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Review Article

Rethinking intraoperative blood loss monitoring: a decision-oriented framework for clinically integrated assessment

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Abstract: Intraoperative blood loss (IBL) monitoring is an important factor in decision-making of anesthesia, and real-time and reliable IBL is vital in the safety of the patient during the perioperative period. But even now after decades of technological development in medicine, this basic clinical issue has not been addressed. The current strategies of monitoring do not usually achieve all the needs of accuracy, timeliness, and procedural flexibility in regular clinical care. This article re-examines this critical issue of intraoperative blood loss monitoring from the perspective of actual clinical surgery and anesthesiology. We analyzed the structural reasons for the long-term unreliability of IBL clinical measurements and proposed some core principles for future surveillance strategies. Traditional methods for assessing intraoperative blood loss include visual estimation, gravimetric methods, volumetric methods, and laboratory or spectrophotometric methods. These methods all have inherent limitations. We believe these shortcomings are not isolated technical problems, but rather stem from a design philosophy that did not address the needs of clinical decision-making from the outset. To better explain the clinical challenges faced by IBL monitoring, we propose the "Irreconcilable Triangle of IBL Monitoring" model. This model consists of three conflicting requirements: accuracy, timeliness, and workflow compatibility. Optimizing one dimension of technology inevitably compromises other dimensions. Therefore, we redefine accuracy as "functional accuracy". That is, the accuracy of intraoperative bleeding monitoring should reach the level necessary to support intraoperative clinical decision-making, without pursuing absolute accuracy. Simultaneously, it should be made as time-relevant and clinically feasible as possible to meet clinical needs. This paper envisions future strategies for intraoperative blood loss monitoring. Future clinical practice requires automated equipment capable of continuously quantifying free blood, absorbed blood, and blood clots, shifting from inferential estimation to direct automated measurement. Furthermore, this equipment must be seamlessly integrated into the anesthesia workflow. The paper discusses the availability of artificial intelligence (AI) in surgical blood loss monitoring. We believe that while AI has limitations in interpretability, it can serve as a complication prediction and backend computational tool for the entire monitoring system. In the future, we hope to develop IBL monitoring into an integrated system centered on clinical usability and decision relevance through new technology development and system integration.

Keywords: Intraoperative blood loss, monitoring techniques, irreconcilable triangle, theoretical framework, anesthetic intervention

Introduction

Proper measurement intraoperative blood loss (IBL) is a cornerstone of the safety of the perioperative process and the enhancement of anesthetic care [1]. It is the foundation for anesthesiologists to formulate key decisions such as fluid resuscitation, blood transfusion, and hemodynamic support, which directly affect the postoperative outcome of patients [2, 3]. The underestimation of blood loss can result in the delay of vital interventions leading to the likelihood of hypovolemia and tissue hypoxia, whereas its overestimation leads to a risk of unnecessary transfusions, subjecting patients to transfusion-related lung injury, circulatory

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overload, and coagulation disorders [4]. Despite the clinical importance of blood loss monitoring, reliable IBL monitoring remains one of the most challenging issues in modern anesthesiology [5].

Other conventional ways of estimation which comprise of visual estimation and weight-based estimation are the simplest and easy to carry out but not that accurate [6-9]. There have been reports in the literature that even in experienced clinicians, interobserver variability generally ranges over 30 percent -50 percent, even though alternative quantitative procedures based on laboratory or photometric methods are possible, at a cost of dramatically multiplying the physician-to-patient task load as well as disturbing the regular clinical workflow [5, 7, 10-13]. Furthermore, the delays associated with these methods diminish their clinical utility [14, 15]. Therefore, intraoperative blood loss monitoring still largely relies on the most traditional visual experience, despite its proven low accuracy.

Anesthesiologically speaking, the clinical results of intraoperative blood loss are related to the change in circulating blood volume, oxygen delivery, and tissue perfusion. Therefore, intraoperative blood loss is not just a number; it's a living body's signal [16, 17]. The clinical significance of IBL monitoring does not depend solely on its accuracy, but also on how timely and feasible it is. At present, there is no one method that can meet all of these needs at the same time, indicating a structural problem rather than a technological issue. Thus, this review re-examines IBL monitoring from a decision-centered framework, aiming to clarify the reasons for the inadequacy of existing methods and provide theoretical insights for the development of future IBL monitoring systems.

Clinical significance and current challenges

Safety and anesthetic care in the operating room largely depends on reliable monitoring of intraoperative blood loss (IBL). To anesthesiologists, it gives the basic physiological data in making the decision regarding fluid resuscitation and blood transfusion. Anesthesiologists can evaluate the circulatory changes of patients based on blood loss volume and implement timely clinical interventions [18]. Accurate and dynamic assessment of intraoperative blood loss can help anesthesiologists identify hemorrhage early and prevent hypoperfusion, while avoiding the risks of excessive transfusion and fluid overload [19]. For surgeons, real-time blood loss information can guide them to perform hemostasis in a timely manner and control the surgical pace. More so, the availability of blood loss data allows more precise and effective substitution of information between surgeons and anesthetic personnel, and this, in turn, directly influences the decision-making process during intraoperative conditions, as well as patient safety [20].

As well as an immediately hemodynamic control, IBL represents a variable central in the wider scope of patient blood management (PBM). In the PBM model, it is considered to be an important marker of measuring surgical quality and complexity [21]. In terms of blood product management, quantitative assessment of intraoperative blood loss serves as a key evidence-based medical basis for intraoperative transfusion practices [22, 23]. Meanwhile, in clinical research, the recorded blood loss volume is often used as an indicator of surgical trauma, technical proficiency and prognostic risk. Moreover, numerous studies have demonstrated that blood loss is highly correlated with postoperative morbidity, length of hospital stay and mortality [24-26].

Although quantification of intraoperative blood loss has much clinical and scientific value, timely and accurate quantification in clinical practice is still challenging to control. Despite the appearance of a great number of methods of intraoperative blood loss monitoring during the past decades, the ugly truth is that the overwhelming majority of clinicians continue to use the most inaccurate visual estimation of the latter in real clinical practice. This lack of correspondence between technological innovation and clinical use is not merely about the technical flaws of a certain person, but also the structural limitations of the majority of the existing measurements.

As illustrated in **Table 1**, different representative estimation techniques, such as gravimetric, colorimetric, photometric, spectrophotometric, feature-based imaging, formula-based computation and physiological surrogate indices conceptually conform to a shared collection of failure mechanisms. Common limita-

Table 1. Conceptual mapping of representative blood loss estimation approaches to shared structural limitations in anesthetic practice

Representative approach category	Illustrative clinical implementation	Core underlying assumption	Dominant structural limitation in anesthetic practice	Related subsection
Visual estimation [13]	Subjective assessment of blood on sponges, drapes, and suction canisters	Human observers can reliably estimate blood volume	High interobserver variability and cognitive bias, especially during large or rapid bleeding	2.4
Gravimetric methods [27]	Weighing blood-soaked sponges or suction canisters	Weight change reflects true blood volume	Marked susceptibility to dilution by irrigation and nonblood fluids	2.1
Direct measurement methods [28]	Calibrated collection bags or delivery drapes	Collected fluid volume approximates blood loss	Inability to separate blood from other fluids; limited applicability outside selected settings	2.1, 2.5
Calculated blood loss (formula-based) [15, 37-49]	Hb or Hct change combined with estimated blood volume (e.g., Nadler, Moore, ICSH formulas)	Changes in laboratory values directly reflect hemorrhage	Strong model dependence and error propagation due to fluid shifts, transfusion, and delayed equilibration	2.2, 2.3
Colorimetric methods (Triton system) [30, 42]	Image-based estimation of blood on sponges or in canisters	Optical features reliably represent hemoglobin content	Dependence on controlled acquisition conditions; partial coverage of bleeding sources	2.4, 2.5
Photometric/spectrophotometric methods [50]	Hb extraction or optical absorbance analysis	Hemoglobin concentration can be accurately quantified	High analytical accuracy but delayed availability and workflow disruption	2.2
Physiologic surrogate methods [51]	IVC ultrasound, esophageal Doppler, near-infrared spectroscopy	Hemodynamic or tissue signals indirectly reflect blood loss	Indirect inference; lack of specificity for hemorrhage	2.2, 2.5
Noninvasive hemoglobin monitoring [52]	Continuous SpHb or similar optical sensors	Peripheral Hb trends reflect acute blood loss	Susceptibility to motion, perfusion, and dilution effects; delayed correlation with true bleeding	2.2, 2.3

Note: This table provides a conceptual illustration of shared structural limitations rather than a comparative evaluation of accuracy or performance. Categories are derived from commonly described methods in the perioperative literature.

tions of the methods are susceptibility to dilution, time lapse between measurement and clinical intervention, dependency on simplifying assumptions, operator variability, and an incomplete characterization of the sources of bleeding and not the defect of the specific method.

These structural limitations will be discussed in detail in the following subsections.

Dilution effect

Irrigation fluids, urine, amniotic fluid, and peritoneal effusions are some of such non-blood fluids that change the composition of the collected fluids during surgery. Thus, the quantity of fluid as indicated by the suction cup or damp sponge is hardly accurate for the quantity of blood loss. Both gravimetric and volumetric methods assume that the amount of collected volume is an accurate measure of blood loss. However, the dilution effect of other body fluids and irrigation fluids invalidates this assumption [27-29]. This difference leads to a significant increase in the error in blood loss measurement and misleads critical decisions such as fluid resuscitation and transfusion, especially in cases of prolonged surgery or when extensive irrigation is required [30]. Accordingly, such methods may remain operationally simple but are intrinsically limited in decision-relevant accuracy under fluid-contaminated conditions.

Analytical latency

A central limitation of many intraoperative blood loss monitoring methods is analytical latency. In real clinical settings, the value of a monitoring signal depends not only on how accurate it is, but also on whether it becomes available early enough to support intervention. Measurements that are obtained only after blood collection, laboratory processing, or delayed physiological equilibration may be analytically informative, yet still provide limited help for real-time anesthetic decision-making. This problem is especially evident in formula-based approaches relying on hemoglobin or hematocrit changes, because these indicators often lag behind acute bleeding and are easily influenced by fluid redistribution, transfusion, and ongoing resuscitation [31-33].

The same limitation applies to many photometric or laboratory-based techniques. Although these approaches may perform well under controlled conditions, the time required for sample handling and analysis often reduces their usefulness during rapidly changing intraoperative events. By the time the result is available, the patient's hemodynamic condition may already have changed, weakening the practical value of the measurement for immediate fluid or transfusion management. In this sense, a method with slightly lower analytical precision may still be more clinically useful if it provides timely and actionable information.

Physiologic surrogate signals can respond quickly. However, they are indirect and not specific to bleeding. Similar changes may also result from anesthetic depth, vasoactive drugs, patient positioning, or other nonhemorrhagic factors. Noninvasive hemoglobin monitoring can support continuous trend tracking. However, its performance can be affected by poor peripheral blood flow, patient movement, and dilution of blood after fluid infusion. This limits its reliability as a stand-alone method for precise intraoperative blood loss assessment. These limitations show that timeliness alone is not enough. A clinically useful monitoring method must also provide information that is interpretable and relevant to real-time anesthesia care.

Formula constants generates propagation of errors

The estimation techniques based on the formula are often the computations of variations in the red blood cell volume or even the hemoglobin concentration. The approaches usually consider the blood volume of the patient as a central data number into the formula [34]. These methods typically incorporate the patient's blood volume as a core data point into the formula. Before surgery, the physician or anesthesiologist calculates the patient's blood volume using a blood volume calculation formula and simply incorporates this value as a constant into the formula [35-38]. However, in reality, the blood volume upon which these models rely is highly sensitive to physiological variations such as vascular tone and changes in capillary permeability. Even small deviations in the assumed parameters can propagate through subsequent calculations, leading to significant estimation errors [39, 40]. Therefore, these mathematically complex models often perform poorly when faced with the dynamic fluid transfer and hemodynamic fluctuations specific to real surgical conditions.

Subjective estimation leads to huge errors

Visual estimation still dominates in clinical practice. The main reason is that it provides immediate feedback and has minimal disruption to the workflow [10]. However, it is also the most error-prone method. Perceptual differences, cognitive load, and environmental factors can lead to large inter-observer variability, thus reducing reliability. Literature has demonstrated that semi-quantitative visual aids or colorimetric tools can be biased. However, for routine use, the increased clinical workload is too costly to justify the slight improvement in accuracy [13, 41]. Despite the widespread recognition of the inaccuracy of visual estimation, this method remains popular. The biggest reason is that it is more compatible with workflow requirements than any other method.

Troubled monitoring due to fractionated blood loss

Another major reason why intraoperative blood loss is difficult to quantify is that bleeding is often scattered across multiple sources rather than collected in a single measurable stream. In real surgical settings, blood may be found at the same time in suction canisters, blood-soaked gauze, drapes, the surgical field, hidden cavities, and clotted areas [29, 30, 42]. Because of this, it is difficult for any single method to capture the full amount of blood loss in a complete and coordinated way. Even if one part is measured well, the unmeasured part may still be clinically significant. This incomplete capture may create a false sense of precision, especially when the measured portion is treated as if it reflects total blood loss.

This challenge affects both traditional and newer monitoring methods. Direct collection-based approaches can measure blood gathered in a specific container, but they cannot fully account for diffuse bleeding, retained blood, or blood spread across multiple surfaces. In the same way, image-based and optical methods can improve the objectivity of visible blood assessment, but they are still limited by what can actually be seen and recorded within the measurement area. In practice, colorimetric systems offer a relatively good balance between accuracy and near real-time use, but their performance still depends on imaging conditions and they may not capture every source of bleeding.

The irreconcilable triangle in intraoperative blood loss monitoring

In the context of anesthesiology the clinical goal of IBL follow-up is entirely different compared to the clinical goal of retrospective surgical reports. In the case of anesthesiologists, blood loss is a complex sporadic physiological stress factor that constantly changes intravascular volume, oxygen delivery and cardiovascular stability. The informational worth of any measurement thus is not based solely on numerical accuracy, but also temporal relevance as well as compatibility with the intraoperative workflow.

The decades of the research have proven that no single method can suit all the three dimensions at the same time. What one gets better, the other gets worse, which forms the idea of a structural conflict that can be viewed as the concept of the irreconcilable triangle (**Figure 1**). The conflicting priorities that limit present and future monitoring systems are indicated by its vertices namely accuracy, timeliness, and workflow integration.

Accuracy: clinical precision and functional relevance

Accuracy is an essential part of any clinically credible monitoring system. However, in anesthetic practice, accuracy does not mean perfect agreement with the exact blood loss volume in every milliliter. What matters more is whether the information is accurate enough to support timely and appropriate action. Although photometric and laboratory-based methods may show low analytical bias under controlled conditions, their complexity and delay often reduce their usefulness during rapidly changing intraoperative events [43].

In daily practice, anesthesiologists need monitoring results that help guide the next decision. This may include continuing routine observation, increasing surveillance, reassessing the patient more closely, or preparing for fluid resuscitation and transfusion. Current transfusion guidelines provide useful reference points

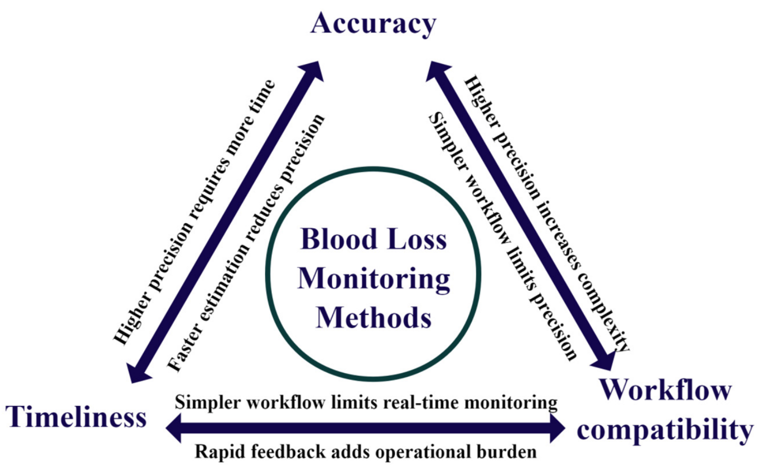

Figure 1. The irreconcilable triangle of intraoperative blood loss monitoring.

for this kind of decision-oriented accuracy. The 2023 AABB guideline recommends a restrictive strategy and suggests considering transfusion when hemoglobin is below 7 g/dL in most hemodynamically stable adults. It also notes that clinicians may choose thresholds of 7.5 g/dL for cardiac surgery and 8 g/dL for orthopedic surgery or for patients with preexisting cardiovascular disease [44]. NICE guidance similarly supports a threshold of 70 g/L for patients without major hemorrhage or acute coronary syndrome, and a threshold of 80 g/L for acute coronary syndrome [43].

We use the term functional accuracy to describe this clinically useful level of performance. A method is functionally accurate if it provides information reliable enough to support the same general management direction that would be chosen under a better reference-based assessment. This does not mean that the method must reproduce the true blood loss volume exactly. Instead, it should help clinicians judge whether the patient is still in a routine monitoring phase, is entering a higher-risk zone, or may be approaching a point where stronger intervention is needed [45].

Hemoglobin should not be treated as the only decision trigger. Existing reviews of intraoperative transfusion decision-making show that current guidance also considers blood loss, hemodynamic status, and signs of end-organ ischemia. This is especially important during active intraoperative bleeding, when a single laboratory value may lag behind the clinical situation. For this reason, functional accuracy is better understood as decision-relevant accuracy rather than milliliter-level precision alone [45].

Timeliness: the necessity of real-time response

Timeliness is very important in converting the data of blood loss into good data of clinical action. Surgical bleeding may be unpredictable and increases within minutes meaning that there is a very small period when it is reasonable to intervene before the situation is beyond repair. The data concern blood loss, derived either post-operative or retrospectively once physiological homeostasis has been regained are only utilized largely either in documentation or research purposes. This delayed information is not of much use in informing intraoperative decisions on fluid resuscitation, vasopressor support, or transfusion. Even the minor delays in some cases, like obstetric uterine atony, or major vascular surgery, may result in the hemodynamic collapse. With regard to patient safety, untimely feedback probably would be more hazardous than moderate inaccuracy.

Nowadays, the vast majority of quantitative monitoring techniques do not suffice this requirement to use instantly. Most photometric techniques involve laboratory work which delays reports through processing of the samples. As the results are provided, the hemodynamic state of a patient can be different. The effect of this lack of place and time is the sabotage of the aim of monitoring. Both theoretically and practically, timely signals, albeit somewhat less precise, are more clinically useful in comparison with delayed but true measurements. This is in the sense that it allows the anesthesia staff to intervene, instead of dealing with it passively.

Workflow compatibility: an underestimated dimension

The issue of compatibility of the workflows is the deciding factor of the survivability of an intraoperative bleeding monitoring technology

Table 2. Multidimensional semi-quantitative comparison of representative intraoperative blood loss (IBL) monitoring approaches

Method class (aligned with **Table 1**)	Accuracy (1-5)	Timeliness (1-5)	Workflow compatibility (1-5)	Cost	Training burden	Evidence anchor (key refs)
Visual estimation	1	5	5	Low	Low	High interobserver variability; rapid but subjective [6, 10, 13, 38]
Gravimetric methods	2	4	3	Low	Low	Dilution by irrigation/fluids limits validity [8, 9, 27]
Direct Measurement Methods	2	4	3	Low–Moderate	Low	Collected volume confounded by non-blood fluids; restricted settings [28, 29]
Formula- and surrogate-based monitoring	2	1	2	Low	Moderate	Model dependence + delayed equilibration; error propagation [15, 34, 32-35]
Photometric/spectrophotometric methods	4	1	1	High	High	High analytic accuracy but offline/slow and workflow disruptive [50]
Physiologic surrogate methods	2	4	3	Moderate	High	Indirect, nonspecific inference for hemorrhage [40, 51, 53]
Colorimetric methods (Triton system)	4	3	2	High	High	Sensitive to lighting/positioning; algorithm robustness limits [30, 42]
Noninvasive hemoglobin monitoring	2	4	4	High	Low	Continuous trend but affected by perfusion/motion/dilution [31, 52]

Note: Ratings are presented as semi-quantitative comparative assessments of representative intraoperative blood loss estimation methods under routine operating-room conditions. Scores were assigned on the basis of published validation evidence, consistency relative to available reference standards, and pragmatic feasibility in anesthetic practice; they are intended to support structured comparison rather than formal evidence-weighted ranking. Accuracy refers to functional (decision-relevant) accuracy, namely whether a method is sufficiently reliable to support intraoperative management decisions such as escalation of surveillance, fluid resuscitation, and transfusion-related intervention, rather than strict milliliter-level equivalence to true blood loss. Accuracy (1-5): 1 = highly variable or systematically biased, with limited value for clinical decision support; 2 = low reliability and substantial susceptibility to confounding factors; 3 = moderate reliability, generally sufficient for rough estimation or trend recognition; 4 = good reliability in clinically relevant settings, with acceptable agreement for most practical purposes; 5 = consistently high reliability approaching reference-standard performance. Timeliness (1-5): 1 = retrospective or offline output not suitable for immediate intraoperative intervention; 2 = substantial delay before actionable information becomes available; 3 = intermittent or near-real-time output; 4 = promptly updated information with minor delay; 5 = continuous real-time output. Workflow compatibility (1-5): 1 = substantial manual burden or major disruption to routine workflow; 2 = considerable additional handling, equipment interaction, or operator attention required; 3 = feasible in routine practice but requiring moderate user interaction; 4 = generally well integrated with minor workflow burden; 5 = highly automated and seamlessly integrated into intraoperative workflow. Cost and training burden are presented as qualitative implementation requirements at the institutional level and are categorized as Low, Moderate, or High.

in the conditions of an operating room. Anesthesiologists must be able to accomplish many tasks in a highly limited period of time in the high-intensity surgical setting: ventilator control, administration of medication, observation of the provided data, and contact with the surgical team. Monitoring that interrupts the workflow by distracting the healthcare professionals regardless of the level of its analytical capability will hardly be embraced among the masses.

Numerous high technologies fail to comply with this need. Most forms of monitoring have physicians manually adjusting devices or machinery or re-processing of samples, complicating the operation and teamwork. Even semi-automated systems might force the user to be interrupted with operation or trouble shooting to generate workflow friction in a subtle but cumulative way. Such minor breakdowns eventually can erode trust among the anesthesiologists and the surgical team leading to less compliance and at times well-intended innovations may be pushed out of circulation.

The only way to achieve the actuality of workflow compatibility is to have blood loss monitoring technology act as an independent, nonstop, and non-obtrusive element of the perioperative ecosystem, and not a proactive unit that adds the extra labor expenses. Ideally, technology on blood loss monitoring should be installed flawlessly on the prevailing anesthesia workstations, electronic medical records, and decision support interfaces. It must be able to give the needed information without having to undergo more operations.

Balancing the triangle

In intraoperative blood loss monitoring, improving one aspect often comes at the expense of another. Methods with higher accuracy usually require more time, more processing steps, or greater manual effort, which reduces their value in fast-changing clinical situations. By contrast, methods that are rapid and easy to use are often more subjective and less reliable. Likewise, approaches that fit smoothly into routine workflow do not always provide sufficiently rigorous quantitative information. This persistent imbalance among accuracy, timeliness, and workflow compatibility helps explain why decades of technical development have not yet produced an ideal monitoring method for routine clinical use.

This problem is not simply due to the limitations of individual technologies. More fundamentally, it reflects a structural conflict within current models of blood loss monitoring. To make this contradiction more visible, **Table 2** presents a semi-quantitative comparison of current IBL monitoring approaches using predefined criteria for accuracy, timeliness, and workflow compatibility. These ratings are intended to summarize published evidence together with practical clinical usability, rather than to provide a formal evidence-weighted ranking. The comparison shows a consistent pattern: highly accessible methods such as visual estimation perform well in timeliness and workflow integration but poorly in accuracy, whereas analytically stronger methods often suffer from delayed results or poor clinical integration.

Figure 2 further illustrates this problem from a developmental perspective. It shows how intraoperative blood loss monitoring has evolved from subjective empirical estimation toward more quantitative and technology-assisted approaches. Although later methods improved objectivity and analytical capability, the basic trade-offs among accuracy, timeliness, and workflow compatibility have remained largely unchanged. In other words, the field has advanced in technique, but not yet fully in paradigm. This ongoing tension suggests that the limitations of current monitoring are not only technical, but also conceptual.

Recognizing this conflict, we argue that meaningful progress in IBL monitoring will not come from incremental technical refinement alone, but from redefining what counts as clinical success. A useful monitoring approach must achieve a workable balance among accuracy, timeliness, and workflow compatibility, rather than maximizing only one of these dimensions. From the perspective of anesthesia practice, the value of a method lies not only in how precisely it measures blood loss, but also in whether it can deliver actionable information at the right time and in a form that fits routine care.

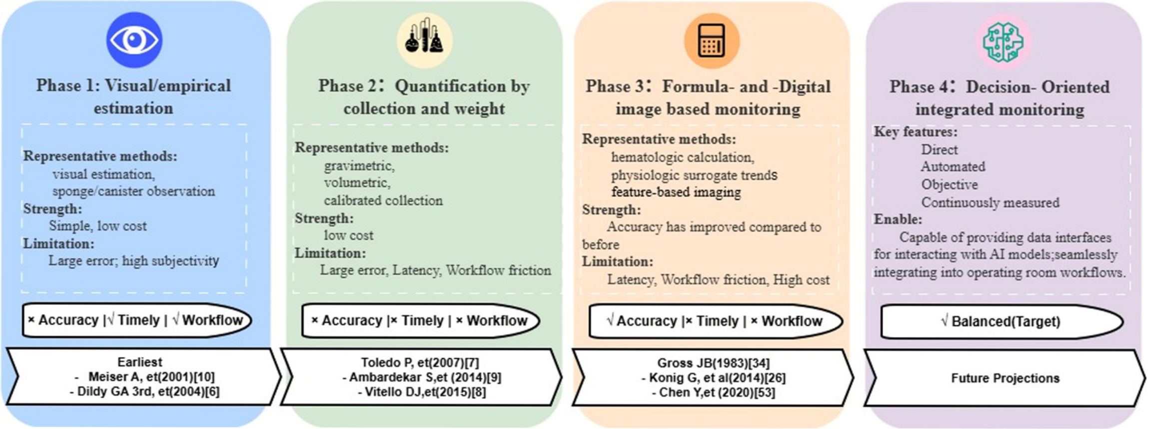

Figure 2. Evolution of intraoperative blood loss monitoring paradigms.

Future projections: to automated and intelligent monitoring

The constraints outlined under the irreconcilable triangle model tend to indicate that future developments in IBL surveillance will not be due to some kind of advancements on the current processes. The next generation surveillance systems should balance accuracy in analysis and clinical usefulness by incorporating automation, direct measurement, decision relevancy, and together develop them into a new design philosophy. The critical attributes of the future surveillance systems can be summed up as follows.

Automation and direct measurement

Future blood loss monitoring technologies should focus on accurate, objective direct quantification of blood loss, while abandoning conventional empirical estimation methods. Unlike current techniques that depend on surrogate indicators such as hemoglobin levels or aspirated fluid volume, direct measurement approaches must capture total blood loss in full scope - covering free blood, blood adsorbed on surgical instruments, and residual coagulated blood. Systems built on this principle can reduce interference from key confounding factors, including intravenous fluid infusion, internal fluid redistribution, and fluctuations in vascular tone.

Automation is another core priority for future development. Fully automated systems support uninterrupted real-time data analysis without disrupting clinical workflows or requiring manual operation. By removing manual calibration and subjective judgment from the process, automation improves data uniformity and ensures timely, reliable results. Furthermore, such robotic medical devices add no extra workload for surgical staff, and can deliver continuous blood loss updates directly to anesthesiologists [46].

This study also proposes several design ideas for intraoperative blood loss (IBL) monitoring systems. For instance, regarding blood absorbed by surgical gauze, we envision an automated monitoring device that elutes residual blood from gauze; the resulting eluate can then be analyzed by an automatic detection module. That said, there is currently no feasible method to directly measure hemoglobin concentration inside blood clots, so direct quantification of clotted blood remains unachievable at this stage. As a practical weight-based workaround, we recommend establishing a linear correlation between clot weight and corresponding blood volume. Since clots formed from blood with different hemoglobin concentrations differ in weight, a standardized weight correction factor must be introduced for calibration. Notably, no weight-based automated equipment of this type has been documented in existing literature, making it a valuable direction for future research and innovation. This multidimensional detection approach is critical to reflecting the true volume of actual perioperative blood loss.

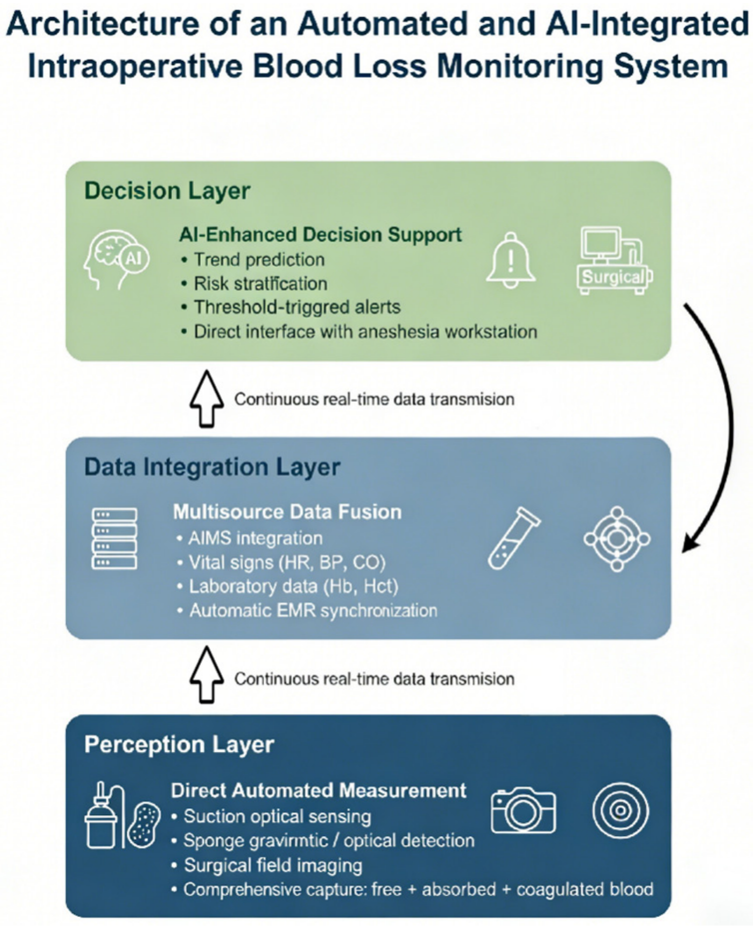

Figure 3. Conceptual architecture of automated and AI-enhanced intraoperative blood loss monitoring.

Integration and workflow synergy

Ideally, IBL monitoring systems are only meant to complement current workflows, and they are not to compete with them. To be more specific, both the data acquisition and computation are supposed to be active in the background, yet with the inactivity of the surgical or anesthesia team.

The appropriate bleeding data ought to be presented in the screen in a cumulative curve, just like the one presented in ECG monitors. Such systems would be able to produce predictive early warning with an appropriate integration of these systems. Alerts are automatically issued by pre-established thresholds, and only when significant clinically, they are issued in form of brief and actionable messages. Transfusion algorithms or hemodynamic support recommendation can also be correlated directly with such alerts.

We suggest a new closed-loop architecture as presented in **Figure 3**. This framework includes three layers, which are interdependent: a perception layer that measures data directly, an integration layer that fuses and multi-source data and uses it to help make a decision, and a decision layer that will rely on AI-enabled clinical decision support. IBL monitoring systems can be introduced with existing anesthesia information management systems (AIMS), vital signs displays and decision support dashboards under this architecture. This will dramatically improve physician dependency, which will see the system continue to be clinically used.

Artificial intelligence and predictive decision support

Considering the architecture depicting in **Figure 3**, we consider artificial intelligence (AI) as an interpretation layer relying upon reliable and continuously obtained data. In conceptual terms, AI solutions can enhance accuracy, timeliness, and compatibility of workflow simultaneously through adaptive learning, and, in fantasy, would be used to solve the irreconcilable apparent contradictions between the three aspects [47, 48]. Nevertheless, even the existing implementations are still constrained by black-box operation, the generalization of data and the interpretation of the clinical meaning.

We would suggest a more realistic and clinically plausible application path forward that is to install AI into a closed loop mechanism founded on direct automated measurement. Pattern recognition, risk prediction and trend extrapolation need to be regarded as the priorities of AI when the data that can be trusted upon (e.g. heart rate or blood pressure in the arteries) are measured constantly. In this paradigm of automated direct measurement, AI is invaluable or cannot be replaced because it can read and comprehend the numerous streams of data created by direct measurement which is what is referred to as seamless integration of these diverse streams.

On one side, AI is able to do data computed and integrated, eliminating human mistakes and delays that can take place during the course of manual data processing. Moreover, it could identify early variations in the trends of bleeding that may have been missed by observing the patients in a clinical setting, by implementing machine learning or deep learning models and promptly provide intervention suggestions. The other benefits of artificial intelligence are that it can match predictions to the physiological features of the individual patients simultaneously that the recommendations are in line with the clinician-specific characteristics of the individual customers. The objective measurement and intelligent interpretation hybrid type is an approach to predictive anesthesia management giving a transparent and clinically traceable pathway.

Conclusion

Years of technological progression have not made intraoperative blood loss measurement to satisfy the necessities of precision, quickness and smooth incorporation, which has comparatively confined the progression of the perioperative medicine. To cope with this challenge, this paper will introduce an irrefutable triangle framework, which explains why the existing previous solutions have failed and what directions should be taken to achieve the most effective future innovations. We also highlight that technical precision is not the most critical aspect of the successful clinical implementation of the IBL monitoring technology, and it is clinical applicability and decision relevance.

We establish the desirable attributes of future IBL monitoring systems. Above all, these systems should transition to direct, automated and integrated measured data, as opposed to estimation, to present dependable real-time data without disrupting clinical work. Such systems, in conjunction with artificial intelligence-based interpretation tools, can enable to convert the intraoperative blood loss monitoring as a descriptive indicator to into a predictive indicator with support decisions to assist anesthesiologists in developing focused intervention plans.

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Disclosure of conflict of interest

None.

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