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Review article

Artificial intelligence in vascular surgical decision making

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ABSTRACT

Despite advances in prevention, detection, and treatment, cardiovascular disease is a leading cause of mortality and represents a major health problem worldwide. Artificial intelligence and machine learning have brought new insights to the management of vascular diseases by allowing analysis of huge and complex datasets and by offering new techniques to develop advanced imaging analysis. Artificial intelligence–based applications have the potential to improve prognostic evaluation and evidence-based decision making and contribute to vascular therapeutic decision making. In this scoping review, we provide an overview on how artificial intelligence could help in vascular surgical clinical decision making, highlighting potential benefits, current limitations, and future challenges.

1. Introduction

Health care systems have evolved rapidly over the past several decades and have benefited from advances in computer science, including global connection with the use of internet and the development of powerful devices at affordable costs that have allowed the widespread implementation of electronic health records. Progress in information technology, along with technical advances in various fields, including biology, imaging, pharmacology, and devices, have generated a huge amount of data ("big data") and there is a need to optimize

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their management and analysis to enhance evidence-based clinical practice [1,2].

Artificial intelligence (AI) has brought innovative techniques to enable analysis of large and heterogeneous datasets. Machine learning (ML) and deep learning (DL) algorithms have allowed us to identify patterns and non-linear relationships among complex data without any *a priori* assumptions [3]. Unlike the classic statistical approach, they are dynamic, can learn automatically from the available data, and require no or minimal human intervention [3]. Although the former leads to the development of a probabilistic model based on the assumption that the provided data are a representative sample and subset of a larger population that can be described by a model, the latter concentrates on prediction by using learning algorithms to find patterns in often rich and unwieldy data [3]. ML and DL are thus able to unravel hidden patterns and complex associations, although they are less easily interpretable [3]. AI has brought innovative applications to improve the detection and characterization of vascular diseases, which can help in the diagnosis, prognosis, or treatment of patients [4–6]. Despite current challenges including technical, methodological, ethical, administrative, and political considerations, AI has the potential to enhance evidence-based decision making. In this review, we present practical examples on how AI can help clinicians in vascular surgical clinical decision making through various applications, including triage of patients, identification of acute life-threatening vascular condition, early diagnosis, stratification of vascular diseases, surgical risk assessment, or preoperative planning. In light of current findings, we discuss limits and suggest future directions for implementation of AI technology in daily practice to provide aid-decision support and propose a personalized approach for the management of patients with vascular diseases.

2. Early diagnosis of acute vascular disease

Emergency clinical departments face high pressure and complex decision-making challenges managing patient flow in an unpredictable and constantly changing environment. The main challenge for clinicians is to quickly and efficiently distinguish patients with life-threatening disorders from those with less urgent and non-critical conditions.

2.1. *Acute aortic syndrome*

Chest pain is one of the most common reasons for admission in emergency departments and the diagnosis of the cause is essential to directing the patient and initiating therapeutic interventions in a timely fashion. There are many causes for chest pain and the main acute life-threatening condition that requires immediate referral to vascular surgeons is acute aortic syndrome. Prehospital evaluation and triage of patients are of utmost importance to optimize resources and transfer the patients in specialized units, such as aortic centers or departments of vascular surgery [7]. Some investigators aimed to build a prediction algorithm based on an ensemble ML method to assist prehospital triage and detect acute aortic syndrome [7]. The area under the curve for the ML method was 0.73 (95% CI, 0.66–0.79; $P = .038$) in the validation cohort [7]. Although the method needs to be evaluated and validated in other cohorts, it exemplifies how ML could help early detection and management of acute aortic syndrome.

2.2. *Acute ischemic stroke*

Acute ischemic stroke is another vascular life-threatening disease that requires early identification and treatment in specialized units [8]. Endovascular therapy has revolutionized the management of large-vessel occlusion ischemic stroke and time to treatment is a decisive factor of clinical outcomes. Computer-aided triage systems have the potential to streamline workflow. Some centers have evaluated the use of an application including an image viewer, a communication system, and an AI algorithm to automatically detect large-vessel occlusion stroke and trigger alerts to clinicians [9]. The initial time interval from door to neuro-interventional team notification was improved considerably, and there was a tendency toward a reduction in the time interval from door to skin puncture, indicating the interest of such an approach to optimize the management of stroke [9]. In addition to optimizing workflow, pioneering studies suggest that ML could also help to develop new tools to identify patients with stroke on the basis of blood sample analysis [10]. Some investigators used an artificial neural network to discriminate patients with stroke from input data collected from red blood and white blood cell counts and their results suggested that such algorithmic analysis could potentially be of interest in emergency departments to flag patients with potential diagnosis of stroke, or to provide information to clinicians to help in triage decisions in cases when imaging techniques or neurologic expertise are not immediately available [10].

3. Inpatient monitoring

Patients with vascular diseases can present acute life-threatening decompensation and early diagnosis is a critical issue that impacts on the outcomes and prognosis of patients.

3.1. *Cardiorespiratory instability*

Cardiorespiratory instability of patients during their hospital stay is a frequently occurring and undesirable complication that requires prompt diagnosis and immediate treatment to prevent the consequences of reduced oxygen delivery to tissues. Continuous monitoring of vital signs, including heart rate, mean arterial pressure, respiratory rate, and peripheral oxygen saturation, is used systematically in operating rooms, post–anesthesia care units, and intensive care units in order to promptly detect and react to vital deterioration [11]. Despite continuous monitoring, having predictive models that could warn clinicians before the occurrence of the decompensation might help to prevent it and save lives. Pioneering studies are currently ongoing toward that aim, with, for example, the development of ML-based algorithms that predict the risk of tachycardia (which can indicate cardiac decompensation) on the basis of monitoring the 3-hour period preceding the event [11]. Non-invasive monitoring combined with ML analysis might help to develop new tools to detect changes in vital signs early, before the occurrence of cardiorespiratory decompensation, and could help to prevent critical hemodynamic events. Although further studies and external validation are required, that kind of application could benefit patients admitted for acute vascular conditions.

3.2. *Hemodynamic instability*

One of the common risks during surgery, including vascular interventions, is the occurrence of intraoperative hypotension. This is especially the case in vascular surgery when patients present with hemodynamic instability or massive hemorrhage. ML-based methods have been developed to predict hypotension events in the next 5 to 15 minutes and have been evaluated in patients undergoing non-cardiac surgery [12,13]. The method provided an early warning system a few minutes before blood pressure decreases [12,13]. The algorithm, called the Hypotension Prediction Index, has been demonstrated to reduce intraoperative hypotension in two randomized controlled trials via real-time prediction of upcoming hypotensive events [12,13]. That kind of early warning system could be useful in the operating room to detect and manage hypotension early and prevent complications linked to low blood flow.

4. Risk stratification of vascular disease

By allowing the identification of hidden patterns among complex data without any *a priori* assumption, ML can be used to develop personalized risk stratification to evaluate and predict the outcomes related to vascular diseases. Several literature reviews previously summarized AI-predictive models in various non-cardiac vascular diseases, including aortic disease, lower extremity artery disease (LEAD), or carotid stenosis [5,14–16].

4.1. *Aortic aneurysm*

Current guidelines for the management of aortic aneurysm state that they should be treated promptly if they are symptomatic or ruptured [17]. For asymptomatic aneurysms, decision making is more complex and indication for repair relies on the evaluation of the risk of aneurysm growth and rupture, mainly assessed by the measurement of maximal aneurysm diameter on imaging data [17]. However, some patients with small aneurysms below the threshold for repair do develop a rupture, which highlights the need for innovative techniques to better assess the risk of aneurysm progression [17]. Several ML models have been proposed to predict the risk of aneurysm growth and rupture using various input data, including clinical, biological, and imaging data [6,18,19]. The results of these studies showed good accuracy to predict these risks, showing a proof of concept, although validation in multicenter prospective cohorts is necessary to generalize their use.

4.2. *Lower extremity artery disease*

Other examples of how ML can help stratify the severity of disease are also provided in other vascular disorders, including LEAD [4,5]. LEAD is a major health concern, as it affects more than 237 million people worldwide and is associated with risk of cardiovascular mortality and amputation [20]. The management of LEAD takes into consideration the severity and stage of the disease, as well as the evaluation of cardiovascular risk factors, to maximize limb survival and limit cardiovascular complications [20]. In this context, some investigators aimed to develop ML algorithms to classify LEAD severity on the basis of multiple routine clinically available parameters, including clinical and biological data [21]. The score successfully classified patients with Fontaine class I and II LEAD from patients with Fontaine class III and IV and positively correlated with the intrahospital mean ankle-brachial index [21]. By enabling rapid identification of patients with severe LEAD on the basis of basic clinical and biological features, that kind of application could be used to promptly detect and identify patients requiring vascular intervention before having more specialized imaging diagnostics. LEAD is one of the leading causes of amputation and individualized risk prediction would help clinical decision making. On the basis of preoperative clinical and laboratory information of 14,444 patients who underwent LEAD procedures, some investigators developed an ML model to predict the risk of 30-day amputation with an area under the curve of 0.81 [22]. Although external validation is required, adding that kind of assessment in clinical decision trees might help to better adjust revascularization strategies and enhance precision medicine. Finally, LEAD is associated with atherosclerosis and patients are at high risk of developing cardiovascular complications, and several ML models have been built to better assess the risk of major adverse cardiac and cerebrovascular events [4]. Taken together, integrating the severity of LEAD with the risk of amputation and cardiovascular events might help clinicians optimize the medical treatment and determine the most appropriate strategy for revascularization in a timely fashion.

4.3. *Carotid stenosis*

Carotid stenosis is another atherosclerosis-related disease and is associated with risk of cerebrovascular events, including ischemic stroke or transient ischemic attacks [8]. When carotid stenosis is diagnosed, the main questions for clinicians are: Should it be treated? If yes, when and how? [8]. Several ML predictive models have been built to identify predictive patterns of stroke risk from carotid plaques characterization on imaging, including magnetic resonance imaging, computer tomography angiography, or ultrasound [16,23]. These studies support the use of AI to help clinical decision making for the management of carotid stenosis, although the models still need further validation before their use for clinical practice.

5. Preoperative planning

AI brings opportunities to develop advanced imaging techniques to better detect, diagnose, and classify vascular diseases [4–6],[16]. Automatic segmentation of the vascular system has brought new insights to the management of aortic aneurysms, with the development of methods that allow easy, robust, and fast quantification of the anatomic characteristics of the vessels, such as the measurement of aneurysm maximal diameter or aneurysm volume [24–26]. Such methods can be used to develop AI-driven solutions and software to improve preoperative planning, especially in eligible endovascular aortic aneurysm repair, where sizing can be necessary to order endografts adapted to the patient's anatomy. Some investigators trained and applied a fully automated pipeline using a convolutional neural network to automatically segment the thoracic aorta, detect proximal landing zones, and quantify geometric features that are relevant for thoracic endovascular aortic repair planning [27]. The system allowed to automatically identify the adequate landing zones for endograft deployment and to provide measurements of relevant aortic metrics in order to facilitate preoperative planning. Another study used finite element computational simulation to predict the deployment of a fenestrated device [28]. Compared with results obtained on postoperative computed tomography angiography, the numerical model demonstrated its accuracy for planning the position of the fenestration [28]. The performance of the numerical simulation of fenestrated stent-graft deployment was further evaluated compared with in vitro studies and demonstrated its accuracy for positioning the fenestrations [29]. Taken together, these results emphasize the interest in AI for preoperative planning, by generating, easy, fast, and reproducible measurements of the vessels for endograft sizing and for predicting and simulating the deployment of the device.

In addition to preoperative planning, imaging techniques, such as completion digital subtraction angiography, are frequently used in the operating room to guide endovascular procedures. AI can help in the development of applications to enhance image-guided surgery. As an example, some investigators developed a fully automatic method for stent-graft segmentation on digital subtraction angiography during endovascular aortic aneurysm repair using a DL network [30]. The method demonstrated its accuracy to segment endograft with a Dice similarity score of 0.957 ± 0.041 and can serve as a basis to develop useful tools for vascular surgeons, such as applications to analyze stent-graft deployment accuracy or to allow early detection and visualization of endoleaks [30]. Applications for surgical planning and image-guided surgery is a very active area in vascular surgery, as witnessed by an increasing number of companies and startups offering services to advance vascular visualization and improve decision making in the operating room [31–35]. It is anticipated that such applications may soon be widespread and become standard in daily clinical practice.

6. Surgical risk assessment and outcome prediction

Depending on the symptoms and severity of vascular diseases, surgical and/or endovascular interventions can be required to treat the lesions. Risk stratification in preparation for surgery helps clinicians identify high-risk patients to optimize resources, plan the intervention, and anticipate peri- and postoperative complications [1].

6.1. *General surgical risk assessment*

Several studies used ML algorithms to identify high-risk surgical patients. Using clinical and surgical data across 37 million clinical encounters from electronic health records, Corey et al [36] developed a model that predicted postoperative complication risk with a sensitivity of 76% and a specificity of 76%. Another model to evaluate surgical complexity score was built using ML to predict adverse outcomes among patients undergoing elective surgery [37]. Using administrative billing data from 1,049,160 patients undergoing elective surgery, this novel surgical Complexity Score outperformed three of the most commonly used risk-adjustment indices (ie, Charlson Comorbidity Index, Elixhauser Comorbidity Index, and Centers for Medicare and Medicaid Service's Hierarchical Condition Category) to predict perioperative morbidity and 90-day readmission [37]. Although further work is necessary to evaluate the impact of these models on clinical workflow and postoperative outcomes, they could help as decision support tools to identify high-risk patients, plan the intervention, and anticipate postoperative outcomes.

6.2. *Specific risk assessment for vascular procedures (aortic, LEAD, and carotid procedures)*

Although the previous scores were developed for patients undergoing surgery regardless of the type of interventions, ML-based scores have also been developed to predict the outcomes of patients specifically after vascular interventions. For instance, ML algorithms were used in patients undergoing repair of aortic aneurysms to predict the risk of mortality, re-intervention, and postoperative complications, such as the occurrence of endoleaks or aneurysm sac expansion [6,16]. In patients with LEAD, AI-based prediction models were also developed to predict limb survival and risk of amputation after revascularization [4,16,22]. In patients undergoing carotid intervention, ML algorithms were used to predict various postoperative outcomes, including risk of ischemic stroke, hemodynamic depression, major adverse cardiovascular events, and risk of re-intervention [16]. ML predictive models can not only serve as innovative tools to evaluate surgical risk, but also to assess the probability of therapeutic success. By balancing the severity and risks related to the disease itself and risks linked to vascular interventions, AI can lead to the development of aid-decision support to propose individualized therapeutic approach for patients with vascular diseases.

7. Challenges

Although AI offers a wide range of applications to improve vascular surgical decision making, there are several barriers to immediate implementation in clinical practice. First, the performances of the ML models are dependent on datasets used for training. Building large international databases may help to ensure algorithmic fairness by developing robust models that are still accurate, even in case of rare conditions or events. Training AI models from dynamic and continuously updated real-world data might also help to develop real-time prognostication, guide personalized therapy, and enhance evidence generation for clinical guidelines.

Second, most of the ML algorithms developed so far have been trained and validated using retrospective cohorts. External validation in multicenter cohorts and prospective studies is required to assess the generalizability of the models. To the best of our knowledge, no results from randomized clinical trials have been published that evaluated the use of AI tools in vascular surgery, although some trials have been registered recently and might provide new insights. Most of the studies performed so far compared the performances of AI models with the ground truth provided by human experts. In addition to the accuracy, the clinical benefits in terms of patient outcomes and economic impact remain to be evaluated.

An additional aspect raised by AI is the explicability, as well as accountability, of the models, as they function as "black boxes," making it difficult to explain precisely how they work, to determine causal links, and to define who is responsible for the process [38]. AI and ML programs are considered medical products and may therefore meet regulatory requirements. Although the general framework on legal considerations for medical products has been defined by the European Union laws and the Food and Drug Administration in the United States, multidisciplinary groups of experts are currently working on guidelines related to AI and health that will help to improve standardization to validate AI tools [38]. AI models should guarantee patient privacy, data protection, and security at all stages, from conception to development, validation, and service delivery to end users, in accordance with the European Union general data protection regulation and the Health Insurance Portability and Accountability Act of 1996 [39] in the United States. Finally, technical and economic considerations are also at stake for the implementation of AI-driven decision-making support systems. Computational power and computational time must fit with the resources, infrastructure, and organization of health care systems to meet the expected benefits according to the intended use. Also, who should provide financial support for the implementation of AI technologies? Only a few studies have so far investigated the cost-effectiveness of AI techniques for the management of vascular diseases. Deeper analysis of medico-economic impact might help to better define health care system strategies for the development, implementation, and re-imbursement policies of AI applications.

8. Conclusions

AI holds great promise for the development of aid-decision support for patients with vascular diseases, with a wide range of applications, including early detection of life-threatening conditions; balanced risk assessment integrating the severity of the disease; and risks related to intervention, presurgical planning, or image-guided surgery. Although legal, ethical, technical, and economic challenges must still be overcome, AI technologies have the potential to bring new applications to support vascular clinical decision making and personalized care by enhancing real-time diagnosis, prognostication, and visualization. Although they can improve evidence-based decision, they should be considered as a resource tool available for clinicians, without replacing their knowledge, expertise, responsibilities, and duties to patients. Applying AI in medical practice will require health care professionals to learn how to work with these innovative technologies and adapt their work in evolving health care systems [38,40]. Education, training, and involvement of vascular specialists to provide expertise and feedback on the use of AI technology are cornerstones to develop fair, safe, accurate, and efficient applications to improve care provided to patients with vascular diseases.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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