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# Reducing Blood Loss by Changing to Small Volume Tubes for Laboratory Testing

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## Abstract

**Objective:** To reduce diagnostic blood loss by using small volume tubes for routine laboratory testing throughout the hospital, as blood loss from laboratory testing can be substantial for patients and may lead to hospital-acquired anemia.

**Patients and Methods:** Diagnostic blood loss was evaluated in hospitalized patients between April 1, 2017, and June 1, 2018. The preintervention, during intervention, and postintervention mean diagnostic blood loss per hospitalized patient was compared across the floors and for each type of tube for hematology, basic metabolic panel, and coagulation tests. Mean hemoglobin levels, blood transfusions per hospitalized patient, and percent redraws were also compared.

**Results:** The total volume of blood drawn for all the 3 tests decreased across each implementation phase; however, only patients admitted to the transplant and critical care (T/CC) units had increased hemoglobin levels. In addition, there was a significant reduction in transfusions across implementation phases. The incidence risk ratio for transfusion reduced even more in patients admitted to the T/CC units. Finally, there was no significant difference in the overall percent redraws across all the units.

**Conclusion:** The use of small volume tubes in exchange for standard sized tubes markedly decreased diagnostic blood loss by 25.7% in all the units and 22.9% in the T/CC units. Also, the number of transfusions decreased across units, with the greatest decrease in the T/CC units. An increase in mean hemoglobin levels was observed specifically in patients admitted to the T/CC units, with no corresponding change in percent redraws across all the units.

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Hospital-acquired anemia (HAA) is new-onset anemia that develops during hospitalization in patients without active bleeding whose hemoglobin level was normal on admission.[1] Hospital-acquired anemia is relatively common and highly associated with poor patient outcomes including congestive heart failure, acute myocardial infarction, chronic kidney disease, and even death.[2] A study conducted in 2013 revealed that up to 74% of patients admitted to the hospital because of surgical or medical reasons developed HAA[3] using a cutoff of 120 g/L hemoglobin level for women and of 130 g/L hemoglobin level for men for mild HAA; the incidence of HAA ranged from 20% to 70% in patients with renal impairment, admitted to the intensive care unit (ICU), or hospitalized posttrauma.[4-6] When Salisbury et al[7] conducted a retrospective study based on the Translational Research Investigating Underlying disparities in acute Myocardial infarction Patients' Health Status (TRIUMPH) registry, they found that HAA ranged from 33.3% to 69.2% in patients with acute myocardial infarction; importantly, moderate and severe HAA was a strong and independent risk factor for mortality.

The development of HAA is multifactorial with numerous potential etiologies, including longer hospital stays, ICU admissions, hemorrhages, coagulopathy, surgical procedures, and medications.[8] Frequent and large amounts of blood drawn for diagnostic testing in

 

hospitalized patients have been identified as major modifiable contributing factors.[1,9] Diagnostic blood loss (DBL) can amount to the equivalent of 1 to 2 units of red blood cells during a single admission.[10] Diagnostic blood loss was 17% of the estimated total blood loss with a range of 12% to 21% in different subgroups in a study of patients in the medical intensive care unit by von Ahsen et al.[11] The estimates for mean daily DBL in hospitalized patients range from approximately 12 mL per day in general medicine wards to 40 to 50 mL per day in the ICU, the latter being higher because critically ill patients typically require more testing.[10] Salisbury et al[7] estimated that for every 50 mL of blood collected during hospitalization, the risk of developing HAA increases by 20%.

Collection of larger than necessary amounts of blood samples for laboratory testing can be minimized as a strategy to reduce patient blood loss over and above the laboratory test utilization measures.[12] Patients having blood testing done multiple times a day benefit the most from the use of smaller volume tubes, with several milliliters less blood collected at every collection. Over time, laboratory instrumentation has improved, and testing can be performed on smaller volumes of blood; however, the amount of blood collected has generally not decreased. Hospital laboratories collect 8.5 times more blood than the required analytical volume for complete blood count and 12 times more for the basic metabolic panel (BMP). Furthermore, a large portion of the sample is often discarded.[13] A study of 57 hospitals found that particularly large DBL was noted during hospitalization in patients who developed moderate to severe HAA, which was highly associated with poor outcomes.[14] In addition, patients hospitalized for more than 15 days had a higher risk of requiring transfusion because of cumulative phlebotomy volume from blood drawn throughout their hospital stay.[15]

In 2012, the American Board of Internal Medicine Foundation implemented the "Choosing Wisely" campaign in the United States and Canada to advocate for avoiding unnecessary and wasteful medical tests, treatments, and procedures.[16] Our organization has embraced the Choosing Wisely recommendations and has implemented several strategies focused on laboratory utilization projects before the present study. In the spirit of the Choosing Wisely campaign,[17] we implemented changes to blood collection practices by using small volume tubes as an alternative to adult volume tubes for hospital patients. This change decreases DBL and provides further opportunity to reduce HAA risk.[18,19] In our institution, standard volume laboratory tubes were collected for blood testing, and often, a large portion of each blood sample was not used. As such, our goal was to significantly decrease the volume of DBL, without affecting the number of redraws, to reduce HAA.

## PATIENTS AND METHODS

This study was conducted in a 304-bed tertiary care teaching hospital in Florida. All data were obtained from the laboratory information system and the electronic medical record. The study timeline was divided into 3 phases—preintervention, during implementation, and postintervention—and included patients admitted in the following inpatient units: cardiovascular, hematology-oncology, abdominal transplant, medical ICU, surgical ICU, medical, neurology, progressive care unit, orthopedic/urology, and surgical units. Patients admitted from April 1, 2017 to June 30, 2017 were included in the preintervention phase. The implementation of small volume tubes started in the surgical ICU on July 1, 2017 and continued unit by unit until completion on January 31, 2018. As such, July 1, 2017 to January 31, 2018 was considered the "during implementation" phase of the study. Finally, those admitted after January 31, 2018 until June 30, 2018 were included in the postintervention phase. The study protocol was waived as the study was of minimal risk, and no patient-specific information was involved.

### Dependent Variables

Our outcome measures included mean hemoglobin level, number of transfusions, total milliliters of blood drawn for each diagnostic test, and percent redraws occurring during each phase of the implementation. The mean hemoglobin level was obtained by calculating the mean of the hemoglobin levels of individual patients during their in-hospital stay. This

**TABLE 1. Demographic Characteristics of the Patient Care Units**

| Characteristic | Preimplementation phase (n=30) | During implementation phase (n=70) | Postimplementation phase (n=50) | Total (N=150) | *P* value |
|---|---|---|---|---|---|
| **All patient care units** | | | | | |
| Age (y) | | | | | .0051 |
| Median (range) | 61.1 (55.0-66.2) | 61.4 (52.8-68.5) | 63.9 (52.9-69.4) | 62.2 (52.8-69.4) | |
| Mean ± SD | 61.1±3.22 | 61.5±3.77 | 63.4±3.66 | 62.0±3.74 | |
| MS-DRG score | | | | | .491 |
| Median (range) | 5.2 (2.3-8.6) | 4.7 (1.9-9.3) | 4.6 (2.4-7.6) | 4.7 (1.9-9.3) | |
| Mean ± SD | 5.2±2.19 | 5.0±2.06 | 4.6±1.56 | 4.9±1.94 | |
| Percentage of female patients | | | | | .571 |
| Median (range) | 44.3 (24.5-64.6) | 46.5 (28.6-65.5) | 44.5 (27.2-66.3) | 44.8 (24.5-66.3) | |
| Mean ± SD | 44.3±8.94 | 46.3±8.18 | 45.8±8.55 | 45.8±8.44 | |
| Percentage of white patients | | | | | .091 |
| Median (range) | 85.7 (74.5-96.1) | 83.6 (67.3-89.9) | 84 (73.5-92.8) | 84 (67.3-96.1) | |
| Mean ± SD | 85.1±5.01 | 82.7±4.53 | 83.6±4.67 | 83.5±4.73 | |
| Percentage of black patients | | | | | .021 |
| Median (range) | 8.7 (2.6-20.4) | 10.9 (2.4-20.2) | 9.8 (2.1-18.0) | 10.4 (2.1-20.4) | |
| Mean ± SD | 9.4±4.30 | 11.2±3.40 | 9.8±3.27 | 10.4±3.61 | |
| Percentage of other races | | | | | .181 |
| Median (range) | 4.9 (1.3-10.8) | 5.7 (1.1-15.7) | 6.2 (1.3-11.8) | 5.7 (1.1-15.7) | |
| Mean ± SD | 5.5±2.75 | 6.1±2.81 | 6.5±2.76 | 6.1±2.79 | |
| Average census | | | | | .611 |
| Median (range) | 22.0 (9.9-26.5) | 23.0 (11.7-26.8) | 22.9 (12.3-27.3) | 23.0 (9.9-27.3) | |
| Mean ± SD | 20.7±4.88 | 21.5±4.18 | 22.2±3.47 | 21.6±4.12 | |
| **Transplant and critical care units** | | | | | |
| Characteristic | Preimplementation phase (n=12) | During implementation phase (n=28) | Postimplementation phase (n=20) | Total (N=60) | *P* value |
| Age (y) | | | | | .051 |
| Median (range) | 60.3 (55.0-63.5) | 61.1 (53.4-66.4) | 63.7 (52.9-68.9) | 61.4 (52.9-68.9) | |
| Mean ± SD | 59.8±2.79 | 60.6±3.29 | 62.6±4.27 | 61.1±3.67 | |
| MS-DRG score | | | | | .001 |
| Median (range) | 7.4 (5.2-8.6) | 6.7 (4.5-8.6) | 5.4 (3.4-7.6) | 6.4 (3.4-8.6) | |
| Mean ± SD | 7.1±1.02 | 6.5±1.16 | 5.5±1.10 | 6.3±1.25 | |
| Percentage of female patients | | | | | .621 |
| Median (range) | 41.9 (29.6-54.5) | 43.1 (33.0-50.5) | 43.4 (31.1-55.2) | 42.8 (29.6-55.2) | |
| Mean ± SD | 41.6±6.77 | 43.1±4.65 | 42.7±5.23 | 42.7±5.26 | |
| Percentage of white patients | | | | | .491 |
| Median (range) | 85.2 (74.5-93.6) | 82.6 (67.3-89.9) | 81.9 (74.7-92.8) | 82.6 (67.3-93.6) | |
| Mean ± SD | 83.8±5.89 | 81.6±5.37 | 81.8±4.78 | 82.1±5.27 | |
| Percentage of black patients | | | | | .701 |
| Median (range) | 10.8 (2.8-20.4) | 11.8 (2.4-20.2) | 11.1 (5.2-18.0) | 11.4 (2.4-20.4) | |
| Mean ± SD | 11.0±5.53 | 11.7±3.78 | 11.3±3.53 | 11.4±4.04 | |

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**TABLE 1. Continued**

| Characteristic | Transplant and critical care units: Preimplementation phase (n=12) | During implementation phase (n=28) | Postimplementation phase (n=20) | Total (N=60) | *P* value |
|---|---|---|---|---|---|
| Percentage of other races | | | | | .181 |
| Median (range) | 4.7 (2.2-9.3) | 5.5 (2.7-15.7) | 6.3 (2.1-11.4) | 5.8 (2.1-15.7) | |
| Mean ± SD | 5.2±2.58 | 6.6±3.30 | 6.9±2.54 | 6.4±2.95 | |
| Average census | | | | | .691 |
| Median (range) | 20.2 (9.9-24.9) | 21.6 (12.1-25.7) | 21.0 (12.3-25.8) | 21.1 (9.9-25.8) | |
| Mean ± SD | 19.3±4.94 | 20.7±3.97 | 20.2±3.94 | 20.3±4.12 | |

MS-DRG, Medicare Severity Diagnosis Related Group.

variable was operationalized as a continuous variable. The distribution of mean hemoglobin level per unit was skewed, and log transformation of hemoglobin level was used to normalize the distribution. Next, the number of transfusions in each unit was available in the form of count data for each of the 3 phases. Similarly, the milliliters of blood drawn for each diagnostic test were also operationalized as count data. Finally, percent redraws was operationalized as a continuous variable.

### Independent Variables

The key independent variable of the analysis was the phase in which the patient was admitted to the hospital unit. In addition, mean age, percentage of females, mean Medicare Severity Diagnosis Related Group (MS-DRG) score, and percentage of each race (white, black, and other) on each unit were calculated and included as covariates. The MS-DRG score was used to determine the severity of patient illness across units and is defined by a combination of principal diagnosis and procedures received as well as any resultant complications or patient comorbidities. The higher the MS-DRG score, the greater the patient's severity of illness.

### Analyses

Kruskal-Wallis tests were used to describe associations between measures across implementation phases. Multivariate linear regression models were used to compare differences in the means of the log-transformed hemoglobin levels on the unit adjusting for covariates, the inpatient unit, and average census per unit across implementation phases. Similarly, multivariate negative binomial regression models were used to compare the number of transfusions as well as the total milliliters of each diagnostic blood draw for each type of tube between the 3 phases adjusting for the same covariates. Average census was used as an exposure in this regression model. For all dependent variables, the analysis was performed across all the units and then separately for patients admitted to the transplant and critical care (T/CC) units, as the frequency of laboratory testing is increased in this subgroup. Finally, linear regression was used to examine whether there was any change in percent redraws across all the inpatient units between the 3 phases. For log-transformed models, results were exponentiated, and percent change is reported.

## RESULTS

The study included results from 10 inpatient units including 4 T/CC units from April 1, 2017 to June 30, 2018. Demographic statistics (Table 1) indicate that the median age of patients increased during the study timeline from 61.1 to 63.9 years ($P$=.005) in all the units and from 60.3 to 63.7 years ($P$=.051) in the T/CC units. The percentage of black patients increased from 8.7% to 9.8% ($P$=.02) when considering all the units, but there were no similar changes in the T/CC units. Furthermore, there were no differences in percent females, percentage of white patients, or average census through the phases of this study when considering all the units as well as the T/CC units. However, unlike other units, T/CC units experience a decrease in

**TABLE 2. Distribution of Mean Hemoglobin Levels, Number of Transfusions, Total Milliliters of Blood Drawn Using Different Tubes**

| All patient care units | | | | | |
|---|---|---|---|---|---|
| Variable | Preimplementation phase (n=30) | During implementation phase (n=70) | Postimplementation phase (n=50) | Total (N=150) | *P* value |
| Hemoglobin level (g/dL) | | | | | .68 |
| Median (range) | 9.8 (8.6-11.5) | 9.6 (8.8-11.2) | 9.7 (8.8-11.2) | 9.7 (8.6-11.5) | |
| Mean ± SD | 9.8±0.70 | 9.7±0.58 | 9.8±0.56 | 9.8±0.59 | |
| Number of transfusions | | | | | .88 |
| Median (range) | 38.0 (7.0-149.0) | 44.5 (7.0-179.0) | 49.0 (4.0-194.0) | 46.5 (4.0-194.0) | |
| Mean ± SD | 60.0±46.73 | 62.5±48.64 | 58.5±44.77 | 60.7±46.72 | |
| Blood volume for coagulation testing (mL) | | | | | .05 |
| Median (range) | 369 (54.0-1831.5) | 331.2 (49.5-1818.0) | 253.8 (13.51169.1) | 290.3 (13.5-1831.5) | |
| Mean ± SD | 566.9±514.46 | 509.4±448.81 | 316.0±270.53 | 456.4±423.38 | |
| Basic metabolic panel (mL) | | | | | .45 |
| Median (range) | 1030 (45.0-2720.0) | 965 (55.0-2960.0) | 661.5 (77.0-2422.0) | 791 (45.0-2960.0) | |
| Mean ± SD | 1058.2±852.83 | 1047.1±842.65 | 807.6±607.21 | 969.5±777.71 | |
| Blood volume for hematology testing (mL) | | | | | .02 |
| Median (range) | 1180 (300.0-2692.0) | 1192 (392.0-2952.0) | 987 (240.0-1968.0) | 1081.5 (240.0-2952.0) | |
| Mean ± SD | 1192.7±591.14 | 1280.0±611.51 | 970.3±418.13 | 1159.3±563.67 | |
| Percent redraws per month | | | | | .004 |
| Median (range) | 1.9 (1.9-2.0) | 2.0 (1.3-2.2) | 2.0 (1.8-2.0) | 2.0 (1.3-2.2) | |
| Mean ± SD | 1.9±0.05 | 1.9±0.29 | 2.0±0.08 | 1.9±0.21 | |
| Transplant and critical care units | | | | | |
| Variable | Preimplementation phase (n=12) | During implementation phase (n=28) | Postimplementation phase (n=20) | Total (N=60) | *P* value |
| Hemoglobin level (g/dL) | | | | | .08 |
| Median (range) | 9.4 (8.6-9.6) | 9.4 (8.8-9.6) | 9.5 (8.8-9.8) | 9.4 (8.6-9.8) | |
| Mean ± SD | 9.3±0.31 | 9.3±0.25 | 9.5±0.29 | 9.4±0.28 | |
| Number of transfusions | | | | | .78 |
| Median (range) | 93.0 (37.0-149.0) | 107.5 (38.0-179.0) | 89.0 (36.0-194.0) | 99.5 (36.0-194.0) | |
| Mean ± SD | 96.3±38.98 | 101.4±41.14 | 94.5±39.57 | 98.1±39.65 | |
| Blood volume for coagulation testing (mL) | | | | | <.0001 |
| Median (range) | 807.8 (153.0-1030.5) | 693.0 (315.9-1575.0) | 342.9 (234.9-707.4) | 576.5 (153.0-1575.0) | |
| Mean ± SD | 736.1±275.72 | 756.5±331.97 | 408.9±141.10 | 636.5±312.13 | |
| Basic metabolic panel (mL) | | | | | .06 |
| Median (range) | 1332.5 (755.0-2715.0) | 1475.0 (460.0-2860.0) | 985.3 (420.0-2187.5) | 1142.5 (420.0-2860.0) | |
| Mean ± SD | 1545.4±673.66 | 1465.3±668.85 | 1077.7±492.96 | 1352.1±637.81 | |
| Blood volume for hematology testing (mL) | | | | | .10 |
| Median (range) | 1488.0 (364.0-2692.0) | 1511.5 (544.0-2952.0) | 1162.5 (504.0-1968.0) | 1342.5 (364.0-2952.0) | |
| Mean ± SD | 1462.7±724.60 | 1627.5±699.49 | 1196.0±425.11 | 1450.7±645.65 | |
| Percent redraws per month | | | | | .11 |
| Median (range) | 1.9 (1.9-2.0) | 2.0 (1.3-2.2) | 2.0 (1.8-2.0) | 2.0 (1.3-2.2) | |
| Mean ± SD | 1.9±0.05 | 1.9±0.30 | 2.0±0.08 | 1.9±0.21 | |

SI conversion factor: To convert g/dL values to g/L, multiply by 10.



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MS-DRG score from 7.4 to 5.4 over the study period (*P*=.001).

Table 2 indicates that the mean hemoglobin level changed from 98 to 97 g/L over the study period in all the units (*P*=.68) and from 93 to 95 g/L in the T/CC units (*P*=.08). The mean number of transfusions changed from 60 in the preintervention phase to 58.5 in the postintervention phase (*P*=.88) and from 93 to 89 in the T/CC units (*P*=.78). The mean milliliters of blood drawn decreased from 566.9 to 316.0 or 44.3% (*P*=.05) for coagulation tests, from 1058.2 to 807.6 or 24% (*P*=.45) for BMP tests, and from 1192.7 to 970.3 or 18.6% (*P*=.02) for hematology tests, with an overall decrease of 25.7% in all the units. The mean milliliters of blood drawn decreased from 736.1 to 408.9 or 44.5% (*P*<.0001) for coagulation tests, from 1545.4 to 1077.7 or 30.3% (*P*=.06) for BMP tests, and from 1462.7 to 1196.0 or 18.2% (*P*=.10) for hematology tests, with an overall decrease of 22.9% in the T/CC units. A steep and significant decrease in DBL was observed in the postintervention phase for all the 3 laboratory tests in all the units as well as the T/CC units (FigureA-C). There was also a significant difference in percent redraws between the phases of the study when considering all the units (*P*=.004), but not when considering the T/CC units (*P*=.11).

When considering the multivariate regression models reported in Table 2, no significant differences were observed between the phases when comparing mean hemoglobin levels across all the units. However, as observed in the Figure and supported by Table 3, there was a general trend toward higher hemoglobin levels. In addition, subgroup analysis of patients admitted to the T/CC units revealed a significant increase in mean hemoglobin levels between "during implementation phase" and "postintervention phase," with a 2.71% increase (95% CI, 1.07% to 4.37%). Regression models for transfusions found a significant reduction in the number of transfusions in all the units across implementation phases. In addition, the incidence risk ratio (IRR) for transfusion reduced even more in patients admitted to the T/CC units (IRR, 0.00; 95% CI, 0.00 to 0.02) between preintervention phase and during implementation phase (IRR, 0.13; 95% CI, 0.02 to 0.77), between during implementation phase and postintervention phase (IRR, 0.01; 95% CI, 0.00 to 0.12), and between preintervention phase and postintervention phase. Finally, the linear regression model comparing the different phases did not find any significant difference in the overall percent redraws across all the units.

The regression models for total volume of blood drawn for all the 3 tests controlling for average census found a significant decrease across each implementation phase (Table 4). Specifically, the BMP test reported a decrease in IRR for more milliliters being drawn from preintervention phase and during intervention phase (IRR, 0.05; 95% CI, 0.00 to 0.26), from during intervention phase to postintervention phase (IRR, 0.21; 95% CI, 0.08 to 0.55), and from preintervention phase to postintervention phase (IRR, 0.10; 95% CI, 0.03 to 0.28). Similarly, the coagulation test collection was associated with decrease from preintervention phase to during intervention phase (IRR, 0.05; 95% CI, 0.01 to 0.31), from during intervention phase to postintervention phase (IRR, 0.13; 95% CI, 0.05 to 0.36), and from preintervention phase to postintervention phase (IRR, 0.09; 95% CI, 0.04 to 0.24). When considering milliliters of blood drawn for hematology testing, a decrease from preintervention phase to during intervention phase (IRR, 0.03; 95% CI, 0.00 to 0.19), from during intervention phase to postintervention phase (IRR, 0.13; 95% CI, 0.05 to 0.33), and from preintervention phase to postintervention phase (IRR, 0.08; 95% CI, 0.03 to 0.21) was found. As also shown in Table 4, the subgroup analysis performed in the T/CC units revealed a similar reduction across each diagnostic blood tube type and each implementation phase.

## DISCUSSION

This study reported a significant increase in the mean hemoglobin level of patients admitted to the T/CC units after the implementation of smaller volume tubes. In contrast, patients in medical wards generally required fewer laboratory tests, resulting in less DBL and thus had less appreciable benefit from the use of small volume tubes. Also, a significant reduction in the number of transfusions was found across units, and a more substantial reduction was observed in the T/CC units across implementation phases. Furthermore, DBL decreased significantly when the

standard or adult-sized blood collection tubes were exchanged for smaller volume tubes. This reduction in DBL was significant across different diagnostic tests included in the analysis. In the T/CC units, the reduction in DBL for coagulation and BMP tests was even more pronounced. At the same time, there was no significant change in percent redraws with the implementation of small volume tubes in the inpatient units, signifying that the use of these tubes provided an adequate volume of blood for laboratory testing.

### Interpretation

This blood conserving intervention has important implications for clinical and quality improvement in the inpatient setting. Previous studies have found that the risk of moderate to severe anemia increases with the volume of DBL.[14] Although our study found a lack of statistical association with improved hemoglobin levels when considering the overall hospital population, there was an association with improved hemoglobin levels in the T/CC units. Patients with the highest risk of large iatrogenic blood loss include those in critical care units including intensive care and coronary care units whose frequent blood testing puts them at a higher risk of HAA.[20] In critically ill patients, larger cumulative volumes of blood loss can further reduce tissue oxygenation by decreasing systemic oxygen delivery to vital organs. Reducing DBL by using smaller volume laboratory tubes in patients may help reduce the risk of HAA and the need for blood transfusions.

Our study also found a strong positive association with reductions in transfusions in the overall model and the T/CC units. Similarly, Corwin et al[21] reported that 49% of the variation in the amount of red blood cells transfused in patients in the ICU is accounted for by routine laboratory test collections. Furthermore, reducing DBL was found to

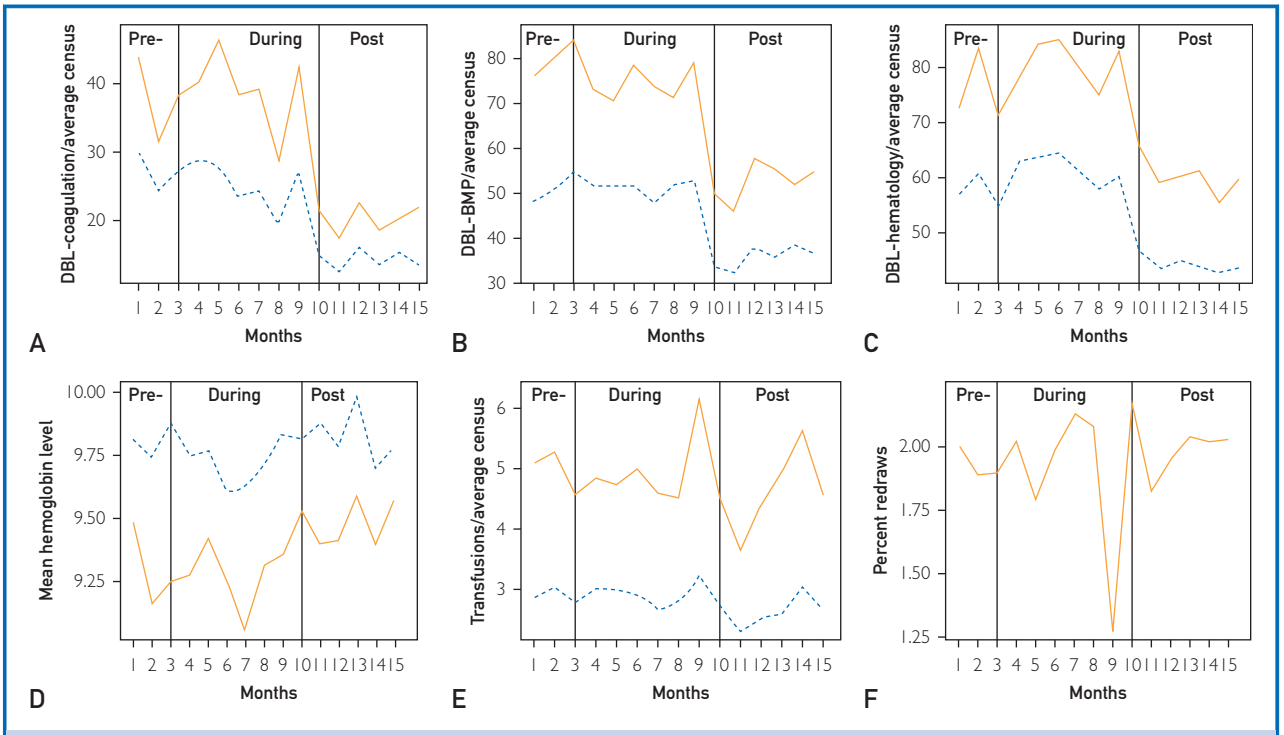


**FIGURE.** Monthly trends in diagnostic blood loss (DBL) in each unit per average census for coagulations tests (A), basic metabolic panel (BMP) tests (B), and hematology tests (C), mean hemoglobin levels in each unit (D), transfusions/average census (E), and percent redraws (F) in the hospital. The solid line indicates entire hospital and the dotted line transplant and critical care units. During, during intervention phase; Post, postintervention phase; Pre, preintervention phase.


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**TABLE 3. Multivariate Regression Comparing Log-Transformed Mean Hemoglobin Levels Between Preimplementation, During Implementation and Postimplementation Phases**

| Mean hemoglobin levels in all the patient care units—linear regression | | | |
|---|---|---|---|
| | Percent change (95% CI) | | |
| Variable | Pre- vs during implementation | During vs postimplementation | Pre- vs postimplementation |
| Phase | −0.51 (−3.04 to 2.09) | 0.46 (−1.57 to 2.54) | 0.06 (−1.35 to 1.49) |
| Percentage of female patients | −0.26 (−0.46 to −0.07) | −0.24 (−0.4 to −0.07) | −0.34 (−0.55 to −0.12) |
| Mean age of patients | −0.14 (−0.53 to 0.25) | −0.2 (−0.5 to 0.11) | −0.38 (−0.82 to 0.07) |
| Mean MS-DRG score | −1.61 (−2.49 to −0.71) | −1.73 (−2.6 to −0.85) | −1.92 (−3.15 to −0.68) |
| Percentage of white patients | 0.29 (−0.16 to 0.74) | 0.35 (−0.01 to 0.71) | 0.09 (−0.37 to 0.54) |
| Percentage of black patients | 0.24 (−0.31 to 0.79) | 0.25 (−0.23 to 0.74) | −0.15 (−0.76 to 0.47) |
| Inpatient care unit | 0.24 (−0.33 to 0.82) | 0 (−0.52 to 0.52) | 0.11 (−0.58 to 0.82) |
| Average census | 0.37 (0.1 to 0.64) | 0.39 (0.13 to 0.66) | 0.5 (0.18 to 0.82) |
| **Mean hemoglobin levels in the transplant and critical care units—linear regression** | | | |
| | Percent change (95% CI) | | |
| Variable | Pre- vs during implementation | During vs postimplementation | Pre- vs postimplementation |
| Phase | −0.49 (−2.15 to 1.2) | 2.71 (1.07 to 4.37) | 0.42 (−0.9 to 1.77) |
| Percentage of female patients | −0.02 (−0.2 to 0.15) | −0.15 (−0.3 to −0.01) | −0.18 (−0.37 to 0.02) |
| Mean age of patients | 0.06 (−0.44 to 0.57) | −0.2 (−0.55 to 0.16) | −0.22 (−0.62 to 0.19) |
| Mean MS-DRG score | 0.14 (−0.99 to 1.27) | 0.21 (−0.83 to 1.27) | −0.77 (−2.2 to 0.67) |
| Percentage of white patients | 0.28 (−0.02 to 0.58) | 0.08 (−0.15 to 0.32) | 0.11 (−0.21 to 0.43) |
| Percentage of black patients | 0.31 (−0.04 to 0.67) | 0.1 (−0.22 to 0.43) | 0.04 (−0.37 to 0.45) |
| Inpatient care unit | 0.22 (−0.62 to 1.07) | 0.98 (0.29 to 1.68) | 0.55 (−0.2 to 1.3) |
| Average census | 0.49 (0.3 to 0.68) | 0.31 (0.09 to 0.52) | 0.49 (0.28 to 0.7) |
| **Transfusions in all the patient care units—negative binomial regression** | | | |
| | IRR (95% CI) | | |
| Variable | Pre- vs during implementation | During vs postimplementation | Pre- vs postimplementation |
| Phase | 0.04 (0.01 to 0.31) | 0.25 (0.09 to 0.71) | 0.10 (0.04 to 0.31) |
| Percentage of female patients | 0.99 (0.90 to 1.11) | 1.02 (0.96 to 1.08) | 1.02 (0.94 to 1.11) |
| Mean age of patients | 1.30 (1.01 to 1.68) | 1.46 (1.17 to 1.82) | 1.63 (1.13 to 2.34) |
| Mean MS-DRG score | 0.53 (0.34 to 1.02) | 0.42 (0.26 to 0.68) | 1.67 (0.68 to 4.11) |
| Percentage of white patients | 0.83 (0.61 to 1.13) | 1.17 (0.85 to 1.61) | 1.15 (0.69 to 1.93) |
| Percentage of black patients | 0.84 (0.60 to 1.18) | 1.08 (0.76 to 1.53) | 1.48 (0.67 to 3.25) |
| Inpatient care unit | 0.17 (0.08 to 0.35) | 0.15 (0.01 to 0.23) | 0.28 (0.15 to 0.52) |
| **Transfusions in the transplant and critical care units—negative binomial regression** | | | |
| | IRR (95% CI) | | |
| Variable | Pre- vs during implementation | During vs postimplementation | Pre- vs postimplementation |
| Phase | 0.00 (0.00 to 0.02) | 0.13 (0.02 to 0.77) | 0.01 (0.00 to 0.12) |
| Percentage of female patients | 1.21 (0.95 to 1.55) | 1.02 (0.92 to 1.13) | 0.97 (0.85 to 1.10) |
| Mean age of patients | 1.47 (0.74 to 2.91) | 1.53 (0.98 to 2.38) | 1.80 (0.88 to 3.68) |
| Mean MS-DRG score | 0.41 (0.11 to 1.55) | 0.19 (0.05 to 0.63) | 0.23 (0.02 to 3.00) |
| Percentage of white patients | 0.94 (0.54 to 1.66) | 1.16 (0.84 to 1.60) | 0.60 (0.38 to 0.96) |

*Continued on next page*

**TABLE 3. Continued**

| Transfusions in the transplant and critical care units—negative binomial regression | | | |
|---|---|---|---|
| | IRR (95% CI) | | |
| Variable | Pre- vs during implementation | During vs postimplementation | Pre- vs postimplementation |
| Percentage of black patients | 0.77 (0.41 to 1.43) | 0.98 (0.69 to 1.39) | 0.74 (0.42 to 1.33) |
| Inpatient care unit | 0.12 (0.06 to 0.24) | 0.09 (0.06 to 0.15) | 0.07 (0.03 to 0.16) |
| Percent redraws across all the patient care units | | | |
| | Pre- vs during implementation | During vs postimplementation | Pre- vs postimplementation |
| Percent redraws | −0.01 (−0.44 to 0.43) | 0.05 (−0.28 to 0.38) | 0.02 (−0.05 to 0.10) |

IRR, incidence risk ratio; MS-DRG, Medicare Severity Diagnosis Related Group.

decrease the need for blood transfusion in the ICU, in which frequent testing commonly occurs.[21] Several other studies have provided support for the use of small sized tubes to reduce mean DBL in the ICU or critical care setting.[10,22] These studies provided insight into the benefits of decreased DBL by changing to smaller volume tubes in a single unit or in a particular population of patients. However, it was previously unclear whether these results could be generalized to nonintensive care inpatient units, in which diagnostic testing is usually less frequent. The results of our study go beyond the previous studies and suggest the effect of similar interventions in multiple areas within the inpatient hospital setting.[23]

Ultimately, this study reports that smaller volume tubes can be an excellent alternative to standard sized tubes without compromising patient care or the quality of laboratory results and without a significant increase in the number of recollections related to this intervention. Of note, collection of the smaller volume tubes was found to be insufficient for special coagulation, transfusion medicine, or referral laboratory testing. Patients with a large number of tests on multiple different instruments that require making several aliquots may also need more blood collected. Depending on the laboratory's instrumentation, automation may not accommodate the "traditional pediatric tubes," which are shorter and thinner; however, newer small volume tubes (reduced vacuum or inserts) are generally the same size as standard volume tubes and can be used on most laboratory instrumentation. Therefore, although smaller volume tubes may be substituted for most routine laboratory testing, there are some settings in which standard volume tubes are necessary.

Finally, concern about overuse of laboratory testing was voiced as early as the 1970s when data suggested excessive use of laboratory testing as more analytes became readily available.[24,25] Attempts at moderating laboratory use included using guidelines, audits, education, and communication; posting costs of testing; physician profiling of high test use; laboratory formularies; benchmarking; clinical pathology consulting services; financial incentives for reduced use; and the use of algorithms and reflex testing.[20,26-32] A particularly effective tool has been the involvement of the electronic medical record using institution-specific rules to track or prevent routine testing, unnecessary testing, expensive testing, and uninformative repeat testing.[26] Although there is still work to be done, improvements have occurred, and most institutions now discourage or block orders for daily "morning round" testing of patients and other unnecessary testing. According to our results, reduction in the volume of collection tubes can augment comprehensive laboratory utilization programs.

## Limitations

This study relies on retrospectively collected administrative and laboratory test data when applied to the entire hospital, though prospective data. Chart review and patient-level data collection were not performed during the rollout process to the entire hospital, limiting the ability to determine specific associations between disease severity and other


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**TABLE 4. Multivariate Negative Binomial Regression Comparing the Total Milliliters of Blood Drawn Between Preimplementation, During Implementation, and Postimplementation Phases for Basic Metabolic Panel, Coagulation, Hematology Tests**

| Variable | IRR (95% CI) | | |
|---|---|---|---|
| | Pre- vs during implementation | During vs postimplementation | Pre- vs postimplementation |
| Total milliliters of blood drawn for basic metabolic panel tests in all the patient care units | | | |
| Phase | 0.03 (0.00-0.26) | 0.21 (0.08-0.55) | 0.10 (0.03-0.28) |
| Percentage of female patients | 1.01 (0.91-1.12) | 1.03 (0.97-1.10) | 1.03 (0.95-1.11) |
| Mean age | 1.30 (1.00-1.68) | 1.43 (1.17-1.75) | 1.49 (1.06-2.10) |
| Mean MS-DRG score | 0.56 (0.32-0.97) | 0.40 (0.25-0.62) | 1.58 (0.67-3.72) |
| Percentage of white patients | 0.84 (0.63-1.12) | 1.14 (0.85-1.53) | 1.18 (0.74-1.89) |
| Percentage of black patients | 0.84 (0.61-1.17) | 1.05 (0.76-1.45) | 1.49 (0.72-3.09) |
| Inpatient unit | 0.17 (0.08-0.35) | 0.16 (0.10-0.23) | 0.29 (0.16-0.53) |
| Total milliliters of blood drawn for coagulation tests in all the patient care units | | | |
| Phase | 0.05 (0.01-0.31) | 0.13 (0.05-0.36) | 0.09 (0.04-0.24) |
| Percentage of female patients | 1.00 (0.91-1.10) | 1.02 (0.96-1.08) | 1.01 (0.94-1.09) |
| Mean age | 1.33 (1.05-1.68) | 1.44 (1.17-1.77) | 1.42 (1.01-2.00) |
| Mean MS-DRG score | 0.51 (0.33-0.81) | 0.38 (0.25-0.57) | 0.99 (0.44-2.23) |
| Percentage of white patients | 0.95 (0.71-1.26) | 1.15 (0.85-1.54) | 1.24 (0.81-1.90) |
| Percentage of black patients | 0.91 (0.66-1.25) | 1.03 (0.75-1.43) | 1.54 (0.78-3.07) |
| Inpatient unit | 0.18 (0.10-0.33) | 0.15 (0.11-0.22) | 0.23 (0.14-0.38) |
| Total milliliters of blood drawn for hematology tests in all the patient care units | | | |
| Phase | 0.03 (0.00-0.19) | 0.13 (0.05-0.33) | 0.08 (0.03-0.21) |
| Percentage of female patients | 0.99 (0.89-1.10) | 1.01 (0.96-1.07) | 1.02 (0.94-1.10) |
| Mean age | 1.39 (1.07-1.80) | 1.46 (1.21-1.75) | 1.59 (1.14-2.22) |
| Mean MS-DRG score | 0.39 (0.23-0.64) | 0.30 (0.20-0.45) | 1.17 (0.49-2.76) |
| Percentage of white patients | 0.82 (0.62-1.10) | 1.11 (0.83-1.48) | 1.14 (0.71-1.85) |
| Percentage of black patients | 0.86 (0.62-1.21) | 1.08 (0.79-1.46) | 1.31 (0.64-2.66) |
| Inpatient unit | 0.19 (0.09-0.41) | 0.18 (0.12-0.27) | 0.32 (0.18-0.58) |
| Total milliliters of blood drawn for basic metabolic panel tests in the transplant and critical care units | | | |
| Phase | 0 (0-0.01) | 0.16 (0.03-0.75) | 0.02 (0-0.12) |
| Percentage of female patients | 1.21 (0.97-1.5) | 1.05 (0.95-1.16) | 0.99 (0.88-1.12) |
| Mean age | 1.53 (0.81-2.9) | 1.42 (0.98-2.06) | 1.65 (0.85-3.21) |
| Mean MS-DRG score | 0.41 (0.12-1.39) | 0.18 (0.06-0.53) | 0.28 (0.03-2.99) |
| Percentage of white patients | 0.96 (0.59-1.57) | 1.19 (0.91-1.57) | 0.63 (0.41-0.98) |
| Percentage of black patients | 0.78 (0.44-1.36) | 0.98 (0.72-1.32) | 0.76 (0.44-1.33) |
| Inpatient unit | 0.12 (0.06-0.25) | 0.1 (0.06-0.16) | 0.08 (0.04-0.18) |
| Total milliliters of blood drawn for coagulation tests in the transplant and critical care units | | | |
| Phase | 0.00 (0.00-0.03) | 0.09 (0.02-0.48) | 0.02 (0.00-0.12) |
| Percentage of female patients | 1.22 (1.00-1.49) | 1.05 (0.94-1.16) | 0.99 (0.88-1.12) |
| Mean age | 1.70 (0.91-3.21) | 1.52 (1.04-2.22) | 1.69 (0.86-3.35) |
| Mean MS-DRG score | 0.45 (0.13-1.60) | 0.19 (0.06-0.56) | 0.24 (0.02-2.72) |
| Percentage of white patients | 1.04 (0.66-1.66) | 1.21 (0.92-1.60) | 0.74 (0.48-1.14) |
| Percentage of black patients | 0.88 (0.53-1.46) | 1.00 (0.73-1.37) | 0.89 (0.53-1.51) |
| Inpatient unit | 0.13 (0.06-0.24) | 0.11 (0.07-0.17) | 0.09 (0.04-0.20) |
| Total milliliters of blood drawn for hematology tests in the transplant and critical care units | | | |
| Phase | 0.00 (0.00-0.03) | 0.20 (0.04-0.95) | 0.03 (0.00-0.18) |
| Percentage of female patients | 1.18 (0.95-1.47) | 1.03 (0.93-1.14) | 0.99 (0.88-1.11) |
| Mean age | 1.47 (0.77-2.78) | 1.44 (0.98-2.12) | 1.72 (0.93-3.16) |
| Mean MS-DRG score | 0.49 (0.14-1.66) | 0.24 (0.08-0.71) | 0.37 (0.04-3.25) |
| Percentage of white patients | 1.00 (0.59-1.69) | 1.23 (0.92-1.64) | 0.61 (0.40-0.93) |
| Percentage of black patients | 0.83 (0.46-1.48) | 1.04 (0.75-1.43) | 0.75 (0.45-1.23) |
| Inpatient unit | 0.16 (0.08-0.32) | 0.13 (0.08-0.21) | 0.11 (0.05-0.22) |

IRR, incidence risk ratio; MS-DRG, Medicare Severity Diagnosis Related Group.

characteristics for specific patients. Thus, the study was not designed to define if unnecessary orders were a contributing factor to outcomes of interest. However, multiple laboratory utilization strategies are used in our practice to limit much unnecessary testing.

Despite these limitations, this study does provide an example of the outcomes associated with using small volume tubes throughout an entire hospital setting, thus decreasing the amount of blood collected by approximately a quarter to one-third in every patient. In addition, this study provides a clear indication that the amount of blood collected throughout the hospital can be reduced without increasing the number of redraws necessary for diagnostic testing.

## CONCLUSION

The use of small volume tubes in exchange for standard sized tubes significantly decreased DBL for routine hematology, BMP, and coagulation testing by 24% in all the units and 22.9% in the T/CC units. Also, the number of transfusions decreased across all the units, with the greatest decrease occurring in the T/CC units. An increase in mean hemoglobin levels was observed specifically in patients admitted to the T/CC units, with no corresponding change in percent redraws across all the units.

Although many sources of blood loss in patients are not preventable, the use of smaller volume tubes can decrease DBL. The use of these smaller tubes is the new standard practice in our inpatient units. After completing this change for hospital patients, implementation has been extended to outpatient areas. Arterial blood gas analysis was not included in these studies, but could be an area for future investigation. Revisiting minimum specimen requirements for laboratory testing periodically may result in further reduction of blood collection tube sizes with the advances in technology.

**Abbreviations and Acronyms:** **BMP** = basic metabolic panel; **DBL** = diagnostic blood loss; **HAA** = hospital-acquired anemia; **ICU** = intensive care unit; **IRR** = incidence risk ratio; **MS-DRG** = Medicare Severity Diagnosis Related Group; **T/CC** = transplant and critical care

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## REFERENCES

1. Mann SA, Williams LA III, Marques MB, Pham HP. Hospital-acquired anemia due to diagnostic and therapy-related blood loss in inpatients with myasthenia gravis receiving therapeutic plasma exchange. *J Clinl Apher*. 2018;33(1):14-20.
2. Shander A. Anemia in the critically ill. *Crit Care Clin*. 2004;20(2):159-178.
3. Koch CG, Li L, Sun Z, et al. Hospital-acquired anemia: prevalence, outcomes, and healthcare implications. *J Hosp Med*. 2013;8(9):506-512.
4. Pabla L, Watkins E, Doughty HA. A study of blood loss from phlebotomy in renal medical inpatients. *Transfus Med*. 2009;19(6):309-314.
5. Tosiri P, Kanitsap N, Kanitsap A. Approximate iatrogenic blood loss in medical intensive care patients and the causes of anemia. *J Med Assoc Thai*. 2010;93(suppl 7):S271-S276.
6. Branco BC, Inaba K, Doughty R, et al. The increasing burden of phlebotomy in the development of anaemia and need for blood transfusion amongst trauma patients. *Injury*. 2012;43(1):78-83.
7. Salisbury AC, Alexander KP, Reid KJ, et al. Incidence, correlates, and outcomes of acute, hospital-acquired anemia in patients with acute myocardial infarction. *Circ Cardiovasc Qual Outcomes*. 2010;3(4):337-346.
8. Makam AN, Nguyen OK, Clark C, Halm EA. Incidence, predictors, and outcomes of hospital-acquired anemia. *J Hosp Med*. 2017;12(5):317-322.
9. Thavendiranathan P, Bagai A, Ebidia A, Detsky AS, Choudhry NK. Do blood tests cause anemia in hospitalized patients? The effect of diagnostic phlebotomy on hemoglobin and hematocrit levels. *J Gen Intern Med*. 2005;20(6):520-524.
10. Smoller BR, Kruskall MS. Phlebotomy for diagnostic laboratory tests in adults: pattern of use and effect on transfusion requirements. *N Engl J Med*. 1986;314(19):1233-1235.
11. von Ahsen N, Müller C, Serke S, Frei U, Eckardt KU. Important role of nondiagnostic blood loss and blunted erythropoietic response in the anemia of medical intensive care patients. *Crit Care Med*. 1999;27(12):2630-2639.
12. Iams W, Heck J, Kapp M, et al. A multidisciplinary housestaff-led initiative to safely reduce daily laboratory testing. *Acad Med*. 2016;91(6):813-820.
13. Dale JC, Pruett SK. Phlebotomy—a minimalist approach. *Mayo Clin Proc*. 1993;68(3):249-255.
14. Salisbury AC, Reid KJ, Alexander KP, et al. Diagnostic blood loss from phlebotomy and hospital-acquired anemia during acute myocardial infarction. *Arch Intern Med*. 2011;171(18):1646-1653.
15. Koch CG, Reineks EZ, Tang AS, et al. Contemporary bloodletting in cardiac surgical care. *Ann Thorac Surg*. 2015;99(3):779-784.
16. ABIM Foundation. *Choosing Wisely: An Initiative of the ABIM Foundation*. Philadelphia, PA: ABIM Foundation; 2020.

17. Callum JL, Waters JH, Shaz BH, Sloan SR, Murphy MF. The AABB recommendations for the Choosing Wisely campaign of the American Board of Internal Medicine. *Transfusion*. 2014;54(9):2344-2352.
18. van der Bom JG, Cannegieter SC. Hospital-acquired anemia: the contribution of diagnostic blood loss. *J Thromb Haemost*. 2015;13(6):1157-1159.
19. Woodhouse S. Complications of critical care: lab testing and iatrogenic anemia. *MLO Med Lab Obs*. 2001;33(10):28-31.
20. Sanchez-Giron F, Alvarez-Mora F. Reduction of blood loss from laboratory testing in hospitalized adult patients using small-volume (pediatric) tubes. *Arch Pathol Lab Med*. 2008;132(12):1916-1919.
21. Corwin HL, Parsonnet KC, Gettinger A. RBC transfusion in the ICU: is there a reason? *Chest*. 1995;108(3):767-771.
22. Riessen R, Behmenburg M, Blumenstock G, et al. A simple "blood-saving bundle" reduces diagnostic blood loss and the transfusion rate in mechanically ventilated patients. *PLoS One*. 2015;10(9):e0138879.
23. Harber CR, Sosnowski KJ, Hegde RM. Highly conservative phlebotomy in adult intensive care—a prospective randomized controlled trial. *Anaesth Intensive Care*. 2006;34(4):434-437.
24. Griner PF, Liptzin B. Use of the laboratory in a teaching hospital: implications for patient care, education, and hospital costs. *Ann Intern Med*. 1971;75(2):157-163.
25. Schroeder SA, Kenders K, Cooper JK, Piemme TE. Use of laboratory tests and pharmaceuticals: variation among physicians and effect of cost audit on subsequent use. *JAMA*. 1973;225(8):969-973.
26. Sadowski BW, Lane AB, Wood SM, Robinson SL, Kim CH. High-value, cost-conscious care: iterative systems-based interventions to reduce unnecessary laboratory testing. *Am J Med*. 2017;130(9):1112.e1111-1112.e1117.
27. Minerowicz C, Abel N, Hunter K, Behling KC, Cerceo E, Bierl C. Impact of weekly feedback on test ordering patterns. *Am J Manag Care*. 2015;21(11):763-768.
28. McDonald EG, Saleh RR, Lee TC. Mindfulness-based laboratory reduction: reducing utilization through trainee-led daily 'time outs'. *Am J Med*. 2017;130(6):e241-e244.
29. Newman DB, Siontis KC, Chandrasekaran K, Jaffe AS, Kashiwagi DT. Intervention to reduce inappropriate ionized calcium ordering practices: a quality-improvement project. *Perm J*. 2015;19(1):49-51.
30. Sedrak MS, Myers JS, Small DS, et al. Effect of a price transparency intervention in the electronic health record on clinician ordering of inpatient laboratory tests: the PRICE randomized clinical trial. *JAMA Intern Med*. 2017;177(7):939-945.
31. Vidyarthi AR, Hamill T, Green AL, Rosenbluth G, Baron RB. Changing resident test ordering behavior: a multilevel intervention to decrease laboratory utilization at an academic medical center. *Am J Med Qual*. 2015;30(1):81-87.
32. Lee VS, Kawamoto K, Hess R, et al. Implementation of a value-driven outcomes program to identify high variability in clinical costs and outcomes and association with reduced cost and improved quality. *JAMA*. 2016;316(10):1061-1072.