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ADVANCES IN ANESTHESIA

Anesthesia Informatics in 2018

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Keywords

• Anesthesia • Information management • Perioperative • Decision support
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Key points

- Anesthesiologists, other clinicians, and researchers have long endeavored to derive meaningful insights from data captured by electronic health record and anesthesia information management systems to achieve myriad goals: improving patient care, researching perioperative outcomes, enhancing financial oversight and responsibility, and many others.
- Clinical informatics is the application of clinical data to improve health care processes and systems, and anesthesia informatics is a subset of clinical informatics that encompasses the application of informatics to perioperative and anesthesia data.
- This narrative review describes the state of anesthesia informatics in 2018, the historical developments leading to the current state, and potential future applications of informatics in anesthesia care.

INTRODUCTION

Technology is present throughout contemporary anesthesia practice. Vital sign monitors and anesthesia machines capture physiologic and ventilator data that are both immediately available on the devices and transmitted to electronic health record (EHR) systems and anesthesia information management systems, thereby eliminating the need for paper charting. Anesthesiologists, other clinicians, and researchers have endeavored to derive meaningful insights from

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these data with the goals of improving patient care, researching perioperative outcomes, enhancing financial oversight and responsibility, and many others. Clinical informatics is the application of clinical data to improve health care processes and systems, and anesthesia informatics is a subset of clinical informatics that encompasses the application of informatics to perioperative and anesthesia data.

This narrative review describes the state of anesthesia informatics in 2018, the historical developments leading to the current state, and potential future applications of informatics in anesthesia care. The review begins with an overview of clinical and anesthesia informatics, followed by a section on anesthesia information management systems, anesthesia documentation integrated in EHR systems, and clinical decision support (CDS). It next describes secondary uses of anesthesia data and methods by which these data can be mined and analyzed, and goes on to discuss future directions and possibilities.

AN OVERVIEW OF CLINICAL AND ANESTHESIA INFORMATICS FROM THE 1990S TO 2018

Although microcomputers were used routinely in hospitals in the 1990s, it was not until a decade later that initiatives to harness computer and information technology to improve health care became more widespread. Advances in computer and networking technology, patient monitoring systems, and EHR systems enabled hospitals to accumulate a rapidly increasing volume and widening variety of patient data [1,2]. In 2009, the United States Federal Government enacted the Health Information Technology for Economic and Clinical Health (HITECH) Act, which incentivized health care institutions and providers to implement EHRs to enhance the quality and efficiency of health care [3]. EHRs collect patient care data in electronic form that can be explored and analyzed for many purposes, including improving patient care, optimizing resource use, and informing decision making at the clinical and enterprise levels [4].

The pursuit of these goals created an increasing demand for clinicians trained in informatics who were well versed in both the medical and information sciences [5]. In 2007, the American Medical Informatics Association (AMIA) began to develop the core content and training requirements for a subspecialty of clinical informatics because they recognized the unique role that informatics-trained physicians could serve in the setting of the ongoing convergence of the computer and information sciences with health care. AMIA led the establishment of professional-level education and certification for physicians in informatics, which resulted in clinical informatics as a board-certified medical subspecialty under the American Board of Preventive Medicine [6]. Clinical informatics is situated at the convergence between the information and medical sciences, and has been defined as "a body of knowledge, methods, and theories that focus on the effective use of information and knowledge to improve the quality, safety, and cost-effectiveness of patient care as well as the health of both individuals and populations." [3] Clinical informatics covers a wide array

of topics, including electronic clinical documentation, computerized provider order entry systems, and CDS, and ongoing developments in computational power, database management, physiologic monitoring devices, and software applications have set the stage for increasingly sophisticated data analytics and informatics applications in clinical care.

Anesthesia informatics consists of the myriad applications of clinical informatics and the use of EHR and perioperative data to derive meaningful clinical insights and improve anesthesia and perioperative care [7]. Anesthesiologists are included in the growing group of physicians who have obtained expertise and board certification in clinical informatics, and certification involves both a firm understanding of the hardware and software that comprise hospital systems and familiarity with team management strategies and development methodologies [8]. An ever-growing number of anesthesiologists and other health care providers interact with EHRs and other technology on a daily basis. Anesthesia informatics harnesses this interaction and focuses on using information systems to optimize workflow, enable research studies of perioperative physiology on a large scale, and acquire a better understanding of the quality of anesthesia care as well as the outcomes of patients who undergo anesthesia and surgery [8].

Of the 36 physicians who were board certified in both anesthesiology and clinical informatics as of January 1, 2016, most were satisfied with the clinical informatics boards, and most stated that informatics expertise was important to anesthesiology [9]. More than 75% of the anesthesiologist-informaticians held a role in the hospital outside of their anesthesiology departments; these institutional roles are part of what makes clinical informatics so crucial to the future of anesthesiology [8,9]. Until 2022, physicians can obtain certification by spending at least 10 h/wk practicing medical informatics for 3 years (the practice pathway) or by completing a 24-month Accreditation Council for Graduate Medical Education (ACGME)–accredited fellowship in clinical informatics. After 2022, the practice pathway will end, and the only path to certification will be via the fellowship pathway. The respondents were skeptical that anesthesiology residents would elect to complete a 24-month ACGME fellowship in clinical informatics in order to sit for the certification examination [9]. As of 2018, there were approximately 50 individuals who were board certified in anesthesiology and clinical informatics, which constitutes only approximately 0.1% of the more than 53,000 board-certified anesthesiologists in the United States [8].

Before delving into the nuances and many examples of applications of anesthesia informatics, it is important to understand the collection of perioperative data via electronic means. Thus, the evolution of the anesthesia record from paper charting to current electronic methods is discussed next. Anesthesia information management systems (AIMSs) are either integrated components of the EHR or stand-alone software and hardware products that were developed as a means to document the details of an anesthetic and the patient's physiologic status while receiving anesthesia. AIMSs and integrated EHRs are defined

and described next, their features are reviewed, and a brief exploration of their benefits and drawbacks is provided.

THE EVOLUTION FROM PAPER RECORDS TO ANESTHESIA INFORMATION MANAGEMENT SYSTEMS

Hippocrates originated written medical records in ancient Greece. However, paper charts were not used to record the details of patients' anesthetics until the 1890s, when Drs Codman and Cushing created the so-called ether chart. [10] The practice of paper anesthesia recordkeeping spread in the following years, and the paper record still remains in widespread use [11]. With the advent of computers in medical care, automated charting of anesthetics was explored because it was thought to potentially reduce the errors and artifacts of handwritten anesthetic charts [12]. Anesthesiologists embarked on initiatives using computers to capture, store, and retrieve electronic anesthesia records as microcomputers became more widespread in health care in the 1980s [13]. These efforts eventually led to the development of AIMS in the 1980s and 1990s as computer-based, intraoperative record keepers to replace or complement paper charting of patients' anesthetic courses [14]. It was from the 1980s until the early 2010s that AIMS evolved from basic anesthesia record documentation tools to either a stand-alone software product or a component of a hospital's EHR system coupled with hardware components and physiologic device interfaces. AIMS implementations were typically of the best-of-breed type, developed by anesthesiologists for anesthesiologists, such that the anesthesia documentation occurred using an AIMS that was distinct and separate from the hospital's enterprise-level EHR.

ANESTHESIA INFORMATION MANAGEMENT SYSTEMS AND INTEGRATED ELECTRONIC HEALTH RECORDS IN 2018

A significant development over the past few years (approximately 2014–2018) has been the transition from home-grown and best-of-breed stand-alone AIMS implementations to EHRs with integrated AIMS functionality, also referred to as integrated EHRs in the anesthesia informatics literature, such as Epic (Epic Systems, Verona, WI) and Cerner (Cerner, Kansas City, MO) [15]. These replacements of legacy AIMSs with integrated EHRs have been performed for various reasons, including improved data sharing across the entire institution, integration of billing, and a reduction in the need of technical support for disparate software packages.

Most currently available stand-alone AIMSs and integrated EHRs with AIMS functionality offer features that enable anesthesia providers to record, view, and share patient information across the entire perioperative continuum [16]. The primary role of every AIMS and integrated EHR remains the generation of an electronic anesthesia record by capturing physiologic and ventilator data in an automated fashion while allowing the anesthesia provider to document a variety of clinical data: administered medications, fluids, and blood products; clinical events, such as induction of anesthesia and placement of

vascular access catheters; documentation for billing or regulatory guidelines, such as American Society of Anesthesiologists (ASA) physical status and procedure notes; and other anesthetic and patient data, such as train-of-four counts [17,18]. The AIMS or integrated EHR displays the intraoperative anesthesia record as it is generated via a user interface with which the clinician interacts to review and edit. The intraoperative user interface consists of a grid for vital signs and medications that resembles the traditional paper record, with other patient data available in panels surrounding the grid [18]. The patient data displayed vary across different AIMS and integrated EHR software, but typical displays include the patient's name, date of birth, medical record identifier, and allergies. Recent laboratory values, medications, and other relevant clinical data are displayed in some implementations. Drop-down menus and action buttons and are used to access data entry forms to record items such as administered medications and blood products [18]. Procedure documentation, such as for vascular access placement or regional nerve blocks, can also be inputted via the user interface. In integrated EHRs, the user can typically navigate from the intraoperative grid display to the patient's entire EHR record using the software interface [18].

Most AIMS and integrated EHRs offer preoperative patient assessment documentation ranging from manual data entry forms for patient data to comprehensive drop-down menus, systems-based assessments, functionality to add and display patients' photographs, and tools for annotating and editing graphics representing patients' dentition and other physical characteristics [18]. Submitting data via these forms creates preanesthesia evaluation and assessment documentation that typically incorporates important data elements such as the patient's ASA physical status classification and documentation of anesthesia consent. Both stand-alone AIMSs that have access to the data in the EHR and integrated EHRs can integrate other relevant patient data such as medications, allergies, and procedure information into the preoperative documentation [16,18]. Other common preoperative features include the ability to peruse patients' previous anesthesia records, record a review of systems and physical examination, and document an anesthetic assessment and plan [18]. In the case of hospitals that have transitioned from legacy AIMSs to integrated EHRs, researchers have endeavored to retain access to legacy AIMS anesthetic records either by maintaining the legacy AIMS or linking access to previous records via the EHR [19].

Postoperative documentation in most stand-alone AIMSs and integrated EHRs requires the use of a computer workstation at the patient's recovery location, such as the postanesthesia care unit or intensive care unit (ICU). The patient's perioperative record up to that point can be accessed and used during the handoff of patient care to the receiving clinician or clinical team, and postoperative vital signs and patient assessments can be recorded. A postoperative ICU transfer note can also be documented. Some AIMSs and integrated EHRs can be set to mandate that the anesthesia provider input quality improvement data on relevant perioperative events during this handoff [20]. A study of the

long-term effects of such a mandatory quality assurance reporting system for adverse events at 2 academic medical centers found a decrease in preventable intraoperative adverse events [21].

Integrated EHRs and stand-alone AIMSs are used currently not only throughout traditional operating room perioperative care but also wherever anesthesia care is provided both inside and outside of the hospital [22]. This system includes documentation of acute pain services and recommendations as well as the delivery of anesthesia on the labor and delivery unit and during ICU bedside procedures [23,24].

Successful AIMS and integrated EHR implementations as well as transitions from AIMSs to integrated EHRs require substantial investments in hardware, software, and so-called peopleware; that is, clinicians such as anesthesiologist-informaticians with the necessary informatics expertise to lead the decision-making and implementation processes [8,18]. Financial costs for implementations and transitions obviously vary depending on the hardware and software required for the chosen level of sophistication and, most importantly, the lost clinical productivity of the implementation team as clinicians' time is dedicated to site visits, meetings, and other activities [18]. Note that an AIMS is not a one-off purchase but requires an ongoing commitment to technical support and software updates to keep the AIMS current and functional.

Capture and storage of the diverse mix of data via stand-alone AIMSs and integrated EHRs depends on the monitoring devices, computer hardware, and data and networking infrastructure. Typical AIMS and integrated EHR hardware components include a computer workstation and either mounting equipment to affix the computer to the anesthesia machine or a wheeled mobile stand, and devices such as special keyboards, bar code scanners, or syringe pumps may also be included [23]. Compatible physiologic device interfaces are essential to allow patient physiologic monitors, anesthesia machines, ventilators, and other monitors to communicate and record automatically via the AIMS or integrated EHR hardware and software [23]. Stand-alone AIMS software on a workstation is typically in the form of a so-called thick client that stores the anesthesia data on that workstation; the data are then filed periodically to a central server. With integrated EHRs, the software on the computer workstation displays a user interface referred to as a thin client, with most or all of the data filed directly to a central server [18,23]. The physiologic monitor and anesthesia machine data flow from the devices to the client and then the server, or first to the server and then the client workstations, depending on the setup. In some implementations, the physiologic device data flow to the AIMS or integrated EHR through a separate medical device integration interface (also known as middleware) that offers additional functionality such as higher-fidelity data sampling [25]. It is important to keep in mind any disparities in data sampling rates when analyzing data from both the middleware device and the AIMS or EHR, because events such as hypoxemia may look drastically different based on data granularity [26]. For example, a 15-minute rolling average of heart rate might miss the changes associated with a sudden

dysrhythmia that can only be seen in the data when granularity is at the single-second level.

Box 1 lists some of the domains in which stand-alone AIMSs were shown to provide positive benefits to patients, clinicians, and hospitals [27]. Anesthesia

Box 1: Benefits of anesthesia information management systems published in peer-reviewed literature

Improved patient safety and quality of care

- Anesthesia care team does not have to spend time manually recording vital signs
- Enable automated systems to perform drug diversion surveillance
- Provide automatic notification of operating room location errors
- Warn users of potential drug allergy and blood transfusion reactions
- Facilitate implementation of and adherence to departmental protocols, such as perioperative antibiotic prophylaxis administration
- Provide point-of-care clinical decision support, such as perioperative glucose management
- Enable real-time surveillance of patient monitors
- Provide timely post hoc reports via e-mail or text messaging to affect clinicians' behavior

Improved documentation

- Precise, accurate capture of perioperative data and patients' anesthetic details
- Generate high-resolution anesthetic records that are more easily searched, accessed, and used for secondary use than paper records
- Automated, real-time, or near-real-time notification of missing or incomplete documentation
- Facilitate risk management and quality assurance activities

Improved operations management

- Improve billing personnel work flow when reviewing anesthesia records
- Enhance anesthesiology department's administrative role in the perioperative setting
- Facilitate faculty and staff scheduling
- Generate a real-time surgical whiteboard to improve situational awareness and workflow
- Enable operating room modeling for administrative decision support
- Facilitates individual anesthesia provider and departmental performance tracking
- Allows verification of ACGME case requirements for residents and fellows
- Provide post hoc reports to residents with a log of their anesthesia experiences to guide requests for next day's cases

Improved cost containment and reimbursement

- Accurate accounting of anesthesia supplies and medications
- Decrease costs and use of anesthesia medication and supplies
- Facilitate resource management in the operating room
- Enhance anesthesia billing and charge capture
- Increase hospital reimbursement
- Merge financial systems with clinical documentation to improve efficiency

Improved clinical research

- Allows researchers to search for rare events or specific occurrences across a large dataset
- Develop evidence-based medicine guidelines from validated datasets of clinical practice
- Enables linking of perioperative data to outcomes data for research (such as the National Surgical Quality Improvement Program)
- Improves data sharing in national and international consortiums (such as the Multicenter Perioperative Outcomes Group or Anesthesia Quality Institute)

Data from Refs. [16–18,28]

departments and practices that have transitioned from legacy AIMSs to integrated EHRs have typically gained easier access to patient data within the EHR, such as laboratories, medications, and orders, and the ability to more easily incorporate those data into the perioperative record [18]. However, the shift toward transitioning to an integrated EHR in some cases can make the AIMS data more challenging to access for secondary uses such as research and quality improvement projects. Other obstacles that have been stated historically as drawbacks of AIMSs include reluctance to abandon paper records, daunting costs of installation and maintenance, distraction of anesthesia providers, medicolegal fears, and resistance to perturbations of clinical work flow [18,28,29]. These concerns apply also to transitioning from paper records directly to an integrated EHR. Studies have long since established the superior accuracy and reliability of electronic records [30,31]. AIMS and integrated EHR implementations are costly but, depending on the hospital's and anesthesia practice's billing and financial practices, AIMSs can potentially produce a positive net return on investment in 3 areas: (1) more efficient staff scheduling, (2) reductions in anesthesia drug costs, and (3) enhanced charge and billing capture from improved coding and documentation [28,32]. A study of AIMSs' impact on vigilance found no difference in the accuracy of practitioners' recall of patient variables when using either computerized or manual systems [33]. Regarding medicolegal fears, a survey of 24 anesthesia departments determined that AIMSs were viewed as valuable for risk management, and no cases were reported in which AIMSs hindered the defense process [34]. Although these studies primarily studied AIMS implementations rather

than integrated EHRs, many of the same benefits likely apply with integrated EHRs.

CLINICAL DECISION SUPPORT IN ANESTHESIA INFORMATION MANAGEMENT SYSTEMS AND ELECTRONIC HEALTH RECORDS

CDS is another potential benefit of AIMSs and EHRs. CDS can provide clinicians with patient-specific assessments or recommendations to assist with making clinical decisions and has long been one of the primary applications of clinical informatics [35,36]. The crucial features for successful CDS systems are summarized as the 5 rights: delivering the right information, to the right person, in the right intervention format, through the right channel, at the right time in the work flow [37].

CDS has been used throughout various facets of anesthesia practice, and several recently published narrative and systematic reviews of anesthesia-related CDS describe how CDS can affect clinical performance and patient care [38–40]. CDS should ideally integrate seamlessly into clinical work flow and comprise evidence-based recommendations rather than assessments [41]. CDS can typically be categorized into 1 or more types: process of care, such as improving adherence to clinical protocols and guidelines; and administrative and resource management, such as documentation and billing [42].

There have been many studies of anesthesia-related CDS alerts, reminders, and notifications to enhance intraoperative processes: intraoperative glucose monitoring and management [43,44], restoring suspended alarms after completion of cardiopulmonary bypass [45], β-blocker medication compliance [46], optimal fresh gas flows when using inhalational anesthetics [47], and administration of postoperative vomiting and antibiotic prophylaxis [48,49]. A recent study of a real-time intraoperative CDS alert for triple-low events (mean arterial pressure <75 mm Hg, bispectral index <45, and minimum alveolar fraction <0.8) did not show a reduction in 90-day mortality [50].

CDS can also be useful outside of the intraoperative phase of care. In the preoperative period, researchers built a system to automatically detect critical events in prior anesthesia records and alert the anesthesia care team when the same patient returns for another anesthetic [51]. Postanesthesia reports to clinicians to influence clinical care and documentation are another type of CDS; an example includes notifications via real-time alerts or automated e-mail or text messaging to make clinicians aware of documentation deficiencies that should be corrected [52]. A CDS tool has also been shown to improve anesthesiologist end-of-shift relief equity [53]. The implementation of a similar automated decision support tool designed to improve anesthesiology resident relief equity resulted in a lower frequency of residents working beyond 5:30 PM in the operation room on 2 consecutive days [54].

The availability of CDS in anesthesia care depends primarily on the feature set that is available within the AIMS or integrated EHR. Most of the anesthesia CDS research studies were performed at a select few academic institutions with a stand-alone AIMS or a software system that worked in conjunction with an

AIMS [39,55]. Anesthesia departments and practices that transition from legacy AIMSs to integrated EHRs must either attempt to replicate their CDS tools using the alerts and other features available in the EHR system or abandon them. Another option is to use software systems that can run concurrently with the EHR to provide integration of patient data streams and provide CDS functionality. AlertWatch (Ann Arbor, MI) is one such CDS monitoring system that integrates aggregated data from physiologic monitors and the EHR and presents CDS alerts to clinicians [56,57]. The system has been used to manage intraoperative hyperglycemia and to generate automated alerts on the labor and delivery floor [58,59]. AlertWatch was also shown to improve process measures, but not postoperative clinical outcomes, in a recent 6-year study [60].

Research and innovations in anesthesia CDS are ongoing in 2018. The evidence for near-real-time, point-of-care CDS in anesthesia remains promising, albeit limited, despite the proliferation of AIMS in US academic anesthesia departments, with an approximately 84% adoption rate anticipated between 2018 and 2020 [61]. Although the necessary skill and experience to develop research platforms for CDS may not be widely disseminated among anesthesiology practices, one solution may be for anesthesia departments to include more clinical informatics training for trainees [39]. The paucity of near-real-time, point-of-care anesthesia CDS articles may also be caused by the challenges associated with conducting and publishing these studies, and the ongoing transition to integrated EHRs carries the risk of limiting the ability for anesthesia informatics professionals to implement, support, and track CDS tools [39]. However, one benefit to the transition to integrated EHRs is the potential to more easily conduct multicenter studies of CDS tools, because anesthesia departments and practices may have the option to share their CDS implementations with others who are using the same EHR.

Anesthesia CDS is a dynamic and innovative field that is likely to remain an active area of anesthesia informatics research in the near future. Despite the challenges that are associated with conducting studies of anesthesia CDS, such research is necessary to enhance patient safety, improve understanding of which CDS tools are effective, and ensure that CDS development and implementation in anesthesia are based on high-quality evidence from multiple centers.

SECONDARY USES OF ANESTHESIA INFORMATION MANAGEMENT SYSTEM AND ELECTRONIC HEALTH RECORD DATA

Countless institutions, anesthesia practices, and individuals have used AIMS and EHR data that have been collected during the daily process of patient care for various purposes, including clinical research, quality improvement, and collaborative initiatives [62]. Data validity is of great importance, because the quality and reliability of manually entered data in the AIMS or integrated EHR often depend on the users [63,64]. Furthermore, physiologic data that are captured by the AIMS and EHR also have inherent artifacts that must be

considered [65,66]. Research, quality improvement initiatives, and other efforts that rely on anesthesia data must take into account these artifacts to avoid faulty conclusions referred to colloquially as garbage in, garbage out [67]. Clear, consistent definitions of perioperative events and outcomes facilitate valid, reliable documentation; these definitions routinely vary across, and sometimes even within, institutions [18,68]. Anesthesia departments and practices that have migrated from an AIMS to an integrated EHR must also deal with the issue of storing data from the older legacy system in a separate perioperative data "warehouse" if the data are to be used for secondary purposes, because EHRs are typically not designed to store and make the legacy data easily available to users [69]. Data warehouses can also be used to make AIMS data more easily accessible for secondary purposes that might otherwise be difficult to obtain directly from the EHR [70].

One popular and current use of AIMS and EHR data is to combine data from multiple institutions in collaborative data registries to create larger data pools to study rare events or outcomes, or patients with rare diseases or conditions. Many studies have been published in the years up to and including 2018 using data from multicenter anesthesia registries such as the Multicenter Perioperative Outcomes Group and the Anesthesia Quality Institute's National Anesthesia Clinical Outcomes Registry [71,72]. Collaborative data registry efforts such as Wake Up Safe, the Pediatric Craniofacial Collaborative Group, and the Pediatric Difficult Intubation Registry have also recently produced meaningful insights in pediatric anesthesia regarding medication errors, craniofacial cases, and pediatric difficult airway management [73–75]. There are myriad other examples of recently published research studies based on registry data. Although reporting outcomes data can be a sensitive topic among clinicians and anesthesia practices, participation in a collaborative registry allows benchmarking of performance against other providers and practices and enables researchers to conduct novel and generalizable studies using larger datasets [76].

Anesthesia registries are a thriving area of anesthesia informatics and will continue to proliferate, recruit contributors, and increase in size, creating a greater pool of collaborative data for data mining and research. Initiatives such as the US Meaningful Use program will continue to incentivize aggregation of data at a national level through health information exchanges and national repositories [77]. Efforts by the federal government should increase the interoperability and data-sharing capabilities across various EHRs, further fueling the contribution of data to these large anesthesia data collaborations.

ANALYTICAL APPROACHES TO ANESTHESIA INFORMATION MANAGEMENT SYSTEM AND ELECTRONIC HEALTH RECORD DATA

Large anesthesia datasets can arise not only from multicenter collaborative efforts but also from mining a single institution's perioperative vital sign and medication data. Advanced analytical methods offer one solution to managing

such voluminous and diverse datasets. One such approach is visual analytics, which is defined as the science of analytical reasoning facilitated by interactive visual interfaces. Visual analytics has been used to enhance the evaluation of large, complex datasets within health care [66]. Visual analytics tools are computational software that integrate data analytics with interactive visual interfaces and can be used to navigate and manipulate large datasets [4]. These tools enable users to create dashboards that display histograms and graphs in order to identify data trends. However, proper visual analytics techniques require more than haphazardly arraying graphs and buttons across a display; fundamental principles for effective visual analytics dashboard design include displaying critical information on a single screen while minimizing the object clutter, sparse use of graphical icons, abbreviating displayed context, and using graded color intensities rather than a clashing mix of hues [78].

The data are stored in a dimensional database model rather than a traditional relational database model to facilitate data querying and analysis on a large scale. Dimensional models are implemented using online analytical processing systems that were developed specifically to analyze very large datasets. Dimensional models create a fact table that contains all of the potential data transactions as well as filters (dimensions) around the table that will be used to associate facts and measures throughout the dimensional database. This system results in simplified querying scripts with execution durations that are significantly briefer than those of the more complex relational model scripts [4,79].

After the data have been audited, validated, and stored in a dimensional database, visual analytics tools are used to construct user-friendly dashboards that display histograms and graphs in order to identify and explore data trends. Visual analytics tools enable exploration and hypothesis generation in large datasets, and empower users to access the data in a way that facilitates understanding [68]. Data elements of interest can be tracked over time to assess their appropriateness and proper use, and filters can be applied to visualize trends and patterns. Point-and-click functionality allows the user to access the data, often in near real time, for periodic assessment of progress.

Visual analytics tools have been applied in various ways to anesthesia data in recent years. Researchers have used visual analytics to quickly determine the use of preoperative anesthesia assessments [80]. Perioperative transfusion practice has been analyzed across approximately 230,000 anesthetic records using visual analytics software, and this information has been used to guide policies for ordering blood products [81]. Visual analytics software has also been used to compute millions of data points comprising vital signs, end-tidal volatile agent, end-tidal carbon dioxide, and many other data points across 15 years of anesthetics in infants undergoing surgery [82].

Visual analytics facilitates investigative analysis by showing connections between entities and focusing on essential information [83]. Thus, data exploration using visual analytics can guide the selection and application of other advanced analytics techniques and methods. Visual analytics works well as a

tool to engage in descriptive analytics, which involves deriving meaningful insight from data. This type of analysis is retrospective (ie, showing what has happened), whereas predictive analytics involves mining data to predict an outcome (ie, what will happen).

Machine learning is an advanced analytics technique that involves using computer algorithms that can discover associations in large datasets in a supervised or unsupervised fashion. Although traditional statistical methods such as logistic models can predict postoperative outcomes with a high degree of accuracy, there is a growing movement among anesthesia informatics researchers to apply machine learning algorithms to large, diverse AIMS and EHR datasets for predictive analytics [84]. Many examples of machine learning being applied to perioperative and anesthesia data were published in 2017 and 2018: defining and predicting pain volatility in users of a pain management app [85], improving the efficiency of the operating room environment [86], predicting postinduction hypotension [87], modeling postintubation hypoxia [88], predicting periventricular leukomalacia in neonates after cardiac surgery [89], detecting airway management technique in anesthesia records [90], predicting postoperative in-hospital mortality [91], and predicting hypotension based on arterial pressure waveforms [92].

This small sample is only a few of the applications of machine learning in anesthesia informatics over a 2-year period. The complexity and size of large anesthesia and perioperative datasets are clearly fertile ground for machine learning algorithms to be designed and used to derive meaningful information and provide predictive analytics. Anesthesiologist-informaticians who are well versed in advanced analytics methods or who have teams with advanced analytics experts are poised ideally for the current increasing trend of machine learning in anesthesia informatics.

THE FUTURE OF ANESTHESIA INFORMATICS

This review is not intended to be an exhaustive description of the ongoing convergence of information technology and anesthesiology. As stand-alone AIMSs continue to give way to integrated EHRs, anesthesia modules in EHRs should continue to advance in use and functionality, and automated data capture will be made possible from a growing array of devices, such as barcode medication labeling systems and smart medication infusion pumps [93,94]. Analytical techniques such as machine learning and visual analytics will enable descriptive and predictive analytics of large anesthesia datasets and perioperative data warehouses [4]. Machine learning algorithms will also be applied to anesthesia data to automate perioperative event capture and derive clinical meaning from, or assign clinical relevance to, physiologic data. Real-time analysis of patient data across disparate health information systems through the use of sophisticated CDS and surveillance systems is another promising application of technology to anesthesia data [95]. AIMS-based and EHR-based CDS will continue to be developed in more sophisticated and meaningful ways to enhance various facets of patient care, and interoperability across different

software platforms will facilitate data sharing across practices and institutions. The rapid pace of development of informatics tools and sophisticated monitoring equipment will help to unlock the potential of analytics combined with genomics and real-time CDS to optimize the care of patients [96].

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