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REVIEW

How anesthesiology can deal with innovation and new technologies?

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ABSTRACT

Innovation and new technologies have always impacted significantly the anesthesiology practice all along the perioperative course, as it is recognized as one of the most transformative medical specialties specifically regarding patient's safety. Beside a number of major changes in procedures, equipment, training, and organization that aggregated to establish a strong safety culture with effective practices, anesthesiology is also a stakeholder in disruptive innovation. The present review is not exhaustive and aims to provide an overview on how innovation could change and improve anesthesiology practices through some examples as telemedicine (TM), machine learning and artificial intelligence (AI). For example, postoperative complications can be accurately predicted by AI from automated real-time electronic health record data, matching physicians' predictive accuracy. Clinical workflow could be facilitated and accelerated with mobile devices and applications, assuming that these tools should remain at the service of patients and care providers. Care providers and patients connections have improved, thanks to these digital and innovative transformations, without replacing existing relationships between them. It also should give time back to physicians and nurses to better spend it in the perioperative care, and to provide "personalized" medicine keeping a high level of standard of care.

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Innovation is not so easy to define as most of the time it is associated with a new technology, a drug discovery or a new medical device. Innovation also encompasses many other fields including the economics and the environmental and/or social sustainability from its inception through to its implementation. A recent review conceptualizes innovation attributes in health environment,[1] and characterizes innovation according to eight attributes: novelty, step change, substantial benefits, an improvement over existing technologies, convenience and/or adherence, added value, acceptable cost, and uncounted benefits based on the similar concept. Medical innovation applies to various fields all along the patient's care course, like new care models including the care itself but also better processes, improved technologies and cost-effective business models. Innovation should bring *value* to all stakeholders in the healthcare environment with a patient centered care model. It benefits to care providers in their routine practice and acceptable health expenses. Innovation could be either incremental enhancing the performance of an existing product, drug or process, or disruptive with radical changes. Lastly, innovation is sometime assimilated to research. Research aims to increase scientific or technic knowledges. Innovation brings additional value to existing product, drug or process.

Anesthesiology has been a major player in innovation and new technologies for years because of the need of intraoperative monitoring of vital signs and oxygenation. Anesthesiology is recognized as one of the most transformative medical specialty regarding patient safety in the perioperative course.[2] Mortality from elective anesthesia has declined 10-fold in the past several decades as a result of a joined effort to improve safety.[3] Indeed, it has relied on the widespread implementation of hundreds of small changes in procedures, equipment, training, and organization that aggregated to establish a strong safety culture with effective practices. In contrast, sometimes innovation could be "disruptive" as this term was first introduced by Clayton Christensen in 1997, referring to it as a process "by which a product or service takes root initially in simple applications at the bottom of a market and then relentlessly moves up market, eventually displacing established competitors."[4] This was the case when Archie Brain published the first report about the laryngeal mask in 1983 as a realistic alternative to the endotracheal tube.[5] The laryngeal mask was a clear disruptive innovation as compared to the endotracheal tube, with more than that 7300 publications cited by PubMed.

The present review is not exhaustive but aims to open new areas of interest and to provide an overview on how innovation could change and improve anesthesiology practices (Table I) through some examples as telemedicine (TM), machine learning (ML) and artificial intelligence (AI).

Preoperative setting

Innovation in this field has to facilitate the patient course and to improve its safety with a personalized preoperative medical assessment to better organize surgery or interventional procedures.

Difficult airway (DA) is still a leading cause of anesthesia-related death and morbidity. It is an important and interesting topic with the necessity to improve difficult airway management with an accurate prediction, and thus a better anesthetic safety. Because the use of simple physical characteristics test remains poorly informative, with low predicting positive values averaging 30%,[6, 7] DA prediction remains a challenge. One of the main issue in better prediction of difficult tracheal intubation according to DA test or scores is to decrease the "inconclusive or gray zone". Nevertheless, DA assessment using simple clinical signs is possible, pending a changing paradigm in this prediction, and took into account both interactions between variables to reduce the inconclusive zone in a study.[7] The score used by the authors and performed 10 years ago, relied on a mathematic model which is not easy to implement in routine DA assessment. It emphasized on the need to develop user friendly prediction tools.[7] During the last decade, some publications popped up in DA prediction with modern tools involving facial image analysis and deep learning models.[8-10] It is interesting to notice that according to the date of publication, in 10 years from about 2010 to 2020, methods processing to predict a difficult airway moved from complex mathematical models to the use of database with images and videos analysis from patient's faces.[9, 10] These database collection can be performed quite differently according to the studies, for example one focused much more on difficult airway prediction test[9] like Mallampati,

Table I.—*Overview of innovations and digital care fields in anesthesiology during the perioperative course.*

Preoperative setting	Intraoperative setting	Postoperative setting
Assessment and risk management	Anesthesia support: DOA, CAD, USG, event prediction	Assessment and risk management
mHealth apps and help in preoperative program	Decision making and adverse events management using vital parameters data extraction and decision analysis, tool related to HER and peer-reviewed literature implementation	mHealth apps and help in postoperative program including rehabilitation
Telemedicine		Telemedicine

mHealth apps: mobile health applications; DOA: depth of anesthesia; CAD: control of anesthesia delivery; USG: ultra-sound guidance; HER: electronic health record.

and another one[10] used deep learning model with frontal face features analysis to classify the patient as "easy" or "difficult" airway to perform tracheal intubation. It is also interesting to note that these automatic morphology-based methods allowing difficult tracheal intubation prediction have developed performances at least comparable to state-of-the-art medical diagnosis-based predictions by experienced doctors.[9, 10]

Preoperative evaluation is mandatory and could be performed before scheduled surgery by utilization of telemedicine (TM). The main objective of preoperative evaluation is to assess medical readiness required for the patient according patient's medical status and planned surgery. This preoperative assessment impacts perioperative care and patient outcome. Documented pre-anesthesia patient consultation is an indicator of quality and safety as previously reported.[11] Recommended evaluation content according the American Society of Anesthesiology (ASA) task force includes: readily accessible medical records, patient interview, a directed pre-anesthesia examination, preoperative tests when indicated, and other consultations when appropriate.[12] Since more than 20 years, TM has been available for preadmission anesthesia for scheduled surgery despite the fact that physical examination cannot be performed properly at that time.[13] Nowadays, technology improvements allow two-way video communication, controllable examination cameras, and electronic stethoscopes. These new possibilities allow to stick to ASA task force recommendations which indicated that a directed pre-anesthesia physical examination should include an assessment of the airway, lungs, and heart.[12] As a result, TM represents a useful tool when in-person consultation preoperative is difficult or when an additional consultation to optimize patient's medical condition before surgery is required. TM may also allow lower healthcare costs with an increased operating room efficiency by decreasing surgery cancellation days around 10% to 20%.[14, 15] To prevent inadequate preoperative evaluation, it has been reported that structured assessment of the airway, along with improvements in information exchange, and use of clearly defined patient management plans would prevent most of the incidents.[16] These goals can be easily reached when TM is used for preoperative evaluation. Moreover, a randomized study has demonstrated that a face to face preoperative evaluation or a TM preoperative consultation were equivalent with high patient and care provider satisfaction.[17] Lastly during the COVID-19 pandemic, it has been demonstrated on a large scale that implementation of a high-quality TM preoperative evaluation could be successful.[18] Thus COVID-19 pandemic has accelerated the TM process. It should also be mentioned that a key point of this study was to define criteria for selecting and referring patients for in-person consultation if the preoperative TM consultation was at risk of failure.[18]

Intraoperative setting

Innovation and technological improvements have made anesthesia and surgery possible, then safer, and seek now to make it increasingly scalable and efficient in healthcare systems weakened by more limited financial and human resources. The operating room (OR) is a bunch of technologies with a lot of medical or surgical processes which coincide for the care of the patient. Standardization of medical and surgical processes in the theater are necessary to increase the patient safety.[11] In addition, collecting many data during anesthesia through patient's monitoring and use these data with various technologies including artificial intelligence (AI) lead to personalized anesthesia and improvement of the patient outcome.[19] Digital care and therapeutics are actually emerging quite rapidly around the world and some software is considered now as medical devices subject to regulatory approval like other medical devices or therapeutic drugs.[20] In November 2021 in the USA, out of 63 approved digital therapeutics extracted from openFDA device databases, 11 were in the anesthesiology field which positioned anesthesiology at the second rank in medical specialities.[20]

Several applications of AI in anesthesiology have been developed during the intraoperative period. Among these applications, prominent advances occurring recently on the monitoring of the depth of anesthesia, control of anesthesia delivery, ultrasound guidance for regional anesthesia and decision support systems related to event prediction have to be quoted.

Depth of anesthesia (DOA)

DOA depends on the balance between the anesthetic dose and the surgical or interventional stimulation. Thus, DOA must be constantly adjusted to anesthetic requirements to avoid either intraoperative awareness or a decrease in organ perfusion related to large anesthetic doses.[21] The combination of a low mean arterial pressure (MAP<75 mmHg) with a low MAC value (<0.8) have been associated with significant poor postoperative outcomes. In addition, an increased postoperative mortality has been observed if a low Bispectral index (BIS < 45) was combined with a low MAP and a low MAC value describing the "triple low" concept.[22] Because monitoring DOA is a key issue to deliver anesthesia properly and distinguish between awake and anesthetized states, a number of electroencephalogram (EEG)-based monitors such as the BIS index or burst-suppression on electroencephalography have been proposed. Nevertheless, to improve analysis of complex data streams from EEG signals, some studies have performed linear and non-linear EEG features analysis with machine learning (ML) approaches enabling a clear AI application in anesthesiology.[23-25] These studies have compared recorded EEG signals with several analyses combining multiple EEG-based features using artificial neural networks aiming a higher accuracy than the BIS index to better classify the patient's state during anesthesia from deep anesthesia to awake state. Indeed, these studies with AI applications have demonstrated a better accuracy of DOA monitoring in comparison with the BIS index technique as a comparator.[23-25] On top of that, AI approaches have been performed using other signal analysis as mid-latency auditory evoked potentials or heart rate variability with satisfactory accuracy and good prediction probabilities for awareness.[19] These studies highlight the power of artificial neural networks and deep learning to analyze complex signals with linear and non-linear features, to better predict DOA level in order to adjust the anesthetic requirements.

Control of anesthesia delivery (CAD)

CAD is the corner stone to perform automated anesthesia. DOA monitoring, with metrics as BIS to achieve target measure, and CAD are part of closed-loop systems. According to the information received, *i.e.* BIS for DOA, the closed-loop system, based on the built-in algorithms, will automatically adjust the infusion rate of anesthetic drugs. The feedback closes the loops of the system, allowing automatic maintenance of the predetermined targets.[19, 26] Actually, closed-loop systems are mainly related to control of DOA, and neuromuscular blockade, improving the accuracy of controlled variables to limit individual patient variability in drug administration, optimizing the workload of the anesthesiologist and finally improving the safety and quality of anesthesia care.[26] It has been recently shown that a complete automated closed-loop anesthesia integrating the three components of general anesthesia, hypnosis, analgesia and muscle relaxation, provided satisfactory performance of CAD during cardiac surgery.[27] Increasing complex closed-loop systems based on embedded algorithms represents the near future of perioperative AI.

Ultrasound guidance (USG) for regional anesthesia (RA)

RA techniques have changed dramatically over the last decade with the use of USG and by addressing a better predefined process with personalized strategies.[28, 29] For many years now, USG for RA has improved the success rates, the quality of RA blocks with decreased time needed for block performance and procedural pain, reducing complications incidence like needle redirections, procedural pain, blood aspiration and paresthesia in comparison with nerve stimulation.[30] This success of USG is related to direct visualization of anatomical structures (nerves, blood vessels, muscles, bones, tendons), visualization of the local anesthetic spread during injection, and timely recognition of maldistribution of local anesthetics with possible prevention of complications like intravascular injection. Thanks to USG, local anesthetic systemic toxicity (LAST) has decreased by 65%, as intraneuronal injection of local anesthetic.[28, 29] The use of AI particularly with neural networks to assist USG is increasing, aiming to improve the quality of USG images to highlight anatomical structures of interest.[19] It has also been reported during an external validation study, that AI-based device improved USG image acquisition and interpretation, reducing by 81% block failure risk and by 63% to 86% needle trauma according the considered anatomical structure (nerves, arteries, pleura and peritoneum).[31] In a recent review,[32] AI has been assessed with several objectives:

- anatomical landmark identification with image tracking including deep-learning performance for nerve tracking in ultrasound images;
- accuracy of real-time AI based on anatomical identification;
- convolutional neural network (CNN)-based framework for needle detection in curvilinear 2D during USG;
- success rate of spinal anesthesia with AI-assisted;
- utility to identify anatomical structures, in teaching and learning USG.

The authors have concluded that AI solutions might be useful in anatomical landmark identification, reducing possible complications related to optimization of the sonographic image including their interpretation, and finally improving also the training process in USG for RA.[32] Augmented reality (AR) is a visualization paradigm that allows the fusion of supplementary information (such as virtual, computer-generated graphics) with the real-world environment.

AR and USG addressing needle visualization during navigation and epidural space identification for needle positioning may improve the success rate of epidural injection and decrease adverse events with this help for a better needle guidance. A study combining a B-mode ultrasound to visualize the needle navigation in a 3-D AR environment, and an A-mode ultrasound with a transducer at the needle tip, to better identify the epidural space, reported an increased success rate (100% *versus* 57%) in an in vitro phantom study in comparison to ultra-sound-only guidance with novice operators or an expert anesthesiologist.[33]

Intraoperative event prediction

Innovation process and techniques rely also on decision support system to prevent intra-operative adverse events occurrence because they may impair outcomes either during the per- and/or the post-operative period. It has been reported that low arterial pressure, *i.e.* MAP<50 mmHg for more than 5 min, was associated with increased 30-day operative mortality.[34] As the patient is highly monitored in the OR, one question raises quite quickly: how the event may be anticipated to react as fast as possible? Two axes may be implemented to properly answer to this challenge: predict the event occurrence according to recent parameters observed in the patient, for example predicting hypotension shortly before it occurs during anesthesia, and provide an alert for the care provider helping with adapted solutions in hypotension management and decision-making process. Concerning prediction of hypotension during anesthesia and AI, the HYPE randomized study reported that a ML derived from 23 variables extracted from the arterial pressure waveform was able to predict the occurrence of a hypotensive event within the next 15 minutes with a probability of about 85%.[35] The authors reported significant less intraoperative hypotension events in the ML group with an early warning system in comparison with the standard of care group. Another approach was developed without AI but with an intraoperative multiparameter decision support system with real-time data extracted from usual monitors. Combination of extracted data, electronic health record (HER) and peer-reviewed literature integrating into a single user interface enables immediate decision adapted to the patient.[36] The authors reported that the use of an intraoperative decision support system improved the process, but was not associated with a better postoperative clinical outcomes. It should be evaluated in a randomized clinical trial.

Postoperative setting

Serious adverse events still occur in post-operative care unit (PACU) despite continuous monitoring of vital signs and closed supervision from healthcare providers. In a retrospective study, closed claims data from the Controlled Risk Insurance Company related to PACU were analyzed between January 2010 and December 2014.[37] The authors reported 43 deaths during this period and observed that the three most frequent serious adverse events were related to: respiratory injuries (33%), nerve injuries (16%), and airway injuries (12%). In addition, the authors emphasized that missed or delayed diagnoses in the PACU were cited as contributing factors in 56% of cases resulting in the death of a patient. Thus, identifying early complications in PACU is a key issue to improve perioperative safety. As event prediction during the intra-operative period, ML could be a new tool for risk stratification and prediction of post-operative complications and serious adverse events. Earlier detection of adverse events and complications in PACU have been implemented in an automated multimodal clinical decision support system according to an algorithm using usual cardiopulmonary parameters and compared to a single parameter alarm system in regular monitoring.[38] This study reported a significant increased performance with an accuracy of 92%, a sensitivity of 91%, a specificity of 93% in detecting adverse events, with a correct classification reducing the number of false alarms by 85%.[38] Going a step further with AI to predict postoperative mortality, some authors described models using generalized additive models (GAMs) as a sum of univariate models which can be applied to neural networks (NNs) through an architecture referred to as generalized additive models with neural networks (GAM-NNs).[39] In this study, the development and the validation of an interpretable neural network model for prediction of postoperative in-hospital mortality with learned feature patterns was reported from 59,985 surgical records with a high performance (area under the curve [AUC] of 0.921). Using this model, in-hospital mortality was 0.81% in the training set and 0.72% in the testing set.[39] In a recent systematic review about ML in perioperative medicine, it was reported that risk stratification was an excellent objective to apply ML with optimization of patient's course to decrease postoperative complications with an accurate anesthesiologic planning tailored to each patient.[40] In this study, gradient boosting and random forest were found to be the best risk prediction models with a high accuracy.[40] Thus, AI and ML should be implemented for risk prediction and stratification in current perioperative care for a better personalized medicine and risk management.

Performance of a ML algorithm using HER data to predict postoperative complications with report directly available on a mobile platform searchable by surgeons was tested on a large scale. The validation cohort included 22, 300 inpatient surgical procedures involving 19,132 patients.[41] Algorithms for GAMs and random forest models were used in this model prediction. Postoperative complications were accurately predicted by this AI system using automated real-time EHR data, with minimal performance degradation during prospective validation, matching surgeons' predictive accuracy. In addition, clinical workflow was facilitated and accelerated with mobile device outputs and applications. Because patient-centered care and shared decision making will replace gradually current physician-centered care, specifically when patients are undergoing day-case surgery, recovery on their own requires protocols implementation to manage postoperative pain, nausea and vomiting. This approach belongs also in an enhanced recovery after surgery (ERAS) program and has been shown to be effective and to result in improved patient satisfaction and better postoperative outcomes, including a reduced length of stay and risk of hospital-acquired infections.[42, 43] Thereby mobile health (mHealth) or digital health technologies using mobile phones, tablets, and wearables enable nowadays perioperative care by providers to assess patient condition and pain, answer questions, and provide guidance.[44] Thus, these digital technologies are useful in many pre, per or postoperative clinical settings using dedicated mobile applications (apps) as it was previously reported.[44] Nevertheless, the use of mHealth apps in the postoperative follow-up care requires validation and sometime improvement before full implementation by care providers, patients, and hospital systems.[43, 44] Otherwise these digital solutions are not enough customized to patients and care providers, and miss completely the personalized medicine goals and decreased satisfaction from both patient and care provider.[45] During the postoperative period, it has also been reported that mHealth app use with an open medication protocol driven by patients combined with augmented physician rounds improved significantly pain relief.[46] A significant decreased opioid consumption and better patient's satisfaction were observed in comparison to usual treatment or only augmented physician rounds group.[46] Lastly, a multicenter randomized study reported that the use of the mHealth app was cost-effective without any impact on recovery quality during a systematic e-assessed follow-up of postoperative recovery after day surgery.[47]

In 2022, 255 billion of new apps have been downloaded all over the world making a 11% growing in comparison to 2021.[48] As in the number of apps increase in the daily life, mHealth apps are innovation tools and they improve the patient perioperative care. MHealth apps should facilitate systems-wide change including a culture to improve quality and safety in perioperative care. However as previously reported,[44] demonstrating mHealth apps usefulness is not sufficient. Their use should be assessed with studies evaluating protocols and outcomes, but also an improved communication (not replaced) between anesthesiologists and patients, improvement of workflow efficiency and reduced hospitals costs.

Conclusions

Innovation and health digital transformations should bring value to all: patients and their family, care providers, healthcare environment and organization. Anesthesiology is one of the most transformative medical specialty regarding patient safety in the perioperative period. Several applications of AI in anesthesiology are dedicated to the perioperative period. Innovation and health digital transformations must support and improve anesthesiology practice and quality all along the perioperative course, keeping a patient centered care model. In addition, all care providers and patients, sometime with their relatives, have to be involved in this digital and innovative transformations, without replacing relationships between care providers and patients but making these relationships improved with this support. It should also give time back to physicians and nurses, to be spent during consultation and perioperative care, and to provide "personalized" medicine keeping a high level of standard of care.

Key messages

- Anesthesiology has always been involved in a high technologic environment, taking the advantage to develop innovations and to participate in digital health transformation during the perioperative course.
- ML and AI already support anesthesiology in a better risk prediction and decision making perspective during the perioperative course. This is why these digital solutions are validated by all the stakeholders, including the patient.
- All these deep innovations and transformations must improve safety and medical management without replacing the unique relationship between care providers and patients.

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Conflicts of interest
The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

Authors' contributions
All authors read and approved the final version of the manuscript.

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