula. Indeed, he found the Ward formula was not easy to use in routine practice due to the natural logarithm function and found the Bourke formula was "cumbersome and difficult to remember". Therefore, his new formula, derived from the logarithmic equation was:

$$\text{Estimated blood loss} = EBV \times \frac{Hct_0 - Hct_f}{Hct_{AV}}$$

where EBV is calculating using Moore's formula; Hct_0 is the initial haematocrit before surgery, Hct_f is the patient's minimum allowable haematocrit and Hct_{AV} is the average of the initial and minimum haematocrit.

Gross tested his formula in adult patients undergoing major procedures including THA. The estimated blood loss using Gross' formula is therefore expressed in millilitres of blood.

Brecher's formula [19]

With the goal of designing a very accurate and reproducible method of blood loss estimation in order to have an estimation which could fit 90 % of patients for a given procedure,

Brecher et al. divided the surgical procedure into three phases and the final estimation is the sum of each estimation calculated for each phase. Their work was based on the concept of "acute normovolaemic haemodilution" where the patient's blood volume is maintained using volume replacement solution until the minimum haematocrit allowable.

Lisander's formula [20]

Lisander et al. created their formula to test whether or not autotransfusion could decrease allogeneic blood transfusion with a minimum allowable haematocrit of 33 %. The estimated blood loss is expressed in millilitres of RBC, haematocrit values are in percentage and the formula is:

$$\text{Estimated blood loss} = (BV \times Hct_i \times 0.01) + V_t + V_a$$
$$- (BV \times Hct_e \times 0.01)$$

where BV is calculated using Nadler's formula; Hct_i is the preoperative haematocrit, Hct_e is the haematocrit at the end of the hospital stay, V_t is the volume of allogeneic RBC transfused and V_a is the volume of RBC returned by the autotransfusion device. Volumes are all in millilitres. Lisander et al. tested their model on patients undergoing THA and concluded that autotransfusion has a poor effect towards decreasing the need for allogeneic blood transfusion. The estimated blood loss using Lisander's formula is expressed in millilitres of RBC.

Method based on the haemoglobin

Meunier's formula [21]

Meunier et al. tested the haemoglobin (Hb) dilution method with blood donors in order to know whether or not this method is accurate for blood loss estimation:

$$\text{Estimated blood loss}: \ BV \times \frac{Hb_i - Hb_e}{Hb_e}$$

where BV is calculating using Nadler's formula; Hb_i and Hb_e are the Hb concentrations before and on a given day after blood donation, respectively. Meunier et al. compared the estimated blood loss and the donated blood volume from day one to day 14 post-donation. They showed that the minimum Hb concentration was reached on day six and at this time the difference between the two volumes was 30 %. Therefore, they concluded that the haemoglobin dilution method dramatically underestimates the true blood loss. With this method, the estimated blood loss is expressed in millilitres of blood.

Other methods

The remaining methods consist in weight swabs, drapes and drainage bottle volumes. Most of the time these methods are used all together. However, some authors [7, 22, 23] used the volume in the drainage bottle as a sole method to estimate blood loss.

Estimated blood volume

Among the formulas, the blood volume is mainly estimated using Nadler's formula [14], which takes into account the gender, the weight and the size. Therefore, the formula is different for females and males. The formula is:

$$\text{Male}: 604 + 0,0003668 \times [\text{size(cm)}]^3 + 32,2$$
$$\times \text{weight(kg)}$$

$$\text{Female}: 183 + 0,000356 \times [\text{size(cm)}]^3 + 33$$
$$\times \text{weight(kg)}$$

Discussion

The number of Americans older than 65 years will increase by 104 % in 2030 [24]. Given the fact that 60 % of this population will have more than one chronic disease, the question of blood loss in major orthopaedic surgery is critical. Blood loss in TKA and THA usually represents at least 20 % of the blood volume, which is balanced either by colloid/crystalloid or units of blood. However, we have shown that there are many ways to estimate blood loss in orthopaedic surgery, but they all differ with regard to accuracy, precision and ease of use. Most of the formulas were initially designed to better estimate blood loss during surgery and thereby to decrease blood wastage, which is the reason why studies using these formulas have focused on autologous blood donation. However, with an exponential increase of new surgical techniques, devices and biomaterials in orthopaedic surgery, these formulas came to be used by surgeons in clinical research to compare the blood loss. The best formula would be close enough to the real blood loss to be accurate and user-friendly for routine use. Thus, formulas containing a logarithmic function seem to be cumbersome for routine use. Bourke et al. rewrote their initial logarithm function into an easier formula; however, due to the lack of accuracy on the timing of the final blood sample, this formula is hard to reproduce. Gross used the patient's minimum allowable haematocrit as the final value.

Therefore, his formula better fits a use for autologous blood donation calculation rather than a use for prospective or retrospective studies. Brecher et al. divided the surgical procedure into three phases thereby increasing the number of calculations and the complexity. Moreover, Brecher et al. used an exponential function in their calculation which is hard to use routinely. Although very accurate by taking into account the acute normovolaemic haemodilution in their calculation, the Brecher formula is cumbersome for routine use. Lisander et al. designed a formula to estimate the autologous blood donation in order to keep a minimum allowable haematocrit as low as 33 %. However, 32 % of the patients required an additional allogeneic blood transfusion indicating the lack of accuracy to predict the required volume to transfuse with this formula. Moreover, in Lisander's formula, the final Hct is the value at the patient's discharge, which may be very different from one patient to another. Mercuriali et al. designed a formula based on the haematocrit at post-operative day five plus the volume of RBC transfused. It has the advantage of being very clear in time, well reproducible and user-friendly in routine practice. However, it suggests that there is no blood loss after the fifth post-operative day and that the haematocrit reaches its minimum value at this time. Nevertheless, as the patient's own erythropoiesis begins by post-operative day six as shown by Meunier et al. [21], Merculiari's formula is particularly interesting as it avoids this confounding bias. Meunier et al. tested their formula with a blood donation model of 10 % of the blood volume. They found out that the lowest haemoglobin value was reached at the sixth post-donation day meaning the onset of erythropoiesis. Furthermore, they showed a difference of 30 % between the blood donation volume and the calculated volume using the haemoglobin dilution method. With such an underestimation, this formula is not recommended for acute blood loss estimation. Other methods such as weight swabs, drapes and drainage bottles are not reproducible with the exception of drainage bottle volumes. Such methods are not suitable for preoperative blood loss estimation but could be used for clinical studies albeit not accurately. Lastly, to convert millilitres of RBC to millilitres of blood, the mean Hct must be used. This mean Hct is the average between the preoperative Hct and the final Hct depending on the formula. The key is to use a rule of three. For example, with an estimated blood loss of 700 ml of RBC and a mean Hct of 35 %, the conversion would be: $(700 \div 35) \times 100 = 2000$ ml of blood.

Conclusion

Many formulas to estimate blood loss in surgery are available. However, these formulas have different features, which can be used either for preoperative blood loss estimation or prospective/retrospective clinical studies. Taken together, Mercuriali's formula is, in our opinion, the most suitable formula for comparable studies regarding blood loss in surgery. For a more meaningful result, a conversion to millilitres of blood should always be done.

Conflict of interest   The authors declare that they have no conflict of interest.

References

1. Kurtz S, Ong K, Lau E, Mowat F, Halpern M (2007) Projections of primary and revision hip and knee arthroplasty in the United States from 2005 to 2030. J Bone Joint Surg Am 89:780–785
2. Orpen NM, Little C, Walker G, Crawfurd EJP (2006) Tranexamic acid reduces early post-operative blood loss after total knee arthroplasty: a prospective randomised controlled trial of 29 patients. Knee 13:106–110
3. Ishii Y, Matsuda Y (2005) Perioperative blood loss in cementless or hybrid total knee arthroplasty without patellar resurfacing: a prospective, randomized study. J Arthroplasty 20:972–976
4. Hinarejos P, Corrales M, Matamalas A, Bisbe E, Cáceres E (2009) Computer-assisted surgery can reduce blood loss after total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc 17:356–360
5. Wong J, Abrishami A, El Beheiry H, Mahomed NN, Roderick Davey J, Gandhi R, Syed KA, Muhammad Ovais Hasan S, De Silva Y, Chung F (2010) Topical application of tranexamic acid reduces postoperative blood loss in total knee arthroplasty: a randomized, controlled trial. J Bone Joint Surg Am 92:2503–2513
6. Levy O, Martinowitz U, Oran A, Tauber C, Horoszowski H (1999) The use of fibrin tissue adhesive to reduce blood loss and the need for blood transfusion after total knee arthroplasty. A prospective, randomized, multicenter study. J Bone Joint Surg Am 81:1580–1588
7. Hays MB, Mayfield JF (1988) Total blood loss in major joint arthroplasty. A comparison of cemented and noncemented hip and knee operations. J Arthroplasty 3 Suppl:S47–S49
8. Sehat KR, Evans RL, Newman JH (2004) Hidden blood loss following hip and knee arthroplasty. Correct management of blood loss should take hidden loss into account. J Bone Joint Surg Br 86:561–565
9. Billote DB, Glisson SN, Green D, Wixson RL (2002) A prospective, randomized study of preoperative autologous donation for hip replacement surgery. J Bone Joint Surg Am 84-A:1299–1304
10. Charrois O, Kahwaji A, Vastel L, Rosencher N, Courpied JP (2001) Blood loss in total hip arthroplasty for rapidly destructive coxarthrosis. Int Orthop 25:22–24
11. Lemos MJ, Healy WL (1996) Blood transfusion in orthopaedic operations. J Bone Joint Surg Am 78:1260–1270
12. Bierbaum BE, Callaghan JJ, Galante JO, Rubash HE, Tooms RE, Welch RB (1999) An analysis of blood management in patients having a total hip or knee arthroplasty. J Bone Joint Surg Am 81:2–10
13. Mercuriali F, Inghilleri G (1996) Proposal of an algorithm to help the choice of the best transfusion strategy. Curr Med Res Opin 13:465–478
14. Nadler SB, Hidalgo JH, Bloch T (1962) Prediction of blood volume in normal human adults. Surgery 51:224–232
15. Bourke DL, Smith TC (1974) Estimating allowable hemodilution. Anesthesiology 41:609–612

16. Ward CF, Meathe EA, Benumof JL, Trousdale F (1980) A computer nomogram for blood loss replacement. Anesthesiology 53:S126

17. Furman EB, Roman DG, Lemmer LA, Hairabet J, Jasinska M, Laver MB (1975) Specific therapy in water, electrolyte and blood-volume replacement during pediatric surgery. Anesthesiology 42:187–193

18. Gross JB (1983) Estimating allowable blood loss: corrected for dilution. Anesthesiology 58:277–280

19. Brecher ME, Monk T, Goodnough LT (1997) A standardized method for calculating blood loss. Transfusion 37:1070–1074

20. Lisander B, Ivarsson I, Jacobsson SA (1998) Intraoperative autotransfusion is associated with modest reduction of allogeneic transfusion in prosthetic hip surgery. Acta Anaesthesiol Scand 42:707–712

21. Meunier A, Petersson A, Good L, Berlin G (2008) Validation of a haemoglobin dilution method for estimation of blood loss. Vox Sang 95:120–124

22. Porteous AJ, Bartlett RJ (2003) Post-operative drainage after cemented, hybrid and uncemented total knee replacement. Knee 10:371–374

23. Kalairajah Y, Simpson D, Cossey AJ, Verrall GM, Spriggins AJ (2005) Blood loss after total knee replacement: effects of computer-assisted surgery. J Bone Joint Surg Br 87:1480–1482

24. Iorio R, Robb WJ, Healy WL, Berry DJ, Hozack WJ, Kyle RF, Lewallen DG, Trousdale RT, Jiranek WA, Stamos VP, Parsley BS (2008) Orthopaedic surgeon workforce and volume assessment for total hip and knee replacement in the United States: preparing for an epidemic. J Bone Joint Surg Am 90:1598–1605

25. Demey G, Servien E, Pinaroli A, Lustig S, Ait Si Selmi T, Neyret P (2010) The influence of femoral cementing on perioperative blood loss in total knee arthroplasty: a prospective randomized study. J Bone Joint Surg Am 92:536–541

26. Lotke PA, Faralli VJ, Orenstein EM, Ecker ML (1991) Blood loss after total knee replacement. Effects of tourniquet release and continuous passive motion. J Bone Joint Surg Am 73:1037–1040

27. Molloy DO, Archbold HAP, Ogonda L, McConway J, Wilson RK, Beverland DE (2007) Comparison of topical fibrin spray and tranexamic acid on blood loss after total knee replacement: a prospective, randomised controlled trial. J Bone Joint Surg Br 89:306–309

28. Prasad N, Padmanabhan V, Mullaji A (2007) Blood loss in total knee arthroplasty: an analysis of risk factors. Int Orthop 31:39–44

29. Tanaka N, Sakahashi H, Sato E, Hirose K, Ishima T, Ishii S (2001) Timing of the administration of tranexamic acid for maximum reduction in blood loss in arthroplasty of the knee. J Bone Joint Surg Br 83:702–705

30. Goodnough LT, Despotis GJ, Merkel K, Monk TG (2000) A randomized trial comparing acute normovolemic hemodilution and preoperative autologous blood donation in total hip arthroplasty. Transfusion 40:1054–1057

31. Good L, Peterson E, Lisander B (2003) Tranexamic acid decreases external blood loss but not hidden blood loss in total knee replacement. Br J Anaesth 90:596–599

32. Ajwani SH, Jones M, Jarratt JW, Shepard GJ, Ryan WG (2012) Computer assisted versus conventional total knee replacement: a comparison of tourniquet time, blood loss and length of stay. Knee 19:606–610

33. Jansen AJ, Andreica S, Claeys M, D'Haese J, Camu F, Jochmans K (1999) Use of tranexamic acid for an effective blood conservation strategy after total knee arthroplasty. Br J Anaesth 83:596–601

34. Benoni G, Lethagen S, Fredin H (1997) The effect of tranexamic acid on local and plasma fibrinolysis during total knee arthroplasty. Thromb Res 85:195–206

35. Cushner FD, Friedman RJ (1991) Blood loss in total knee arthroplasty. Clin Orthop Relat Res 269:98–101

36. Slagis SV, Benjamin JB, Volz RG, Giordano GF (1991) Postoperative blood salvage in total hip and knee arthroplasty. A randomised controlled trial. J Bone Joint Surg Br 73:591–594