Evaluation of Perioperative Medication Errors and Adverse Drug Events

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ABSTRACT

Background: The purpose of this study is to assess the rates of perioperative medication errors (MEs) and adverse drug events (ADEs) as percentages of medication administrations, to evaluate their root causes, and to formulate targeted solutions to prevent them.

Methods: In this prospective observational study, anesthesia-trained study staff (anesthesiologists/nurse anesthetists) observed randomly selected operations at a 1,046-bed tertiary care academic medical center to identify MEs and ADEs over 8 months. Retrospective chart abstraction was performed to flag events that were missed by observation. All events subsequently underwent review by two independent reviewers. Primary outcomes were the incidence of MEs and ADEs.

Results: A total of 277 operations were observed with 3,671 medication administrations of which 193 (5.3%; 95% CI, 4.5 to 6.0) involved a ME and/or ADE. Of these, 153 (79.3%) were preventable and 40 (20.7%) were nonpreventable. The events included 153 (79.3%) errors and 91 (47.2%) ADEs. Although 32 (20.9%) of the errors had little potential for harm, 51 (33.3%) led to an observed ADE and an additional 70 (45.8%) had the potential for patient harm. Of the 153 errors, 99 (64.7%) were serious, 51 (33.3%) were significant, and 3 (2.0%) were life-threatening.

Conclusions: One in 20 perioperative medication administrations included an ME and/or ADE. More than one third of the MEs led to observed ADEs, and the remaining two thirds had the potential for harm. These rates are markedly higher than those reported by retrospective surveys. Specific solutions exist that have the potential to decrease the incidence of perioperative MEs. (ANESTHESIOLOGY 2015; XXX:00-00)

MEDICATION administration in the perioperative setting presents particular patient safety challenges compared with other hospital settings.[1] Unlike in the inpatient hospital ward setting, perioperative medication administration today often bypasses standard safety checks, such as electronic physician order entry with decision support, pharmacy approval of specific drugs before administration, and multiple nursing checks at the time of medication administration. Furthermore, the high-stress, time-sensitive nature of operating room care may lead to both higher rates of medication errors (MEs) and errors of high severity.

Perioperative syringe swaps, ampoule swaps, and wrong dose errors can all cause serious harm.[2] In fact, the most frequently cited critical incidents in anesthesia are drug administration errors.[3] However, the literature on the perioperative ME rates is sparse and contains largely self-reported data,[4–7] consisting of either spontaneous self-reports of errors[5,7] or facilitated incident reporting of whether an error occurred.[1,6] The validity and reliability of studies based on self-reporting of MEs in other patient care areas has been called into question.[8–10] For example, in a study of 2,557 doses of medications administered on hospital wards, Flynn *et al.*[8] found 456 MEs by direct observation, 34 by chart review, and only 1

What We Already Know about This Topic

- The literature on perioperative medication error rates is sparse and consists largely of self-reported data, which underrepresents true error rates
- Reductions in medication errors in other patient care areas have occurred because error rates were systematically measured, errors were categorized to determine their root causes and potential for harm, and solutions were designed and implemented

What This Article Tells Us That Is New

- This prospective observational study found that approximately 1 in 20 perioperative medication administrations, and every second operation, resulted in a medication error and/or an adverse drug event
- More than one third of these errors led to observed patient harm, and the remaining two thirds had the potential for patient harm

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Submitted for publication March 30, 2015. Accepted for publication July 23, 2015. From the Department of Anesthesia, Critical Care and Pain Medicine, Massachusetts General Hospital, Boston, Massachusetts (K.C.N., A.P., S.S.); Departments of Anesthesia (K.C.N.) and Medicine (D.W.B.), Harvard Medical School, Boston, Massachusetts; Partners Healthcare Systems, Inc., Wellesley, Massachusetts (K.C.N., D.L.S., D.W.B.); and Division of General Internal Medicine, Department of Medicine, Brigham and Women's Hospital, Boston, Massachusetts (D.W.B.).

 Anesthesiology 2015; XXX:00-00

 <zdoi;10.1097/ALN.0000000000000904>

by self-report. Without valid and reliable assessments of perioperative errors and their root causes, proposed solutions may be less effective, more costly, and subject to considerable resistance to implementation, and their impact cannot be accurately measured.

Reductions in MEs in other patient care areas, including inpatient units and outpatient clinics, have occurred because error rates were measured, errors were categorized to determine their root causes and potential for harm, solutions were designed and implemented, and error rates were then systematically remeasured to show a reduction. In addition, typically the costs of the solutions were assessed to justify their widespread adoption. This process has occurred with solutions such as computerized physician order entry systems,[11,12] bar code scanning systems for medication administration in hospital pharmacies,[13] and outpatient electronic prescribing systems.[14,15] Perioperative areas are among the only remaining patient care areas that have not had rigorous assessments of MEs to guide proposed solutions. Thus, it is not surprising that there have been few specific improvements to perioperative MEs because they were originally flagged as a problem in 1978.[16]

The aim of this epidemiologic study was to assess the rates, types, severity, and preventability of MEs and potential adverse drug events (ADEs) in the perioperative setting, from initiation of anesthesia care to handover of patient care in the recovery room or intensive care unit.

Materials and Methods

Data for the study were collected during a 7-month period from November 2013 to June 2014. We obtained approval from the Partners Human Research Office (Boston, USA, protocol 2012P000833).

Study Site

This study was conducted in the perioperative area at a 1,046-bed tertiary care academic medical center that performs more than 40,000 operations annually in 64 operating rooms excluding off-site anesthetizing locations. The anesthesia providers use an electronic anesthesia information management system (MetaVision, iMDSoft, USA) to document patient demographic information, vital signs, medications administered, and perioperative events. The hospital also recently introduced a bar code–assisted syringe labeling system (Safe Label System, Codonics Inc., USA). Providers scan the manufacturer-issued bar code on each medication vial, and the system prints a color syringe label containing, at a minimum, drug name, strength, quantity, diluent and diluent volume, expiration date and time, and the provider's initials. The system also provides audio and visual readback of drug name and concentration and clinical alerts for recalled and expired vials.

Definitions

The perioperative medication administration process starts when a medication is requested or obtained from the anesthesia cart and ends with appropriate monitoring after the medication has reached the patient. The stages in this process are described in table 1, and any of these stages may involve one or more errors. An ME is defined as failure to complete a required action in the medication administration process, or the use of an incorrect plan or action to achieve a patient care aim.[17] An ADE is defined as a patient harm or an injury due to a medical intervention related to a drug, regardless of whether an error in the medication process occurs.[11]

To adapt these definitions for the perioperative setting, we built on a previously described framework used to identify and classify MEs in inpatient and outpatient settings.[14,17] By using this ME detection framework, we assessed various ME scenarios with consultation from clinical and ME experts to make the necessary iterative revisions to ensure that all elements of the framework were mutually exclusive and collectively exhaustive in the perioperative setting. We then created an observer training manual based on the error definitions outlined in the framework. A full list of definitions with examples is given in table 2, and their associated severity levels are defined in table 3.

Study Participants

All 237 anesthesia care providers (excluding study staff) were eligible to participate. The providers included 81 (34.2%) anesthesiologists, 53 (22.4%) certified registered nurse anesthetists (CRNAs), and 103 (43.5%) house staff. We held an informational session in conjunction with department-wide grand rounds to describe the study purpose and provide an opportunity for anesthesia providers ask questions. We subsequently sent a consent email to all anesthesia providers, providing them with the option to opt out of participation at any time during the study period.

Observers

Four fully trained, practicing clinician observers (three anesthesiologists and one nurse anesthetist) independently observed medication administration by anesthesia

Table 1. Stages of Medication Administration

Term	Definition
Requesting	Prescriber requests medication from pharmacy or from medication dispensing system; this step may be bypassed when provider obtains a medication directly from anesthesia cart
Dispensing	Pharmacist dispenses a medication directly to the provider, or provider withdraws medication from dispensing system
Preparing	Medication is prepared by provider (*e.g.*, drawn from vial, placed into a labeled syringe, diluted)
Administering	Medication reaches the patient either by self-administration or administration *via* an anesthesia provider
Documenting	The medication and dose are documented in the anesthesia information management system
Monitoring	Following vital signs or relevant laboratories after medication administration (*e.g.*, checking glucose after insulin administration)

Table 2. Event Definitions

Term	Definition	Examples
Medication errors	Failure to complete a required action, or the use of a wrong plan to achieve an aim; may involve any of the stages of medication administration (table 1) regardless of whether an injury occurred or the potential for injury was present.	Patient given a dose of medication that was not intended. Significant hypotension (mean arterial pressure < 55 mmHg) that is not treated.
Error with no potential for harm	Violates strict standards but has essentially no potential for patient harm.	Not including provider initials on a syringe label.
Error with little potential for harm	A medication error that has little possibility of causing injury.	Propofol infusion increased from 50 to 150 μg kg^{-1} min^{-1} but not documented.
Error with potential for an ADE	A medication error that has the possibility of causing injury.	A patient with history of upper gastrointestinal bleed given a nonsteroidal antiinflammatory drug with no resultant bleeding.
Error with an ADE	An injury due to a medical intervention related to a drug that resulted from an error in the medication process.	A patient with positive cocaine toxicology screen receives β-blockers and has severe hypertension. Administering penicillin to a patient with a penicillin allergy who subsequently develops a rash. A patient who develops mean arterial pressure < 55 mmHg after 4 mg/kg propofol bolus.
ADE without error	An injury due to a medical intervention related to a drug with no error in the medication process.	An allergic reaction in a patient not previously known to be allergic to that particular medication. A patient with a history of PONV who is given a combination of antiemetics perioperatively and subsequently develops PONV. A patient who develops mean arterial pressure < 55 mmHg after a standard dose of propofol.
Ameliorable ADE	An ADE whose severity could have been substantially reduced if different actions had been taken.	A patient with continuing PONV who did not receive antiemetics within 30 min. A patient with > 4/10 pain on emergence that is not treated until after arriving in the recovery room.

ADE = adverse drug event; PONV = postoperative nausea and vomiting.

providers during routine patient care without intervention, to detect MEs and/or ADEs per our error detection framework. Observer training before participation included thorough review of the observer training manual, which includes ME and ADE definitions and examples; at least one 3-h formal training session led by an ME expert to review error terminology and classification, including scenario-based case discussions; and collecting data simultaneously with an experienced, trained observer for a minimum of 10 cases, with an emphasis on techniques used to minimize the effect of the observer on the observed Hawthorne effect[10] such as minimizing interaction with participants and remaining outside of the participants' immediate workspace.

Data Collection

We randomly selected operating rooms for data collection, excluding pediatric, cardiac surgery, and off-site locations due to unique medication administration considerations in these areas. A two-pronged approach was used to capture suspected MEs and/or ADEs: direct observation and chart review.

The primary method of data collection was a continuous direct observation, originally described by Barker *et al.*[10] and Allan and Barker,[18] who demonstrated that with properly trained observers, there is negligible if any Hawthorne effect. Observations began when the anesthesia provider assumed care for the patient and ended when the patient arrived in the recovery room or intensive care unit. By using paper data collection forms, observers documented in real time all medications administered and any MEs and/or ADEs observed. They recorded the event type (ME and/or ADE), error type, time of event, provider type, and other comments (free text) associated with the event. If an ADE occurred in conjunction with an ME, the observer completed the Naranjo Algorithm[19] to determine the likelihood that the ADE was related to the ME. All field observations were entered into our study database by a clinical research coordinator.

The second data collection method was a guided chart abstraction from our anesthesia information management system by trained anesthesiologists. For all directly observed patient care encounters, we also queried our anesthesia information management system database for cases of drug dosages and/or vital signs during the observational period that were outside of our defined acceptable range, some of which are outlined in table 2. These cases were put forward for further review to determine whether an ME or an ADE was

Table 3. Severity of Medication Error or Adverse Drug Event

Term	Definition	Examples
Life-threatening	The event has the potential to cause symptoms that if not treated would put the patient at risk of death.	More than three consecutive premature ventricular contractions. Patient with a previous anaphylactic reaction to penicillin who is given penicillin or cefazolin.
Serious	The event has the potential to cause symptoms that are associated with a serious level of harm that is not high enough to be life-threatening.	Failing to administer antibiotics before incision in a person requiring antibiotics. Patient given insulin without subsequently checking blood glucose levels.
Significant	The event has the potential to cause symptoms that while harmful to the patient pose little or no threat to the patient's function.	Blood glucose levels not checked in a patient with diabetes.

present. Duplicate events (detected by both chart review and observation) were deleted.

Event Classification

The study team, including observers, met weekly to review and discuss events, further assess and reclassify them as needed. All events identified during this data collection phase subsequently underwent review by two independent members of the adjudication committee, which comprised board-certified anesthesiologists and/or ME experts. Events not deemed to be MEs and/or ADEs were excluded. For example, moderate hypotension (with mean arterial pressure > 55 mmHg) in a patient without cardiac risks factors after receiving a standard dose of propofol (< 3.5 mg/kg) was excluded. Mean arterial pressure less than 55 mmHg was classified as an adverse event.[20] The committee judged ADE and potential ADE severity on a four-point Likert scale (significant, serious, life-threatening, and fatal), and preventability on a four-point Likert scale (definitely preventable, probably preventable, probably not preventable, and definitely not preventability), with the scale collapsed to two categories (probably preventable or probably not preventable) before analysis. The committee also assigned each ME type to a prevention strategy that, in their judgment, has potential to reduce the likelihood of the ME and/or associated ADE. Rater disagreements were resolved by consensus through discussion between the two raters.

Statistical Analysis

We present the results as the number and rate of MEs and ADEs per 100 medication administrations as well as the percentage of medication administrations with at least one error. On the basis of ME rates in other patient care areas, we expected 10% of medication administrations to involve at least one error.[1,15,16,21] Sample size estimation was performed using the binomial distribution to ensure that the width of the 95% CI for the number of medication administrations involving at least one error was approximately ±1.5%. With approximately 1,380 medication administrations and an expected rate of 10%, the 95% CI for the number of medication administrations having at least one error was approximately 3%. Due to the large number of expected cases with zero errors, the association between error rate and demographic/clinical characteristics was assessed using the zero-inflated poisson regression, and we considered that a single-medication administration could involve multiple errors. The interrater reliability between adjudication committee members for incident classification, severity, and preventability was assessed using Cohen κ statistic. All analyses were performed using SAS(R) version 9.3 (SAS Institute Inc., USA), and statistical significance was defined as $P < 0.05$.

Our primary outcomes were the incidence of MEs and ADEs in the perioperative setting. Secondary outcomes were MEs and ADEs by patient characteristics, specifically age, sex, race, American Society of Anesthesiologists (ASA) physical status score,[22] body mass index (BMI), procedure type, procedure duration, and number of medication administrations.

Results

Data were collected during an 8-month period from November 2013 to June 2014. Of 237 eligible anesthesia care providers, 11 opted out: 7 attending anesthesiologists, 2 CRNAs, and 2 house staff. Thus, our eligible study population consisted of 74 (32.7%) attending anesthesiologists, 51 (22.6%) CRNAs, and 101 (44.7%) house staff. During 105 observation days, 4 anesthesia-trained observers observed 277 operations on 275 patients, with a total of 3,671 medication administrations (table 4) by 24 (8.7%) attending anesthesiologists, 160 (57.8%) CRNAs, and 93 (33.6%) house staff. Of the 277 operations observed, 124 (44.8%) included 1 or more ME and/or ADE. A total of 227 (82.0%) operations required general anesthesia, and 37 (13.4%) involved sedation only. There was no significant difference between event rates for general anesthesia (227 operations, 3,297 medication administrations, and 5.3% event rate) *versus* sedation (50 operations, 374 medication administrations, and 4.6% event rate, $P = 0.52$).

A total of 211 MEs and/or ADEs were detected, of which 172 (81.5%) were directly observed and 39 (18.5%) were discovered through targeted review of the anesthesia records

Table 4. Patient and Procedure Characteristics

	Total Patients (N = 275)*	Medication Administrations (N = 3,671)†	Events (N = 193)‡	Medication Errors (N = 153)‡	Adverse Drug Events (N = 91)‡
Age (yr), mean: 55.73; range: 20–94			*P* = 0.59	*P* = 0.63	*P* = 0.69
18–30	15 (5.5)	163 (4.4)	9 (5.5)	8 (4.9)	3 (1.8)
30–50	86 (31.3)	1,132 (30.8)	63 (5.6)	49 (4.3)	26 (2.3)
50–65	90 (32.7)	1,294 (35.2)	57 (4.4)	45 (3.5)	30 (2.3)
65+	84 (30.6)	1,082 (29.5)	64 (5.9)	51 (4.7)	32 (3.0)
Sex			*P* = 0.95	*P* = 0.79	*P* = 0.38
Female	165 (60.0)	2,209 (60.2)	116 (5.3)	93 (4.2)	58 (2.6)
Male	110 (40.0)	1,462 (39.8)	77 (5.3)	60 (4.1)	33 (2.3)
Race or ethnic group			*P* = 0.01	*P* = 0.03	*P* = 0.002
Caucasian	232 (84.4)	3,103 (84.5)	168 (5.4)	132 (4.3)	79 (2.5)
Asian	9 (3.3)	107 (2.9)	4 (3.7)	3 (3.7)	0 (0.0)
Hispanic	8 (2.9)	128 (3.5)	9 (7.0)	6 (4.7)	6 (4.7)
Black	3 (1.1)	51 (1.4)	4 (7.8)	3 (5.9)	3 (5.9)
Not recorded	12 (4.4)	149 (4.1)	8 (5.4)	8 (5.4)	3 (2.0)
Other	11 (4.0)	133 (3.6)	0 (0.0)	0 (0.0)	0 (0.0)
ASA score§			*P* = 0.29	*P* = 0.56	*P* = 0.15
1	25 (9.1)	309 (8.4)	10 (3.2)	9 (2.9)	3 (1.0)
2	171 (62.2)	2,329 (63.4)	128 (5.5)	95 (4.1)	68 (2.9)
3	77 (28.0)	1,019 (27.8)	54 (5.3)	48 (4.7)	20 (2.0)
4	2 (0.7)	14 (0.4)	1 (7.1)	1 (7.1)	0 (0.0)
Body mass index (kg/m^2), mean: 28.43; range: 15.5–57.7			*P* = 0.38	*P* = 0.61	*P* = 0.12
Normal: 18–24.9	95 (34.6)	1,195 (32.6)	59 (4.9)	46 (3.8)	27 (2.3)
Overweight: 25–29.9	95 (34.6)	1,328 (36.2)	65 (4.9)	55 (4.1)	27 (2.0)
Obese: 30+	85 (30.9)	1,148 (31.3)	69 (6.0)	52 (4.5)	37 (3.2)
Procedure type			*P* = 0.27	*P* = 0.47	*P* = n.c.
Orthopedic	51 (18.6)	641 (17.5)	35 (5.5)	25 (3.9)	19 (3.0)
Gynecological	46 (16.7)	629 (17.1)	29 (4.6)	25 (4.0)	9 (1.4)
Urology	39 (14.2)	526 (14.3)	20 (3.8)	16 (3.0)	10 (1.9)
General	38 (13.8)	561 (15.4)	43 (7.7)	31 (5.5)	23 (4.1)
Breast	24 (8.7)	258 (7.0)	15 (5.8)	13 (5.0)	7 (2.7)
Thyroid/parathyroid	16 (5.8)	236 (6.4)	12 (5.1)	9 (3.8)	8 (3.4)
Thoracic	14 (5.1)	205 (5.6)	12 (5.9)	10 (4.9)	7 (3.4)
Plastic	13 (4.7)	171 (4.7)	7 (4.1)	5 (2.9)	4 (2.3)
Interventional radiology	12 (4.4)	123 (3.4)	3 (2.4)	3 (2.4)	0 (0.0)
Neurosurgery	9 (3.3)	160 (4.4)	6 (3.8)	6 (3.8)	1 (0.6)
Vascular	6 (2.2)	59 (1.6)	4 (6.8)	3 (5.1)	1 (1.7)
Other	7 (2.5)	102 (2.7)	7 (16.1)	7 (16.1)	2 (4.9)
Duration of procedure (h), mean: 2.4 h; range: 0.3–10.5 h			*P* = 0.0004	*P* = 0.0006	*P* = 0.04
< 1	64 (23.27)	601 (16.4)	20 (3.3)	18 (3.0)	6 (1.0)
1–3	134 (48.73)	1,732 (47.2)	95 (5.5)	72 (4.2)	48 (2.8)
3–6	63 (22.91)	1,093 (29.8)	58 (5.3)	45 (4.1)	28 (2.6)
6+	14 (5.09)	245 (6.7)	20 (8.2)	18 (7.3)	9 (3.7)
Medication administrations, mean: 13.31; range: 2–28			*P* = 0.02	*P* = 0.11	*P* = 0.002
≤ 12	127 (46.2)	1,116 (30.4)	61 (5.5)	54 (4.8)	20 (1.8)
≥ 13	148 (53.8)	2,555 (69.6)	132 (5.2)	99 (3.9)	71 (2.8)

Data are represented as n (%).

* Percentages calculated with denominator of 275 patients. † Percentages calculated with denominator of 3,671 medication administrations. ‡ Percentages calculated with denominator of total medication administrations in corresponding category. § ASA physical status score.[20]

ASA = American Society of Anesthesiologists; n.c. = nonconvergence.

from operations that we observed. Of the 211 errors, 14 (6.6%) were excluded by the adjudication committee and 4 (1.9%) were determined to have no potential for harm, leaving a final sample of 193 events (5.3%; 95% CI, 4.5 to 6.0) associated with 187 unique medication administrations (5.1%; 95% CI, 4.4 to 5.8). Interrater reliability between adjudication committee members for event classification was good (κ = 0.97, 4 cases resolved by consensus).

Errors and Adverse Events

The 193 events detected included 153 (79.3%) MEs and 91 (47.2%) ADEs. A single event can involve both an error and an ADE (fig. 1). Of these events, 40 (20.7%) were ADEs that did not involve an ME, 51 (26.4%) were MEs that led to an observed ADE, 70 (36.3%) were MEs with the potential for an ADE, and 32 (16.6%) were MEs with little potential for harm (fig. 1). Of the 70 MEs with the potential for an ADE, 4 (5.7%) were intercepted. A total of 153 (79.3%) events were deemed preventable, and 40 (20.7%) were deemed nonpreventable. Interrater reliability for preventability classification was good (κ = 0.98, 1 case resolved by consensus). Of the 193 events, 104 (53.9%) occurred within 20 min of the induction period. None of the observed or potential ADEs were fatal, 3 (1.6%) were life-threatening, 133 (68.9%) were serious, and 57 (29.5%) were significant. Interrater reliability for severity classification was good (κ = 0.85, 12 cases resolved by consensus). Of the 51 MEs that led to an ADE, the most prevalent error types were inappropriate medication doses (N = 24; 47.1%) and omitted medications/failure to act (N = 16; 31.4%). Using the Naranjo algorithm, 28 (54.9%) of the observed ADEs with error were probably due to the error, 22 (43.1%) were possibly due to the error, and 1(2.0%) was doubtfully due to the error.

Of the 153 MEs recorded, 51 (33.3%) led to an observed ADE and an additional 102 (66.7%) errors were associated with a potential ADE. The most common overall error type was a labeling error (N = 37; 24.2%), followed by a wrong dose error (N = 35; 22.9%) and omitted medication/failure to act (N = 27; 17.6%). Of the 153 errors recorded (table 5), 117 (76.5%) were associated with a specific medication administration and 36 (23.5%) were associated with other factors such as a delay or failure to treat an adverse event or an error in monitoring. Medications most frequently associated with errors were propofol (30, 25.6%), phenylephrhine (12, 10.3%), and fentanyl (11, 9.4%). No significant difference existed between the event rates of house staff (N = 68 events, 5.1% event rate), nurse anesthetists (N = 111 events, 5.5% event rate), and attending anesthesiologists (N = 14 events, 4.5% event rate, $P = 0.79$).

Patient characteristics and event rates by patient characteristic are given in table 4. No association exists between ME and/or ADE rates and patient age, sex, ASA physical status score,[22] BMI, or procedure type. Longer procedures, especially those greater than 6 h, had higher total event rates ($P < 0.0001$), ME rates ($P < 0.0001$), and ADE rates ($P = 0.004$) than shorter procedures. Also, procedures with 13 or more medication administrations had higher event rates ($P = 0.02$) and ADE rates ($P = 0.002$) than those with 12 or fewer medication administrations. Finally, event rates ($P = 0.01$), ME rates ($P = 0.03$), and ADE rates ($P = 0.02$) varied by patient race.

Contributing Factors and Solutions

We identified several strategies that, in our judgment, can be mapped to particular ME types to reduce the likelihood of ME and/or ADE. These strategies include both technology-based interventions and process-based interventions. Examples of technology-based interventions include point-of-care bar code–assisted anesthesia documentation systems, which have the potential to eliminate 17.0% of MEs and 25.5% of potential ADEs; specific drug decision support, 28.8% of MEs, 13.7% of potential ADEs, and 58.8% of ADEs; and alerts, 52.9% of MEs, 32.4% of potential ADEs, and 94.1% of ADEs. An individual error can be prevented by multiple solutions.

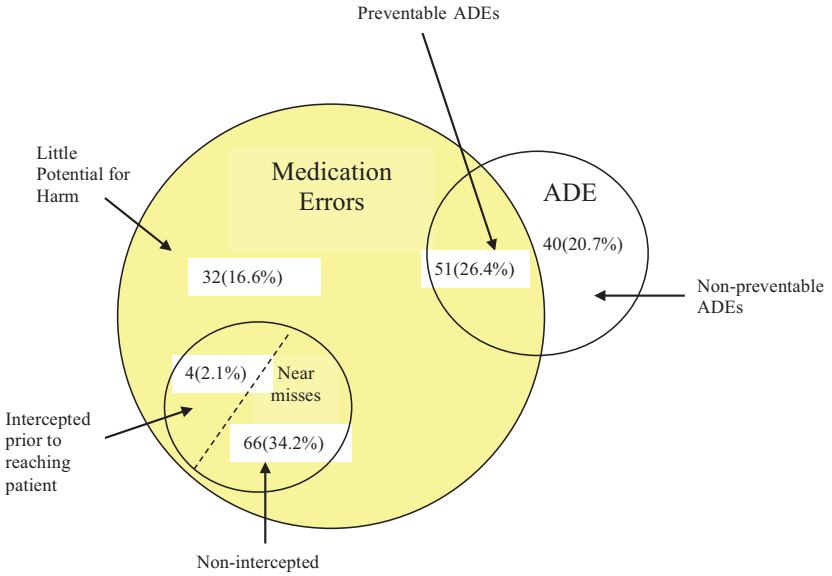

Fig. 1. The 193 events detected included 153 (79.3%) medication errors (MEs) and 91 (47.2%) adverse drug events (ADEs). A single event can involve both an error and an ADE. Of these events, 40 (20.7%) were ADEs that did not involve an ME, 51 (26.4%) were MEs that led to an observed ADE, 70 (36.3%) were MEs with the potential for an ADE (4 intercepted and 66 non-intercepted), and 32 (16.6%) were MEs with little potential for harm.

Table 5. Types of Medication Errors and Examples of Associated Potential ADEs

Error Type	n (%)	Error Example	Potential ADE Example
Labeling error	37 (24.2)	No phenylephrine label.	Wrong dose or drug error
Wrong dose	35 (22.9)	1 mg remifentanil bolus for patient weighing 86 kg	Bradycardia and hypotension
Omitted medication/ failure to act	27 (17.6)	No redosing of cefazolin during all day case	Surgical site infection
Documentation error	26 (17.0)	Intubation not documented. Potential failure to recognize difficult airway on subsequent anesthetic	Airway trauma or hypoxia during unexpected difficult intubation
Monitoring error	10 (6.5)	No blood pressure check prior to induction	Blood pressure > 200 mmHg on first check after induction
Wrong medication	9 (5.9)	CRNA obtained vial from ondansetron slot in omnicell, put needle into vial to draw up drug, and then noticed it was phenylephrine	Life-threatening hypertension
Wrong timing	5 (3.3)	7-min delay in administration of ephedrine in the setting of hypotension	Organ hypoperfusion with mean arterial pressure < 55 mmHg
Inadvertent bolus	2 (1.3)	Phenylephrine infusion connected distal to antibiotic bolus site	Hypertension due to inadvertent phenylephrine bolus with antibiotic
Other	2 (1.3)	Syringe of hydromorphone left unattended on anesthesia machine before case	Narcotic diversion/theft
Total	153 (100.0)		

ADE = adverse drug event; CRNA = certified registered nurse anesthetist.

Process-based interventions included changing the timing of documentation, which had the potential to eliminate 35.3% of MEs, 21.6% of potential ADEs, and 62.8% of ADEs; reducing opportunities for workarounds, 24.2% of MEs, and 36.3% of potential ADEs; connecting infusions to the most proximal intravenous (IV) port, 1.3% of MEs, and 2.0% of potential ADEs; and rigorous vendor selection with strong training, which could work synergistically with the other interventions to reduce MEs and ADEs.

Discussion

We found that approximately 1 in 20 perioperative medication administrations and every second operation resulted in an ME and/or an ADE. More than one third of these errors led to observed patient harm, and the remaining two thirds had the potential for patient harm. More than two thirds of the harm or potential harm was classified as serious. Thus, there is a substantial potential for medication-related harm and a number of opportunities to improve safety in the perioperative setting. Longer procedures, especially those greater than 6 h in duration, had higher event, ME, and ADE rates than those less than 1 h. Also, procedures with 13 or more medication administrations had higher event and ADE rates than those with 12 or fewer medication administrations. Further research is required to assess whether this is related to fatigue and lapses in vigilance over longer time periods and more medication administrations.

The preexisting literature on perioperative ME rates is sparse and often uses self-reports as a primary data source.[4–7] In one study of anesthesiologists, the reported drug administration error rate was 1 per 133 anesthetics.[4] In another survey study, 85% of anesthesiologists reported at least one drug error or near miss during their careers.[5] These error rates are markedly lower than the rates that we found, which may be due to provider reluctance to self-report errors or failure of providers to recognize errors they have made.

Self-reporting results in missing the vast majority of MEs in most settings and should not be expected to reliably assess ME rates.[23] High-fidelity simulation has also been used to assess MEs, with a reported error rate of approximately 10%.[24] Although measures were taken to make errors more likely in this setting, artificially raising the error rate, the simulation setting itself may also inherently lead to different error rates than found in an actual clinical practice setting. Merry *et al.*[1] present the only previous investigation of perioperative errors that used direct observation as a method for data collection. In five operating rooms in a tertiary academic center in New Zealand, they found a perioperative ME rate of 11.6% in a study group that used conventional nonelectronic methods for anesthetic record keeping. However, they did not assess the errors' potential for harm because this was a before and after study designed only to assess the impact of a specific anesthesia information management system on ME rates. Notably, this is also the only study to measure perioperative MEs as a percentage of medications administered, which has been the standard denominator used to measure MEs in other areas.[14–16,21] Previous studies in the perioperative setting had used the number of anesthetics administered as the denominator,[4,5,7] which lacks the benefit of explicitly negative administrations.

In Contributing Factors and Solutions, we identified several strategies to minimize perioperative MEs and/or ADEs, including technology-based interventions and process-based interventions. Examples of technology-based interventions include bar code–assisted syringe labeling systems, point-of-care bar code–assisted anesthesia documentation systems, specific drug decision support, and alerts.

Bar code–assisted syringe labeling systems have the potential to eliminate labeling errors. Despite the recently introduced bar code–assisted syringe labeling system at the study site, 37 (24.2%) events involved a labeling error. These occurred when the provider did not use the labeling system either because it was not installed in that particular location or there was a workaround available to circumvent its use. This is addressed with the process-based interventions.

Point-of-care bar code–assisted anesthesia documentation systems allow the syringe label to be scanned immediately before drug administration and automatically populate the anesthesia record with the medication and/or dose administered. These have the potential to reduce the incidence of documentation errors.

Specific drug decision support, including features such as dose calculators and maximum dose checking, has the capacity to reduce the incidence of wrong dose and wrong drug errors. Alerts that are thoughtfully implemented into an electronic anesthesia information management system in a tiered manner to minimize cognitive overload can decrease the incidence of omitted medication/failure to act errors and monitoring errors. For example, reminders to redose antibiotics or record a blood pressure after 10 min without a reading have the potential to eliminate many of these errors. Process-based interventions include determining optimal timing for documentation, reducing opportunities for workarounds, connecting infusions to the most proximal IV port, rigorous vendor selection, and strong training.

Timing of documentation is critical in taking full advantage of decision support. In our study, most practitioners documented medications after they were administered. If syringe labels were scanned *via* a point-of-care bar code–assisted documentation system immediately before administration, the system could provide decision support such as dose calculators, maximum dose checks, allergy warnings, and other alerts, eliminating many of the wrong dose errors. Even without comprehensive decision support, Merry *et al.*[1] have shown that a system allowing syringe labels to be scanned immediately before administration with visual and auditory medication verification reduced perioperative MEs by 21%.

Reducing the opportunity for workarounds is a key step in ensuring proper use of systems to reduce errors. For example, when a bar code–assisted syringe labeling system is installed and providers are fully trained on its use, manual sticker labels may be removed from the immediate workspace so that the easiest option is for providers to use the bar code–assisted, fully compliant labels. In the event of a bar code scanning system failure, appropriate manual backup labels should be readily available in a nearby location, such as the anesthesia workroom. We found that in most instances where the labeling system was not used, manual sticker labels were available, and the provider used those instead.

Connecting infusions to the most proximal IV port, and ideally through a dedicated carrier line, may minimize the potential for inadvertent boluses of IV infusion. Boluses given through an infusion carrier line have the potential to inadvertently deliver a significant amount of infusion drug along with the intended bolus. Although we observed cases where this led to significant hemodynamic changes, these are decreased when the infusion is connected to the most proximal IV port as the volume of infusion drug in the carrier IV line is minimized.

Rigorous vendor selection, with strong training, should eliminate vendors that are unwilling to commit to iteratively revise and improve a technology based on user feedback. Long-term, on-site training that covers all shifts is also important to minimize workflow disruptions.

This study has several limitations. First, due to the Hawthorne effect, the observed anesthesia providers may have altered their behavior during the observations. Barker *et al.*[10] have shown that with proper observer training, the Hawthorne effect is negligible. If there were some residual Hawthorne effect present during our study, it would have artificially decreased our event rate, suggesting that the actual event rate is likely higher than we have reported. Second, our primary method of data collection was direct observation, which may not capture all events that occurred. We did undertake a corresponding chart abstraction to capture additional events that may have been missed by observation. However, our results may still underrepresent the actual number of events. Third, our study setting was a large tertiary care academic institution, where anesthesia is administered by residents, fellows, CRNAs, and attending anesthesiologists, and our findings may not be generalizable to nonteaching hospitals. Fourth, our sample may not have been large enough to detect small differences in event rates by patient characteristic such as ASA score, BMI, and procedure type. Although we did find that event rates varied by patient race, this result may not be robust or representative of large populations as the proportion of minority patients in our sample was very small. Detecting differences in event rates by patient characteristic was not a primary aim of our study, and future research can be designed to assess whether patient characteristics affect rates of MEs and ADEs. Fifth, although we assumed that each medication administration was an independent event, this assumption was not directly assessed. We indirectly assessed the independence of each medication administration by examining the association between event rates and procedure type (length and complexity), provider type and number of medication administrations in the procedure and found no indication of strong dependence between medication administrations. Finally, our center has an electronic anesthesia information management system and a bar code–assisted syringe labeling system, both of which may reduce the frequency of MEs and/or ADEs.[25] Thus, our findings may not be generalizable to centers without these tools.

In summary, we found that approximately 1 in 20 perioperative medication administrations, and every second operation, resulted in an ME and/or an ADE. More than one third

of these errors led to observed patient harm, and the remaining two thirds had the potential for patient harm. These rates are markedly higher than those reported by existing retrospective surveys. Future analyses should target the creation and implementation of process- and technology-based solutions that may address the root causes of the errors to reduce their incidence.

Acknowledgments

The authors thank Jeffrey Cooper, Ph.D. (Massachusetts General Hospital, Boston, Massachusetts) and Robert Peterfreund, M.D., Ph.D. (Massachusetts General Hospital), for their contributions to the study design. They also thank Kwun Yee Trudy Poon, M.S. (Massachusetts General Hospital), for her contributions to statistical analysis. Finally, they thank Alireza Jafari, M.D. (Shahid Beheshti University of Medical Sciences, Tehran, Iran), for his assistance with the data collection process.

This work was supported by grants from the Doctors Company Foundation (Napa, California) and the National Institute of General Medical Sciences (Bethesda, Maryland) of the National Institutes of Health (Award Number T32GM007592). The content is solely the responsibility of the authors and does not necessarily represent the official views of the Doctors Company Foundation or the National Institutes of Health. Neither the Doctors Company Foundation nor the National Institutes of Health had any role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; or preparation, review, or approval of the manuscript.

Competing Interests

Dr. Bates is a coinventor on Patent No. 6029138 held by Brigham and Women's Hospital (Boston, Massachusetts) on the use of decision support software for radiology medical management, licensed to the Medicalis Corporation (San Francisco, California). He holds a minority equity position in the privately held company Medicalis. He serves on the board of SEA Medical (San Jose, California), which makes technologies that can identify medications in solution. He receives equity and cash compensation from QPID, Inc. (Boston, Massachusetts), a company focused on intelligence systems for electronic health records. The other authors declare no competing interests.

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