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Population-based Assessment of Intraoperative Fluid Administration Practices Across Three Surgical Specialties

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Abstract

Objective—To assess the variation in hospitals' approaches to intraoperative fluid management and their association with postoperative recovery.

Background—Despite increasing interest in goal-directed, restricted-volume fluid administration for major surgery, there remains little consensus on optimal strategies, due to the lack of institution-level studies of resuscitation practices.

Methods—Among 64 hospitals in a state-wide surgical collaborative, we profiled fluid administration practices during 8404 intestinal resections, 22,854 hysterectomies, and 1471 abdominopelvic endovascular procedures. We computed intraoperative fluid balance, accounting for patient morphometry, crystalloid, colloid, blood products, urine, blood loss, duration, and approach. We stratified hospitals by average fluid balance quartile, and compared patterns across disciplines and associations with risk-adjusted postoperative length of stay (pLOS).

Results—There was wide variation in fluid balance between hospitals ($P < 0.001$, all procedures), but significant within-hospital correlation across operations (Pearson rho: intestinal-hysterectomy = 0.50, intestinal-endovascular = 0.36, hysterectomy-endovascular = 0.54, all $P < 0.05$). Highest fluid balance hospitals had significantly longer adjusted pLOS than lowest balance hospitals for intestinal resection (6.5 vs 5.7 d, $P < 0.001$) and hysterectomy (1.9 vs 1.7 d, $P < 0.001$), but not endovascular (2.1 vs 2.3 d, $P = 0.69$). Risk-adjusted complication rates were not associated with fluid balance rankings.

Conclusions—Hospitals' approaches to intraoperative fluid administration vary widely, and their practice patterns are pervasive across disparate procedures. High fluid balance hospitals have 12% to 14% longer risk-adjusted pLOS for visceral abdominal surgery, independent of patient complexity and complications. These findings are consistent with evidence that isovolemic resuscitation in enhanced recovery protocols accelerates recovery of bowel function.

Keywords

enhanced recovery; fluid resuscitation; outcomes; surgery

With the emergence of enhanced recovery protocols and fasttrack discharge pathways after major surgery,^{1–3} there is increasing scrutiny of postoperative length of stay (pLOS)^{4–7} and time to recovery.^{8,9} Increasingly, traditional perioperative care practices, including preoperative fasting, confinement to bed, nasogastric intubation, and narcotic analgesia, have been implicated in delayed recovery from major abdominal surgery.² Likewise, many proponents of enhanced recovery practices have cited hypervolemic crystalloid resuscitation as a cause of delayed return of bowel function, postoperative ileus, and prolonged hospitalization after a variety of operations.^{10–12} In most settings, however, decisions about the volume of intraoperative fluid administered remain largely in the control of anesthesia providers who lack specific clinical guidelines and suffer from a scarcity of evidence to guide their practice.^{13–15} As a result, their fluid administration volumes during otherwise similar procedures can vary 4-fold.^{15,16}

In the past, fluid administration strategies were derived from beliefs about basal fluid requirement, insensible losses, and third space fluid distribution. However, all of these principles have been questioned by more recent physiologic studies.^{13,17} Randomized trials of conservative versus liberal fluid administration after surgery have varied widely in their definitions for high and low volume, and in their methodology, and, as a result, have produced conflicting findings about the relationship between fluid volume and postoperative outcomes.^{11,14,18–21} In observational studies with analyses at the patient level, there is an association between fluid administration volume and pLOS and ileus in colorectal surgery.^{22,23} But it remains unclear whether these outcomes, and the differences in fluid volume, are driven more by differences in patient characteristics and intraoperative events or by true differences in the approach to fluid balance.

To better evaluate the role of intraoperative fluid administration practices on time to postoperative recovery in real-world practice, we evaluated hospital-level patterns in fluid balance, accounting for the patient and procedural factors that typically guide anesthesiologists' treatment decisions. Rather than focusing on difference in fluid received by individual patients, which may reflect operative severity more than practice pattern, we examined hospitals' average intraoperative fluid administration, which more reflects their approach to fluid management practices. We hypothesized that these practices would vary significantly between hospitals, and that, because intraoperative decisions are made largely by anesthesiologists, these practice patterns would extend across varied operations. Thus, we examined variation in intraoperative fluid administration between hospitals participating in a state-wide surgical collaborative, and assessed the relationship between fluid practices and postoperative recovery and clinical outcomes across 3 diverse surgical specialties.

METHODS

Setting

This is a retrospective cohort study from the Michigan Surgical Quality Collaborative (MSQC), a voluntary network of 64 hospitals that collect data on surgical patients for the purpose of quality improvement.^{24,25} The MSQC is funded by Blue Cross Blue Shield of Michigan, a private, not-for-profit insurance company. Although Blue Cross Blue Shield provides financial support for the project, they are not involved in the policy recommendations that are developed within the collaborative. MSQC hospitals are predominantly community hospitals. Each participating hospital employs at least 1 trained Surgical Clinical Quality Reviewer to prospectively collect data on general, gynecologic, and vascular surgery patients, their operations, and 30-day outcomes. Patient selection uses an algorithm designed to minimize selection bias. MSQC data collection is Institutional Review Board exempt, and the current study was performed with University of Michigan Institutional Review Board review, from a limited data set derived from the MSQC database.

Patients and Procedures

We included all patients who underwent 1 of 3 categories of operations under general anesthesia between July 1, 2012 and April 30, 2015 on an elective basis. We excluded urgent and emergency operations to minimize bias. The “intestinal resections” included any small or large bowel resection, with or without anastomosis and/or stoma—CPT codes 44120, 44125, 44140, 44141, 44143, 44144, 44145, 44146, 44147, 44150, 44151, 44155, 44156, 44157, 44158, 44160, 44187, 44188, 44202, 44204, 44205, 44206, 44207, 44208, 44210, 44211, 44212, 44227, 44310, 44661, 45110, 45111, 45112, 45113, 45114, 45119, 45135, 45395, 45397, 45402, 45550. Hysterectomy included open abdominal, minimally invasive abdominal, and vaginal approaches—CPT codes 58150, 58152, 58180, 58200, 58210, 58240, 58260, 58262, 58263, 58267, 58270, 58275, 58280, 58285, 58290, 58291, 58292, 58293, 58294, 58541, 58542, 58543, 58544, 58548, 58550, 58552, 58553, 58554, 58570, 58571, 58572, 58573, 58951, 58953, 58954, 58956. The “endovascular” group included aortoiliac endovascular operations according to CPT codes 34800, 34802, 34803, 34804, 34805, 34825, 37220, 37221, 37222, 37223. We excluded open abdominal vascular operations due to the limited sample size of hospitals performing adequate numbers of these operations within the database. We excluded outpatient cases and intraoperative deaths, as they were not eligible for the primary outcome.

Measures

The primary outcome variable was the pLOS, defined from the calendar day of surgery to the day of discharge. Secondary outcomes included the occurrence within 30 days of surgery of any of the following validated postoperative clinical conditions recorded in the MSQC database (surgical site infection, pneumonia, unplanned intubation, venous thromboembolism, acute renal insufficiency or failure, urinary tract infection, cardiac arrhythmia, myocardial infarction, blood transfusion, sepsis, or death), emergency department visit, unplanned hospital readmission, intensive care unit admission, or unplanned reoperation, and also composite measures of overall morbidity (any of the

complications) and serious morbidity (complications other than renal insufficiency, superficial surgical site infection, and urinary tract infection).

The primary predictor of interest for this study was the hospital-level average intraoperative fluid balance for each type of surgery. Intraoperative fluid, colloid, and blood product administration is recorded in the MSQC database, according to the volumes recorded in the intraoperative anesthesia record. This record is either electronic or hand-written, depending on the institution. For each individual operation, we computed a normalized fluid balance according to a clinically derived formula^{26,27} that accounted for physiologically relevant potentially patient and procedural characteristics, including weight, insensitive fluid loss due to operative time and exposure, and blood loss:

$$\begin{aligned} \text{Fluid Balance} = & [\text{Crystalloid} + 1.5 * (\text{colloid} + \text{blood product})] (\text{Volume In}) \\ & - [\text{Urine Output} + 3 * (\text{estimated blood loss})] (\text{Volume Out}) \\ & - [\text{Operative duration}(\text{hrs}) * (\text{weight}(\text{kg}) + 40)] (\text{Maintenance}) \end{aligned}$$

This formula normalizes the actual volume of resuscitation (Volume In) to the expected amount of fluid requirement (Volume Out, Maintenance Requirement, and Insensible Loss).

While the specific inputs and calculation may be subject to dispute, we were focused on between hospital differences, so the uniform application of the formula makes these uncertainties less important here. Further, because we were primarily interested in the effect of institutional practice patterns, rather than patient characteristics, on fluid administration, we analyzed fluid balance at the hospital level. Average fluid balance for each hospital was then computed as the arithmetic mean of the normalized balance of each of the operations performed in the hospital during the study period.

Statistical Analyses

We evaluated the relationships between fluid balance and patient and procedural characteristics using Kruskal-Wallis analysis of variance on ranks. We constructed caterpillar charts to display variation in scores across hospital for each individual operation, then compared hospital-level correlations in fluid balance across operations using Pearson rank correlation coefficients, and displayed the associations with fitted scatter plots.

To compare hospital characteristics and clinical outcomes according to fluid administration practices, we then ranked and grouped hospitals into 4 evenly-sized quartiles by average normalized fluid balance by operation. There were 64 hospitals eligible for analysis of intestinal resections, 63 hospitals for hysterectomy, and 45 hospitals for endovascular procedures. We compared hospital characteristics and outcomes across quartiles using Kruskal-Wallis tests. Outcomes were risk-adjusted according to the following patient and procedural characteristics: age, sex, race, insurance, body mass index, American Society of Anesthesiologists (ASA) physical status classification, alcohol use, smoking, procedure, operative approach, and number of comorbidities (diabetes mellitus, ventilator dependence, dyspnea before current illness, COPD, pneumonia, ascites, cirrhosis, congestive heart failure within 30 days before surgery, history of cardiac dysrhythmias requiring treatment, hypertension, history of peripheral vascular disease, currently requiring or on dialysis, UTI,

disseminated cancer, HIV/AIDS, open wound, use of steroids/immunosuppressive medications for a chronic condition, >10% loss of body weight in the 6 months before surgery). Length of stay for patients who died during index hospitalization was treated as time from operation to death, because the time to death among mortalities was no different across any of the fluid group comparisons, and there was no difference in the main findings in a sensitivity analysis in which we excluded deaths from length of stay analyses.

RESULTS

Patient and Procedural Characteristics and Intraoperative Fluid Balance

We identified 8404 intestinal resections, 22,849 hysterectomies, and 1471 abdominal endovascular procedures eligible for analysis during the study period. Fluid balance was normalized, according to the method described above. The average fluid balance and standard deviation across all patients was 1758 ± 1654 for intestinal, 1059 ± 1331 for hysterectomy, and 848 ± 1338 for endovascular. As displayed in Figure 1, average fluid balance varied widely between hospitals, from 703 to 2933 for intestinal, 462 to 1612 for hysterectomy, and -597 to 2459 for endovascular. Further, hospitals' fluid practices were significantly and positively correlated across operations (Pearson correlation coefficient: $r = 0.36$ for intestinal vs endovascular, $P = 0.014$; $r = 0.50$ for intestinal vs hysterectomy, $P < 0.001$; $r = 0.54$ for hysterectomy vs endovascular, $P = 0.0057$).

Average fluid balances, according to patient characteristics, are displayed in Table 1. For intestinal resections (Table 1A), average normalized fluid balance was higher for patients who were younger, male, non-white, ASA 2 or 3, with fewer comorbidities, tobacco or alcohol users, and having surgery for inflammatory disease, rather than neoplasm. Findings for hysterectomy (Table 1B) were relatively similar, except that operations for malignancy had significantly higher fluid balance than those for other indications. For endovascular (Table 1C), higher fluid balance was associated with age less than 75, fewer comorbidities, and tobacco use, but not with sex, race, body mass index, ASA class, or alcohol use.

Among patients who received intraoperative vasopressors, the average fluid balance was slightly higher for hysterectomy (1118 vs 1052 mL; $P < 0.001$), but was not significantly different for intestinal or endovascular operations. Epidural use was associated with higher intraoperative fluid balance for intestinal resections (1967 vs 1712 mL; $P = 0.03$) and hysterectomy (1327 vs 1052 mL; $P < 0.001$), but not for endovascular operations. Epidural use was far less common among hysterectomy (2.8% of cases) and endovascular (1.0%) than intestinal resections (17.9%).

Unadjusted associations between hospitals' average fluid balance and procedural characteristics are shown in Table 2. For intestinal resections (Table 2A), normalized fluid balance was greater for pelvic operations, total colectomy, and abdominoperineal resections than for segmental abdominal resections, and somewhat greater for operations performed open or converted from minimally invasive to open. Fluid balance in hysterectomy (Table 2B) was higher for abdominal approaches than vaginal hysterectomy, and was higher for longer operations. Among endovascular operations (Table 2C), fluid balance was higher for aortic aneurysm repairs and for shorter duration operations. For all 3 procedures, operations

with the greatest blood loss had the lowest fluid balance, suggesting that anesthesiologists were not compensating for blood loss with as much volume as the formula had predicted. Operations with longer duration had higher fluid balance for colectomy and hysterectomy, but lower fluid balance for endovascular; this is likely an artifact of the way we computed fluid balance, as operative duration is a variable in the formula.

Hospital Characteristics and Practices

Stratifying hospitals by quartiles of average normalized fluid balance for each operation, we found no significant associations between teaching status, bed size, or sampled volume, and hospital rankings for fluid balance. Likewise, there was no difference between quartiles in the proportion of minimally invasive intestinal resections and hysterectomies, or the proportion of hysterectomies performed vaginally. These data are shown in Table 3.

Association Between Intraoperative Fluid Practices and Postoperative Outcomes

Comparing risk-adjusted postoperative outcomes between quartiles of average fluid balance (Table 4), there were few notable differences. Specifically, the rates of surgical site infection, pulmonary complications, unplanned intubation, venous thromboembolism, renal failure, cardiac arrhythmia, myocardial infarction, and sepsis did not differ consistently between hospitals with highest and lowest average fluid balance. We did find significantly greater rate of emergency department visits after intestinal resection in the lowest (11.2%) and highest (9.9%) fluid balance hospitals, compared with the middle quartiles (8.1% and 8.5%; $P = 0.003$). Emergency department visit rates did not differ for the other 2 operations ($P = 0.30$ for hysterectomy and $P = 0.95$ for endovascular). Likewise, readmissions were higher among hysterectomies in the highest fluid volume quartile (4.8% vs 3.8% in the lowest quartile; $P < 0.001$), but not different for intestinal ($P = 0.38$) or endovascular ($P = 0.08$). Urinary tract infections, blood transfusions, and serious morbidity were also most common among the highest-volume quartile hospitals for hysterectomy, but there was no association for the other operations. Intensive care admissions were significantly more common in high-fluid balance hospitals for all 3 operations (all $P < 0.001$).

Postoperative length of stay, however, was significantly longer among the higher-volume quartiles for both intestinal resections and hysterectomy, as shown in Figure 2. Among intestinal resections, risk-adjusted length of stay was nearly a day greater in the highest volume quartile than in the lowest quartile (6.51 vs 5.74 d, $P < 0.001$). For hysterectomy, the average length of stay and differences between quartiles were less, but the pattern was similar, with highest quartile hospitals averaging 1.9 days to discharge, versus 1.7 days in the lowest volume quartiles ($P < 0.001$). There was no statistically significant difference in length of stay among endovascular operations ($P = 0.69$).

DISCUSSION

There is increasing interest in fast-track recovery protocols to reduce pLOS and improve the efficiency of care after major surgery. After abdominal operations, one of the most important drivers of length of stay in the absence of major postoperative complications is the occurrence of postop ileus,^{1,22,28} which has been associated, in turn, with the volume of

fluid administration during surgery.^{18,22} Thus, a common element of modern enhanced recovery protocols is the limitation of excessive intravenous fluid, and a focus on maintenance of normovolemia.^{1,10,29,30} However, in the absence of clinical guidelines to direct intraoperative fluid management,¹⁵ it is unclear to what extent practices have changed in real-world practice.

In this context, we evaluated the volume of intravenous fluid administered during 3 widely varied major inpatient operations in a state-wide surgical quality collaborative. As hypothesized, we found wide variation between hospitals in fluid administration practices, even after normalizing measures, to account for the factors that commonly contribute to anesthesiologists' fluid management. Moreover, within an institution, these practices are correlated across 3 very different operations, suggesting that there are common institutional approaches to fluid administration that transcend surgical disciplines. And hospitals with the highest average fluid balance tended to have significantly longer pLOS after intestinal resections and hysterectomy, despite no consistent differences in postoperative complications.

Even before considering the clinical outcomes, the wide variation between hospitals in average fluid balance is notable. There was some association between higher fluid balance and patient-specific characteristics such as younger age, lesser comorbidity, specific indications for surgery (inflammatory bowel disease among the intestinal resections and malignancy among the hysterectomies), and operative duration. Other studies that have focused on patient-level variation in fluid administration may be subject to some confounding and selection bias due to such factors. In this study, however, we not only normalized fluid balance for the clinical features most commonly used to determine volume of resuscitation, but also adjusted for patient characteristics and looked at practices and outcomes at the institutional level, removing much of the patient comorbidity and severity of illness from the picture. Thus, the residual differences we observed represent unexplained, and likely unwarranted, variation in clinical care. As care standardization and pathway development have become increasingly important in operationalizing efficiency interventions, this residual variation is itself undesirable. Fortunately, because the tendency toward higher and lower volume resuscitation seems to be a hospital-level characteristic, there is real opportunity to standardize behavior at the hospital level if best practices can be identified and codified.

Our finding that higher volume fluid administration is associated with longer length of stay, in the absence of meaningful differences in adverse events, is consistent with the described association with postoperative ileus in both randomized trials^{13,18,21} and observational studies.^{22,23} These previous analyses are potentially confounded at the patient level, however, by the association between adverse intraoperative events and greater fluid volume administration. Many common predictors of poor postoperative outcomes, including prolonged operative time, excessive blood loss, intraoperative hypotension, tachycardia, and others,^{31–38} are also potentially associated with excessive fluid administration. Thus, there may be confusion about whether fluid volume is a contributor to, or an effect of, the adverse event.

To overcome this limitation, which is inherent to patient-level analyses, we chose the hospital as our unit of analysis. By analyzing fluid administration at the hospital level, we gain information about the effect of a fluid-sparing approach to care, rather than simply comparing patients who receive different volume of fluid, for potentially important clinical reasons. Thus, the findings of this study may inform the development of more generalizable approaches to protocol development in perioperative medicine. Further, by evaluating practices by hospital, rather than the individual patient level, the reliability of measures is substantially more stable and less susceptible to confounding by indication and selection bias.³⁹

This study applied a novel metric to compare intraoperative fluid administration practices-normalized fluid balance. Most previous research has used total fluid administration or volume per hour as the exposure of interest. However, by integrating both the amount of fluid infused and the clinical features that contribute to most anesthesiologists' decisions about fluid volume, we potentially achieved a more clinically relevant comparison. Furthermore, because the measure is averaged over a hospital's sample, and used only in reference to comparisons with other hospitals, the specifics of the calculation could only impart bias if there were a systematic difference in the distribution of key components, which seems unlikely.

As with all observational studies on healthcare practices, there are limitations to our analysis. Although the MSQC data are clinically rich, we lack several key clinical details in this analysis. We did not account for the time of day of the operation, or the amount of time the patient remained without oral intake before surgery. We also did not assess postoperative fluid administration rates, which may vary widely between hospitals. We do not know which hospitals were employing scripted enhanced recovery protocols, using advanced hemodynamic monitoring, or regulating their intraoperative fluid use. Although we have posited ileus as a contributor to differences in postoperative recovery, we did not have ileus as a coded postoperative outcome in our dataset, as it is not collected in MSQC due to concerns about imprecision in definition and measurement. Finally, because the endovascular surgery cohort was far smaller than the other 2 operations, we may have lacked power to detect small differences in outcomes in this group. We included them anyway, because we sought to evaluate clinically nonoverlapping operations that were less likely to be performed by the same surgeon, and these 3 conditions were appropriate examples from within our collaborative.

Nevertheless, this report, from a population-based, state-wide collaborative, offers a real-world assessment of intraoperative fluid management in current clinical practice. The membership of the MSQC is very diverse, including hospitals that are academic and community-based, large and small, urban and rural, some with surgeons who have broad general surgical practices and some with subspecialists.⁴⁰ Recognizing that there is immediate opportunity for standardization and optimization of perioperative care practices within our state-wide collaborative, we will use these findings to continue to improve perioperative care practices state-wide. These efforts will be aided substantially by the close relationship between MSQC and a recently launched state-wide anesthesiology

collaborative, the Anesthesiology Performance Improvement and Reporting Exchange (ASPIRE).

In summary, this study finds that hospitals vary widely in their intraoperative fluid administration practices, and that their management is correlated across intestinal resections, hysterectomy, and abdominal endovascular surgery, procedures for which there is otherwise quite little clinical care overlap. For abdominal operations whose length of stay is driven by the occurrence of ileus, we find small, but consistent prolongation of pLOS, despite no meaningful difference in rates of adverse events. Although the differences we noted in length of stay are small, even very small reductions in length of stay are associated with substantial cost savings, and hospitals are highly motivated to optimize the efficiency of postoperative hospitalization.⁴¹ The association between fluid volume and time to recovery may be causally related, as has been proposed in the enhanced recovery literature, or it may reflect a confluence of care protocols in hospitals that have promoted both limitation of intraoperative fluids and fast-track postoperative care protocols. Either way, these findings reveal systematic clinical care variation that can be evaluated and restructured to optimize the perioperative care protocols for these operations. Going forward, we will evaluate the specific care protocols, monitoring, and approaches to fluid administration in the hospitals with best perioperative care practices and outcomes within the collaborative.

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References

1. Adamina M, Kehlet H, Tomlinson GA, et al. Enhanced recovery pathways optimize health outcomes and resource utilization: a meta-analysis of randomized controlled trials in colorectal surgery. *Surgery*. 2011; 149:830–840. [PubMed: 21236454]
2. Francis, N., Kennedy, RH., Ljungqvist, O., et al. *Manual of Fast Track Recovery for Colorectal Surgery*. London: Springer-Verlag; 2012.
3. Husted H, Troelsen A, Otte KS, et al. Fast-track surgery for bilateral total knee replacement. *J Bone Jt Surg Br*. 2011; 93:351–356.
4. Spanjersberg WR, Reurings J, Keus F, et al. Fast track surgery versus conventional recovery strategies for colorectal surgery. *Cochrane Database Syst Rev*. 2011; 2:CD007635.
5. Khan S, Wilson T, Ahmed J, et al. Quality of life and patient satisfaction with enhanced recovery protocols. *Color Dis*. 2010; 12:1175–1182.
6. Stephen AE, Berger DL. Shortened length of stay and hospital cost reduction with implementation of an accelerated clinical care pathway after elective colon resection. *Surgery*. 2003; 13:277–282.
7. Hendren S, Morris AM, Zhang W, et al. Early discharge and hospital readmission after colectomy for cancer. *Dis Colon Rectum*. 2011; 54:1362–1367. [PubMed: 21979179]
8. Hjort Jakobsen D, Sonne E, Basse L, et al. Convalescence after colonic resection with fast-track versus conventional care. *Scand J Surg*. 2004; 93:24–28. [PubMed: 15116815]
9. Zargar-Shoshtari K, Paddison JS, Booth RJ, et al. A prospective study on the influence of a fast-track program on postoperative fatigue and functional recovery after major colonic surgery. *J Surg Res*. 2009; 154:330–335. [PubMed: 19118844]

10. Miller TE, Thacker JK, White WD, et al. Reduced length of hospital stay in colorectal surgery after implementation of an enhanced recovery protocol. *Anesth Analg*. 2014; 118:1052–1061. [PubMed: 24781574]
11. Brandstrup B, Tønnesen H, Beier-Holgersen R, et al. Effects of intravenous fluid restriction on postoperative complications: comparison of two perioperative fluid regimens: a randomized assessor-blinded multicenter trial. *Ann Surg*. 2003; 238:641–648. [PubMed: 14578723]
12. Adesanya A, Rosero E, Timaran C, et al. Intraoperative fluid restriction predicts improved outcomes in major vascular surgery. *Vasc Endovascular Surg*. 2015; 42:531–536.
13. Doherty M, Buggy DJ. Intraoperative fluids: how much is too much? *Br J Anaesth*. 2012; 109:69–79. [PubMed: 22661747]
14. Holte K, Foss NB, Andersen J, et al. Liberal or restrictive fluid administration in fast-track colonic surgery: a randomized, double-blind study. *Br J Anaesth*. 2007; 99:500–508. [PubMed: 17681972]
15. Chong PC, Greco EF, Stothart D, et al. Substantial variation of both opinions and practice regarding perioperative fluid resuscitation. *Can J Surg*. 2009; 52:207–214. [PubMed: 19503665]
16. Lilot M, Ehrenfeld JM, Lee C, et al. Variability in practice and factors predictive of total crystalloid administration during abdominal surgery: retrospective two-centre analysis. *Br J Anaesth*. 2015; 114:767–776. [PubMed: 25586725]
17. Brandstrup B, Svendsen C, Engquist A. Hemorrhage and operation cause a contraction of the extracellular space needing replacement: evidence and implications? A systematic review. *Surgery*. 2006; 139:419–432. [PubMed: 16546507]
18. Bundgaard-Nielsen M, Secher NH, Kehlet H. “Liberal” vs. “restrictive” perioperative fluid therapy—a critical assessment of the evidence. *Acta Anaesthesiol Scand*. 2009; 53:843–851. [PubMed: 19519723]
19. MacKay G, Fearon K, McConnachie A, et al. Randomized clinical trial of the effect of postoperative intravenous fluid restriction on recovery after elective colorectal surgery. *Br J Surg*. 2006; 93:1469–1474. [PubMed: 17078116]
20. Holte K, Kristensen BB, Valentiner L, et al. Liberal versus restrictive fluid management in knee arthroplasty: a randomized, double-blind study. *Anesth Analg*. 2007; 105:465–474. [PubMed: 17646507]
21. Nisanevich V, Felsenstein I, Almogy G, et al. Effect of intraoperative fluid management on outcome after intraabdominal surgery. *Anesthesiology*. 2005; 103:25–32. [PubMed: 15983453]
22. Thacker JKMM, Mountford WK, Ernst FR, et al. Perioperative fluid utilization variability and association with outcomes. *Ann Surg*. 2016; 263:502–510. [PubMed: 26565138]
23. Aarts M-A, Okrainec A, Glicksman A, et al. Adoption of enhanced recovery after surgery (ERAS) strategies for colorectal surgery at academic teaching hospitals and impact on total length of hospital stay. *Surg Endosc*. 2012; 26:442–450. [PubMed: 22011937]
24. Campbell DA Jr, Kubus JJ, Henke PK, et al. The Michigan Surgical Quality Collaborative: a legacy of Shukri Khuri. *Am J Surg*. 2009; 198:S49–S55. [PubMed: 19874935]
25. Share DA, Campbell DA, Birkmeyer N, et al. How a regional collaborative of hospitals and physicians in Michigan cut costs and improved the quality of care. *Heal Aff*. 2011; 30:636–645.
26. Kaye, AD. Fluid management. In: Miller, RD., Pardo, MCJ., editors. *Basics of Anesthesia*. 6th. Philadelphia, PA: Elsevier Saunders; 2011. p. 364–371.
27. Orbegoza Cortés D, Gamarano Barros T, Njimi H, et al. Crystalloids versus colloids: exploring differences in fluid requirements by systematic review and meta-regression. *Anesth Analg*. 2015; 120:389–402. [PubMed: 25565318]
28. Iyer S, Saunders WB, Stemkowski S. Economic burden of postoperative ileus associated with colectomy in the United States. *J Manag Care Pharm*. 2009; 15:485–494. [PubMed: 19610681]
29. Gustafsson UO, Hausel J, Thorell A, et al. Adherence to the enhanced recovery after surgery protocol and outcomes after colorectal cancer surgery. *Arch Surg*. 2011; 146:571–577. [PubMed: 21242424]
30. Gustafsson UO, Scott MJ, Schwenk W, et al. Guidelines for perioperative care in elective colonic surgery: Enhanced Recovery After Surgery (ERAS((R))) Society recommendations. *World J Surg*. 2013; 37:259–284. [PubMed: 23052794]

31. Gawande AA, Kwaan MR, Regenbogen SE, et al. An Apgar score for surgery. *J Am Coll Surg*. 2007; 204:201–208. [PubMed: 17254923]
32. Regenbogen SE, Ehrenfeld JM, Lipsitz SR, et al. Utility of the surgical apgar score: validation in 4119 patients. *Arch Surg*. 2009; 144:30–36. [discussion 37]. [PubMed: 19153322]
33. Wuerz TH, Regenbogen SE, Ehrenfeld JM, et al. The surgical Apgar score in hip and knee arthroplasty. *Clin Orthop Relat Res*. 2011; 469:1119–1126. [PubMed: 21132410]
34. Charlson ME, MacKenzie CR, Gold JP, et al. The preoperative and intraoperative hemodynamic predictors of postoperative myocardial infarction or ischemia in patients undergoing noncardiac surgery. *Ann Surg*. 1989; 210:637–648. [PubMed: 2530940]
35. Reich DL, Bodian CA, Krol M, et al. Intraoperative hemodynamic predictors of mortality, stroke, and myocardial infarction after coronary artery bypass surgery. *Anesth Analg*. 1999; 89:814–822. [PubMed: 10512249]
36. Barone JE, Bull MB, Cussatti EH, et al. Perioperative myocardial infarction in low-risk patients undergoing noncardiac surgery is associated with intraoperative hypotension. *J Intensive Care Med*. 2002; 17:250–255.
37. Monk TG, Saini V, Weldon BC, et al. Anesthetic management and one-year mortality after noncardiac surgery. *Anesth Analg*. 2005; 100:4–10. [PubMed: 15616043]
38. Reich DL, Bennett-Guerrero E, Bodian CA, et al. Intraoperative tachycardia and hypertension are independently associated with adverse outcome in noncardiac surgery of long duration. *Anesth Analg*. 2002; 95:273–277. [PubMed: 12145033]
39. Dimick JB, Livingston EH. Comparing treatments using observational study designs: what can we do about selection bias? *Arch Surg*. 2010; 145:927. [PubMed: 20956759]
40. Campbell DA Jr, Englesbe MJ, Kubus JJ, et al. Accelerating the pace of surgical quality improvement: the power of hospital collaboration. *Arch Surg*. 2010; 145:985–991. [PubMed: 20956768]
41. Raut M, Schein J, Mody S, et al. Estimating the economic impact of a half-day reduction in length of hospital stay among patients with community-acquired pneumonia in the US. *Curr Med Res Opin*. 2009; 25:2151–2157. [PubMed: 19601711]

FIGURE 1.

Scatter plots of hospitals' average normalized fluid balance in milliliters and intrahospital correlations in average fluid balance across procedures. Each dot represents a single hospital's average, the line represents linear best fit, and the Pearson correlation coefficient is displayed. A, Intestinal resections and abdominal endovascular procedures; B, intestinal resections and hysterectomy; C, hysterectomy and endovascular procedures.

FIGURE 2.
Average postoperative length of stay, by fluid balance quartile, for intestinal resections, hysterectomy, and endovascular procedures.

TABLE 1**Patient Characteristics and Normalized Fluid Balance**

A. Colorectal Resections (N = 8404)			
	N (%)	Fluid Balance (Mean ± SD)	P
Age group			<0.001
<50	1436 (17.1)	1898±1731	
50–64	3169 (37.7)	1862±1754	
65–74	2118 (25.2)	1706±1297	
75	1681 (20.0)	1506±1761	
Sex			<0.001
Male	3835 (45.6)	1812±1540	
Female	4569 (54.4)	1712±1742	
Race			<0.001
White	7077 (84.2)	1728±1602	
Black	941 (11.2)	1803±1291	
Other	386 (4.6)	2199±2868	
BMI			0.09
<18.5 or unknown	242 (2.9)	1630±1170	
18.5–24.9	2243 (26.7)	1705±1412	
25–29.9	2822 (33.6)	1745±1333	
30–34.9	1761 (21.0)	1825±2000	
35	1336 (15.9)	1807±2140	
ASA classification			<0.001
ASA 1	121 (1.4)	1617±1124	
ASA 2	3746 (44.6)	1769±1398	
ASA 3	4181 (49.8)	1757±1777	
ASA 4 or 5	356 (4.2)	1689±2555	
Comorbidities			<0.001
0	2658 (31.6)	1774±1299	
1–2	4692 (55.8)	1792±1786	
3–4	945 (11.2)	1560±1673	
5+	109 (1.3)	1622±2806	
Tobacco use			<0.001
No	6377 (75.9)	1735±1638	
Yes	2027 (24.1)	1828±1703	
Alcohol >2/d			<0.001
No	8138 (96.8)	1749±1653	
Yes	266 (3.2)	2019±1662	
Diagnosis			<0.001
Cancer	3127 (37.2)	1770±1931	
Diverticular disease	2260 (25.9)	1840±1387	
Inflammatory bowel disease	371 (4.4)	1929±1260	

A. Colorectal Resections (N = 8404)			
	N (%)	Fluid Balance (Mean ± SD)	P
Other	2646 (31.5)	1649±1548	
B. Hysterectomy (N = 22,849)			
	N (%)	Fluid Balance (Mean ± SD)	P
Age group			<0.001
<50	14317 (62.3)	1003±1105	
50–64	5895 (25.8)	1170±1807	
65–74	1894 (8.3)	1128±1110	
75	743 (3.3)	1114±1323	
Race			<0.001
White	17300 (75.7)	1072±1309	
Black	4010 (17.6)	972±1427	
Other	539 (6.7)	1152±1302	
BMI			<0.001
<18.5 or unknown	270 (1.2)	1202±1087	
18.5–24.9	5045 (22.1)	1140±1127	
25–29.9	6365 (27.8)	1105±1309	
30–34.9	5071 (22.2)	1022±1713	
35	6110 (26.7)	973±1136	
ASA classification			0.01
ASA 1	2202 (9.6)	1072±1241	
ASA 2	15418 (67.5)	1050±1333	
ASA 3	5096 (22.3)	1090±1367	
ASA 4 or 5	133 (0.6)	809±1017	
B. Hysterectomy (N = 22,849)			
	N (%)	Fluid Balance (Mean ± SD)	P
Comorbidities			0.56
0	13639 (59.7)	1054±1406	
1–2	8519 (37.3)	1069±1229	
3–4	652 (2.9)	1061±970	
5+	39 (0.2)	1035±1084	
Tobacco use			0.25
No	17175 (75.2)	1060±1410	
Yes	5674 (24.8)	1058±1058	
Alcohol >2/d			0.51
No	22649 (99.1)	1060±1334	
Yes	200 (0.9)	991±920	
Diagnosis			<0.001

A. Colorectal Resections (N = 8404)			
	N (%)	Fluid Balance (Mean ± SD)	P
Malignant neoplasm	2517 (11.0)	1327±1286	
Benign neoplasm/carcinoma in situ	7106 (31.1)	1000±1286	
Other	13226 (57.9)	1041±1357	
C. Endovascular (N=1471)			
	N (%)	Fluid Balance (Mean ± SD)	P
Age group			0.02
<50	16 (1.1)	915±949	
50–64	285 (19.4)	939±2002	
65–74	556 (37.8)	945±1128	
75	614 (41.7)	716±1110	
Sex			0.61
Male	1110 (75.5)	842±1374	
Female	361 (24.5)	867±1223	
Race			0.46
White	1319 (89.7)	845±1327	
Black	101 (6.9)	859±1690	
Other	51 (3.5)	894±691	
BMI			0.39
<18.5 or unknown	36 (2.5)	547±1199	
18.5–24.9	381 (25.9)	819±1186	
25–29.9	582 (39.6)	862±1471	
30–34.9	298 (20.3)	979±1389	
35	174 (11.8)	701±1087	
ASA classification			0.15
ASA 2	74 (5.0)	846±1215	
ASA 3	1072 (72.9)	861±1368	
ASA 4 or 5	325 (22.1)	805±1264	
Comorbidities			0.001
0	104 (7.1)	1114±885	
1–2	890 (60.5)	880±1435	
3–4	400 (27.2)	753±1192	
5+	77 (5.2)	608±1349	
Tobacco use			0.02
No	859 (58.4)	794±1400	
Yes	612 (41.6)	923±1242	
Alcohol > 2/d			0.80
No	1391 (94.6)	848±1358	
Yes	80 (5.4)	843±936	

TABLE 2

Procedural Characteristics and Normalized Fluid Balance

A. Colorectal			
	N (%)	Fluid Balance (Mean ± SD)	P
Procedure			<0.001
Small bowel resection	491 (5.8)	1618±1658	
Segmental colectomy	4762 (55.7)	1676±1372	
Segmental resection with stoma	719 (8.6)	1650±1692	
Low anterior resection	1909 (22.7)	1899±1787	
Total colectomy	276 (3.3)	2412±2074	
Abdominoperineal resection	247 (2.9)	2096±3554	
Surgical approach			<0.001
Open	3387 (40.3)	1770±2067	
Laparoscopic	2250 (26.8)	1769±1047	
Laparoscopic, hand-assisted	1253 (14.9)	1649±1024	
Robotic	693 (8.3)	1730±1761	
Lap/robot converted to open	821 (9.8)	1863±1770	
Estimated blood loss			<0.001
<100	4016 (47.8)	1648±980	
100–500	3837 (45.7)	1908±1968	
500–1000	427 (5.1)	1866±2156	
>1000	124 (1.5)	273±3904	
Operative duration			<0.001
<2h	3053 (36.3)	1445±1234	
2–3 h	2633 (31.3)	1691±1261	
3–4h	1429 (17.0)	1899±1530	
>4h	1289 (15.3)	2479±2758	
Vasopressor use			0.129
Yes	3677 (43.8)	1783±1846	
No	4727 (56.3)	1738±1487	
Epidural use			0.034
Yes	1508 (17.9)	1967±2404	
No	6896 (82.1)	1712±1435	
B. Hysterectomy			
	N (%)	Fluid Balance (Mean ± SD)	P
Surgical approach			<0.001
Open	6201 (27.1)	1028±1744	
Vaginal	2119 (9.3)	836±953	
Laparoscopic	4299 (18.8)	1048±1371	
Robotic	9572 (41.9)	1140±984	

A. Colorectal			
	N (%)	Fluid Balance (Mean ± SD)	P
Lap/robot converted to open	658 (2.9)	997±1820	
Estimated blood loss			<0.001
<100	9019 (39.5)	1197±883	
100–500	11775 (51.5)	1048±974	
500–1000	1584 (6.9)	660±1698	
>1000	471 (2.1)	63±5983	
Operative duration			<0.001
<2h	11162 (48.9)	965±855	
2–3 h	7465 (32.7)	1080±1133	
3–4h	2850 (12.5)	1225±1761	
>4h	1372 (6.0)	1379±3147	
Vasopressor use			<0.001
Yes	5481 (24.0)	1118±1248	
No	17368 (76.0)	1041±1356	
Epidural use			<0.001
Yes	648 (2.8)	1327±1409	
No	22201 (97.2)	1052±1328	
C. Endovascular			
	N (%)	Fluid Balance (Mean ± SD)	P
Procedure			<0.001
Aortic aneurysm	1212 (82.4)	888±1370	
Other aorto-iliac	259 (71.6)	658±1160	
Estimated blood loss			<0.001
<100	507 (34.5)	1154±1212	
100–500	794 (54.0)	863±893	
500–1000	127 (8.6)	236±2448	
>1000	43 (2.9)	–1245±2277	
Operative duration			<0.001
<2h	614 (41.7)	1037±1380	
2–3 h	501 (34.1)	816±1104	
3–4h	211 (14.3)	673±1376	
>4h	145 (9.9)	407±1667	
Vasopressor use			0.748
Yes	1006 (68.4)	822±1395	
No	465 (31.6)	904±1206	
Epidural use			0.637
Yes	15 (1.0)	984±1609	
No	1456 (99.0)	846±1336	

TABLE 3
Hospital Characteristics by Quartiles of Average Normalized Fluid Volume, by Procedure

		Lowest Quartile	Second quartile	Third quartile	Highest Quartile	P
Colorectal resection	Number of hospitals	16	16	16	16	
	Number of patients	1487	2530	2150	2237	
	Mean fluid balance	1105	1551	1829	2356	<0.001
	Mean beds	218	392	310	360	0.19
	Mean procedure volume	93	158	134	140	0.12
Hysterectomy	% Minimally invasive	42.5	52.7	52.3	49.4	0.10
	% Teaching	68.8	68.8	62.5	87.5	0.43
	Number of hospitals	16	16	15	16	
	Number of patients	5153	4453	5574	7669	
	Mean fluid balance	693	916	1080	1375	<0.001
Endovascular	Mean beds	231	310	349	400	0.19
	Mean procedure volume	322	278	372	479	0.13
	% Minimally invasive	62.6	60.3	63.8	57.4	0.75
	% Vaginal	9.2	10.2	10.3	8.0	0.51
	% Teaching	62.5	75.0	73.3	75.0	0.84
Endovascular	Number of hospitals	11	11	12	11	
	Number of patients	251	452	361	407	
	Mean fluid balance	368	677	854	1328	<0.001
	Mean beds	355	455	408	373	0.55
	Mean procedure volume	23	41	30	37	0.23
	% Teaching	81.8	100	91.7	81.8	0.47

TABLE 4
Risk-adjusted Postoperative Clinical Outcomes, by Quartiles of Average Normalized Fluid Volume

A. Colorectal				
Outcome	Lowest Quartile (n = 1487)	Second Quartile (n = 2530)	Third Quartile (n = 2150)	Highest Quartile (n = 2237) P
Length of stay, mean days	5.7	6.3	6.1	6.5 <0.001
ED visit within 30 d, %	11.2	8.1	8.5	9.9 0.003
Readmission within 30 d, %	11.5	9.9	10.8	11.2 0.38
Reoperation within 30 d, %	7.3	7.5	8.2	7.9 0.68
Any SSI, %	9.3	7.9	7.6	7.4 0.18
Pneumonia, %	1.7	1.5	2.1	1.5 0.42
Unplanned intubation, %	1.5	1.5	1.9	1.7 0.80
VTE, %	1.3	1.7	1.5	1.8 0.67
Acute renal failure, %	2.3	1.4	1.9	1.6 0.16
Any UTI, %	2.3	2.8	2.3	2.8 0.49
Cardiac arrhythmias, %	2.1	2.1	2.2	2.1 0.99
Transfusion, %	5.8	5.9	6.0	6.6 0.64
Any sepsis, %	4.8	4.0	4.2	5.0 0.31
Myocardial infarction, %	0.3	0.5	0.5	0.7 0.38
ICU after OR, %	1.3	1.5	1.0	4.0 <0.001
Any morbidity, %	17.9	16.8	17.0	17.4 0.85
Serious morbidity, %	9.6	10.4	9.7	10.2 0.82
30-D mortality, %	1.3	1.1	1.1	1.0 0.78

B. Hysterectomy				
Outcome	Lowest Quartile (n = 5153)	Second Quartile (n = 4453)	Third Quartile (n = 5574)	Highest Quartile (n = 7668) P
Length of stay, mean days	1.7	1.7	1.8	1.9 <0.001
ED visit within 30 d, %	9.5	9.6	9.1	8.7 0.30
Readmission within 30 d, %	3.8	3.2	3.8	4.8 <0.001
Reoperation within 30 d, %	2.6	2.2	2.2	2.6 0.17
Any SSI, %	1.8	2.1	2.2	2.0 0.40

A. Colorectal				
Outcome	Lowest Quartile (n = 1487)	Second Quartile (n = 2530)	Third Quartile (n = 2150)	Highest Quartile (n = 2237)
Pneumonia, %	0.3	0.2	0.2	0.2
Unplanned intubation, %	0.2	0.1	0.2	0.3
VTE, %	0.4	0.4	0.4	0.7
Acute renal failure, %	0.1	0.2	0.2	0.3
Any UTI, %	1.7	1.7	2.2	2.5
Cardiac arrhythmias, %	0.2	0.2	0.2	0.3
Transfusion, %	2.0	3.0	2.1	3.0
Any sepsis, %	0.8	0.9	0.7	1.0
Myocardial infarction, %	0.1	0.1	0.0	0.1
ICU after OR, %	0.1	0.1	0.1	0.5
Any morbidity, %	4.6	4.8	5.3	5.9
Serious morbidity, %	1.8	1.7	1.9	2.5
30-D mortality, %	0.1	0.1	0.1	0.1
P	0.75	0.20	0.045	0.31
	0.0028	0.66	<0.001	0.11
	0.27	<0.001	0.01	0.01
	0.98			
C. Endovascular				
Outcome	Lowest Quartile (n = 251)	Second Quartile (n = 452)	Third Quartile (n = 361)	Highest Quartile (n = 407)
Length of stay, mean days	2.3	2.3	2.1	2.1
ED visit within 30 d, %	7.6	7.7	7.8	8.6
Readmission within 30 d, %	10.8	7.9	12.0	7.3
Reoperation within 30 d, %	7.2	5.2	7.3	4.5
Any SSI, %	2.1	1.3	1.5	1.5
Pneumonia, %	0.8	0.9	0.8	0.0
Unplanned intubation, %	2.0	1.3	1.1	1.2
VTE, %	0.0	0.7	0.8	0.3
Acute renal failure, %	1.6	1.3	0.8	1.5
Any UTI, %	2.4	1.6	1.1	0.7
Cardiac arrhythmias, %	2.0	2.2	1.4	1.5
Transfusion, %	2.9	4.3	3.8	4.5
Any sepsis, %	2.3	0.7	1.3	1.0
P	0.69	0.96	0.08	0.27
	0.90	0.32	0.81	0.40
	0.83	0.33	0.78	0.77
	0.33	0.77	0.33	0.33

A. Colorectal					
Outcome	Lowest Quartile (n = 1487)	Second Quartile (n = 2530)	Third Quartile (n = 2150)	Highest Quartile (n = 2237)	P
Myocardial infarction, %	0.0	1.3	1.7	0.3	0.05
ICU after OR, %	2.5	0.5	11.8	2.1	<0.001
Any morbidity, %	9.3	8.8	8.7	6.8	0.64
Serious morbidity, %	5.0	5.3	5.7	3.9	0.67
30-D mortality, %	1.9	1.2	0.8	1.2	0.67

ED indicates emergency department; ICU, intensive care unit; OR, operating room; SSI, surgical site infection; UTI, urinary tract infection; VTE, venous thromboembolism.