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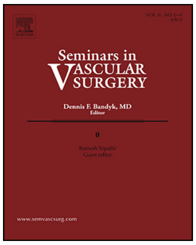

Review article

A look to the future: Pandemic-induced digital technologies in vascular surgery

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ABSTRACT

Like many areas of medicine, vascular surgery has been transformed by the COVID-19 (coronavirus disease 2019) pandemic. Public health precautions to minimize disease transmission have led to reduced attendance at hospitals and clinics in elective and emergency settings; fewer face-to-face and hands-on clinical interactions; and increased reliance on telemedicine, virtual attendance, investigations, and digital therapeutics. However, a “silver lining” to the COVID-19 pandemic may be the mainstream acceptance and acceleration of telemedicine, remote monitoring, digital health technology, and three-dimensional technologies, such as three-dimensional printing and virtual reality, by connecting health care providers to patients in a safe, reliable, and timely manner, and supplanting face-to-face surgical simulation and training. This review explores the impact of these changes in the delivery of vascular surgical care.

1. Introduction

Like many areas of medicine, vascular surgery has been transformed by the coronavirus disease 2019 (COVID-19) pandemic with the rise of digital technology. Critical public health precautions to minimize disease transmission have included the discouragement of unnecessary hospital and health care office visits, coupled with the introduction of enhanced personal protective equipment and social distancing. With the shift in emergency department presentations towards respiratory symptoms and suspected COVID-19 [1], along with critical shortages of personal protective equipment and medical equipment, measures to minimize patient attendance have been vital to disease control. A predictable consequence of these restrictions is reduced care delivery to patients. In a typical vascular surgical service, patients with chronic vascular disease rely on good preventive and maintenance health care to avoid emergent hospital presentation. Therefore, many services have explored alternative ways to deliver care while minimizing the potential spread of COVID-19 to patients, providers, and the public.

Telemedicine or telehealth has existed before COVID-19, but it has not seen broad uptake in its modern form across medical and surgical specialties. At its most basic, it permits the remote diagnosis and treatment of patients by means of telecommunications technology. Modern telehealth delivers health care and health information services via remote digital technologies encompassing live video conferencing, mobile health apps, “store and forward” electronic transmission,

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and remote patient monitoring. In addition, live video conferencing, electronic results systems, and mobile health apps can supplement and assist virtual consultation sessions.

Since the start of the pandemic, telemedicine has gained traction and developed a pivotal role in medical management. In this review, we discuss the rise of telemedicine and the use of digital therapeutics in managing patients with vascular disease and how it can change the model of care in vascular surgery. A "silver lining" to the COVID-19 pandemic might be the permanent, mainstream acceptance of telemedicine, remote monitoring, and digital health technology by connecting health care providers to patients in a safe, reliable, and timely manner.

2. Rise of telemedicine during the pandemic

Telemedicine uses technology to bridge the tyranny of distance by connecting health care providers to patients and each other. The simple act of writing a referral letter or consultation opinion to a specialist colleague, or communicating information to a patient via telephone, are all forms of telemedicine—the first using the technology of the domestic or international mail delivery network, and the second employing the technology of the voice telephony network.

In comparison to these more traditional modes, modern telemedicine platforms introduce new dimensions to this communication paradigm. Current telecommunication technologies permit the rapid exchange of information outside of the conventional clinic environment via mobile devices, changing the physical context in which clinicians can make decisions and the timeframe in which patients can interact with them. In addition, asynchronous messaging allows multiple simultaneous telemedicine interactions with numerous patients to be conducted over a longer timescale—unrestricted to a traditional appointment time.

High-volume data transmission allows interactive, real-time audio, and video consultations to be conducted. It can even permit remote operation of medical equipment for diagnostic or therapeutic purposes supplanting physical clinic attendance or examination. Furthermore, remote telemetry or patient-reported outcome measures via mobile devices can be easily collected for clinician review between clinic visits, obviating inpatient or repeated observations.

"Store and forward" electronic data transmission, distributed cloud-based results access, and electronic medical record platforms permit the review, scrutiny, and update of vast swathes of data regarding a patient to inform clinical decisions and enhance patient care, greatly extending the reach of an individual clinician, or the options available to any particular patient. Table 1 shows various visit types and definitions of virtual care. Table 2 provides a glossary of common telemedicine terms.

Widespread acceptance of telehealth has been limited by a combination of technical and reimbursement challenges. Before the pandemic telehealth uptake was primarily within radiology [2], psychiatry [3], and cardiology, and the American Medical Association data suggest that immunologists, gastroenterologists, and obstetricians and gynecologists use telemedicine the least [4]. Many restrictions have recently been lifted with clear evidence of increased uptake across specialties and jurisdictions during the COVID-19 pandemic [5,6].

2.1. *The rationale for telemedicine*

During the last year, many patients have delayed care for fear of contracting COVID-19, ultimately presenting to the emergency department in advanced or acute disease states. An estimated 41% to 42% of US adults reported having delayed or avoided seeking care during the pandemic because of concerns about COVID-19, including 12% who reported having avoided seeking urgent or emergency care [7]. Concerns about the additional harm, complications, and morbidity caused by this delay have spawned multiple prospective studies in the COVID-19 era, including Vascular Surgery COVID-19 Collaborative (VASCC) [8] and COVER [9] in the vascular surgical space. Telemedicine can ease the strain on conventional health care access by providing in-home communication between providers and patients, potentially minimizing delays in care and their consequential impacts.

Even before the COVID-19 pandemic, access to medical care has been widely recognized to be limited by geography and socioeconomic status—frequently termed *social determinants of health care*. Although it is common to associate poorer medical outcomes, such as leg amputation [10] or aneurysm surgery [11], with remote or low-volume surgical centers, landmark projects, such as the Dartmouth Atlas [12] and the Australian Atlas on Healthcare Variation [13], clearly indicate that geographical disparities in health care are not related simply to the local availability of urgent or emergency surgical services.

Geography modifies access to primary care, specialist referrals, preventive care, and medication adherence, compounded further by social determinants of health, impacting health literacy, health care funding, social supports, and essential utilities and infrastructure to maintain health [14–16]. In addition to telemedicine, digital health tools, such as mobile phone prompts and smart apps, have been proposed and trialed as potential solutions to these barriers [17]. However, they remain imperfect due to the predominant design for technology-literate, nondisabled consumers with the financial capacity to own or access suitable digital devices and data networks [18].

The economic and environmental benefits of telemedicine should not be underestimated. Video teleconferencing combined with point-of-care ultrasound testing can shorten access times for patients, while maintaining the quality of care because of the increased availability of laboratory testing and clinic space through satellite locations [19]. In addition, reduction in distance traveled, related costs, and emission of environmental pollutants can be substantial using telemedicine [20].

2.2. *Can telemedicine work in surgical specialties?*

Several surgical studies have evaluated preoperative consultations using different forms of telemedicine. Kamdar et al [21] examined the development, implementation, and evaluation of a telemedicine initiative for preoperative anesthetic evaluation. Over 2 years, 419 patients were scheduled for

Table 1 – Definitions of virtual care.

Visit type	Definition	Method	Insurance payment (United States)
Video visit	Scheduled appointment with a doctor where the patient does not need to come to a clinic. Video call with their doctor from home, office, or other location using smartphone.	Synchronous	Yes
Clinic to clinic telemedicine	Scheduled appointment with a doctor where the patient is at one clinic and doctor at a different or distant clinic. Patient and doctor communicate using audio and video in real time over a video conference	Synchronous	Yes
eVisits	Nonurgent electronic visit, for a fee. Patient answers online questions based on symptoms. Information sent via electronic message to their doctor to be assessed for diagnosis and treatment.	Asynchronous	Self-pay[a]
Virtual postoperative visit	Post-surgical follow-up evaluation using secure messaging with delayed delivery questionnaire and patient-provided pictures of wound or incision site.	Asynchronous	No
Remote monitoring	Use of devices to collect and send data to a provider/remote facility for interpretation.	Asynchronous	Yes[a]
eMessaging	Common, nonurgent questions, not used as a means to obtain diagnosis or treatment.	Asynchronous	No

Table 2 – A glossary of common terms in telemedicine.

Term	Definition
Telemedicine or telehealth	Conduct of a health care exchange between a clinician and a patient when the two are not in immediate physical proximity
Synchronous communication	Communications between parties where there is an ordered or serial exchange of information. Participants will typically wait for and expect a response from the other party until the episode is complete. This is typically referred to as “real-time” communication and requires high-bandwidth, low-latency, redundant network channels.
Asynchronous communication	Communications between parties where there is no ordered exchange. Transmissions and responses can appear out of order, without any expectation of acknowledgment or response, and there may not be a clear timeframe, beginning, or end to each episode. Asynchronous exchanges are more suited to low-bandwidth, low-latency, or unreliable network channels.
Store and forward	Collection of clinical information to be batched and sent electronically to another site for review at a later time. This can include demographics, clinical history, investigation results, images or other documents and can play a role in a future real-time consultation or asynchronous communications between the clinician and patient.
Remote monitoring or remote telemetry	The transfer of episodic or continuous diagnostic information (eg, medical imaging, vital signs, pathology) to a distant location for interpretation. This can be done synchronously or asynchronously

surgery via telemedicine and 1,785 patients were evaluated in-person, with day-of-surgery cancellation rates of 2.95% and 3.23%, respectively. Ninety-eight percent of patients consulted with telemedicine were satisfied with their experience. Heslin et al [22] found that titration of alpha blockade therapy through patient and surgeon e-mail correspondence before adrenalectomy for phaeochromocytoma was efficacious and saved unnecessary travel time and expense.

Prospective studies have demonstrated that routine surgical care can be effectively delivered using telemedicine, including diagnosis for neonatal surgical consultations through video teleconference [23] and interpretation of computed tomography images over mobile phones [24], which, despite early technology, was sufficient to achieve a reduction in transfers to facilities with on-site neurosurgeons from referring hospitals by 30% to 50%.

Despite the traditional postoperative follow-up mandating in-person review and physical inspection of the operative site, this is no longer necessarily true. A retrospective review of postoperative visits after cholecystectomies and appendectomies indicated that only 14% of patients underwent any intervention, such as wound care, staple or suture removal, drain management, readmission, reimaging, or medication adjustment. Only 9% of such patients required any hands-on intervention [25]. Although this can vary among subspecialties, it highlights that many postoperative patients can be followed up virtually if given the option. A recent prospective pilot study showed that 76% of patients undergoing elective outpatient surgical procedures, including laparoscopic cholecystectomy and hernia repair, preferred online postoperative visits to traditional clinic visits. Although online visits took less time, no complications were missed via online visits [26].

Other studies have demonstrated that telemedicine for postoperative follow-up after cleft lip/cleft palate repair saved significant travel time and distance and allowed access to specialty services within a larger radius than would be possible for a clinical appointment [27]. Similarly, telemedicine for routine postoperative follow-up after parathyroidectomy was safe and effective. [28].

2.3. *What about vascular surgery?*

Vascular surgical implementation is most undoubtedly feasible, with the first author (J.C.L.) successfully using a combination of point-of-care ultrasound services with the Microsoft Skype (Redmond, WA) videoconferencing platform to conduct vascular surgical remote clinical encounters with patients in satellite centers between 2015 and 2016. Of the 82 patients evaluated in this pilot study, 15 new-patient visits, 30 postoperative visits, and 37 follow-up visits were conducted, with 91% highly recommending a virtual physician encounter to a friend or colleague and all respondents reporting that their encounter was more convenient than traditional office visits, replicated in subsequent experiences [19,29].

A 2018 systematic review of telemedicine by Asiri et al [30] identified three articles with vascular surgical applications. These included the use of home-based blood pressure monitoring and web-based videoconferencing monitoring after discharge on day 1 post-carotid endarterectomy, when intermittent video-monitoring identified a hypertensive event requiring medication in 31% of patients [31]. Wirthlin et al [32] used what would now be considered to be a low-resolution digital camera (756 × 504 pixels) for imaging of postoperative and ischemic wounds at a remote vascular clinic, with high concordance between on-site and remote assessments. Hands et al [33] evaluated the use of videoconferencing for vascular surgery consultation to enable diagnosis and management decisions for patients and found it was an adequate means for transmitting information while saving patients significant time. Overall, the systemic review by Asiri et al showed telemedicine to have more advantages over traditional surgical care. Therefore, they suggest that health care providers, specifically in the surgical field, implement telemedicine technologies in hospitals to support health care providers in the delivery of more efficient care.

2.4. *Potential disadvantages to telemedicine*

Acceptance of telemedicine consultations among patients is not universal. In the earlier cited study by Kavousi et al [29] on the use of videoconferencing for the assessment of varicose veins, voluntary uptake of telehealth by patients was 95% among White and 5% among African American patients [29]. A large study among members of the Kaiser Permanente Northern California health plan identified similar ethnic influences and found that adults older than 69 years were significantly less likely to be registered to use the patient portal [34].

This might reflect a lower degree of comfort and experience with digital technology platforms necessary for real-time videoconferencing among these two subpopulations, particularly relevant to vascular surgery due to the predominance of advanced age and minority groups with known socioeconomic disadvantage among this patient population [35]. There is certainly the risk that the introduction of telehealth initiatives without a view to equity of access could further exacerbate disparities among disadvantaged patient groups.

Some providers fear that referral patterns and personalization may be challenging to foster through telemedicine. Patients that have grown to know and trust their primary family doctors are hesitant to speak to new providers via telemedicine. It is believed that if an introduction is made from the referring provider to the surgeon directly, along with a brief explanation of how telemedicine works and its overall convenience to the patient, can aid in a more satisfactory experience.

A prime disadvantage of remote consultations is the inability to conduct in-person physical examinations. The tenet that all patients should have a physical examination is ingrained into medical and surgical training. However, the reality of a post-pandemic world is that this previously low-risk activity is now increasingly perceived as high risk. The calculus then becomes how do we ensure the detection of relevant findings and pathology in the absence of physical examination by the surgeon?

One option is the utilization of self-examination, examination by a remote generalist medical practitioner, or by a trained assistant co-located with the patient supplemented by remote telemetry—a model successfully used in telemedicine conducted with patients in remote locations, such as polar bases or the International Space Station [36,37]. In addition, corroborative information can be obtained by imaging investigations that can be performed either before or during remote consultation (such as plain x-ray study, ultrasound, computed tomography, or magnetic resonance imaging)—and sometimes by a remote-controlled robot [38] or even the patient themselves [39,40]. Lastly, comprehensive history combined with preconsultation imaging can be used to triage those patients who require a physical examination and in-person assessment. In many cases, a verbal history, visual inspection, and results review are enough to formulate a clinical evaluation for expedited decision making.

Another solution is the selective use of telemedicine as part of a streamed-clinic strategy. For example, pre-identification of patients with targeted pathologies (ie, aortic aneurysm, bypass graft surveillance, or varicose veins), or at specific stages in their surgical patient-care journey can permit re-organization of clinic flow, such that only those patients with specific physical interaction needs (such as dressing changes, comprehensive physical or wound assessment, synchronous allied-health intervention, or prolonged discussion of a complex clinical scenario) attend in-person. Those who do not require physical examination are seen via video conferencing or telephone consultation in combination with a review of any combined point-of-care ultrasound or asynchronous imaging results.

Some of these strategies come with a conscious compromise in care and the potential to miss findings otherwise detected only by a physical encounter or impair communication of surgical advice, perioperative risks, and postoperative care. For example, it has long been recognized that significant medicolegal risks accompany the introduction of telemedicine into radiology practice [41]. Indemnity arrangements must consider these compromises, as well as the extraordinary circumstance of the pandemic that has driven these changes.

Furthermore, concerns exist around ethical and medicolegal impacts of telemedicine interactions, including those of

Table 3 – Common Procedural Terminology coding for telemedicine.

POS 02 for telehealth Medicare and modifier 95 for commercial payers

New patients			Established patients		
CPT code	RVU	Minutes	CPT code	RVU	Minutes
99201	0.48	10	99211	0.18	5
99202	0.93	20	99212	0.48	10
99203	1.42	30	99213	0.97	15
99204	2.43	45	99214	1.50	25
99205	3.17	60	99215	2.11	40

Abbreviations: CPT, Current Procedural Terminology; POS, place of service; RVU, relative value unit.

inadvertent or malicious privacy breaches, security of information storage or data transfer pathways in an era of regular cyber-security compromises, and the ability of providers and patients to store audiovisual recordings of their interactions for later reference [42,43]. In some institutions, clinical governance of these matters are rudimentary or scarce despite being HIPAA (Health Insurance Portability and Accountability Act)-compliant and stressed further by the rapidly moving, pandemic-related landscape. It is critical that surgeons worldwide proactively engage in developing guidelines and practices that remain consistent with existing medicolegal and ethical obligations [44].

2.5. *Reimbursement challenges for telemedicine*

Traditionally, surgical providers have delivered little care via telemedicine. In 2012, US Medicare expenditure on telemedicine was little over US$5 million, with the vast majority driven by mental health services [45]. Insurers and health systems have had strict criteria for coverage or compensation for such patient care interactions before 2020. Since the onset of the pandemic, however, several changes have been made to telehealth policy, coverage, and implementation to make telemedicine more widely accessible during this state of emergency.

Table 3 shows the Common Procedural Terminology coding for telemedicine in the US environment [46]. The US Federal Government has loosened restrictions in the Medicare program, including allowing beneficiaries from any geographic location to access services from their homes. Although the US Department of Health and Human Services has waived HIPAA requirements for telemedicine [47], HIPAA-compliant platforms, such as Epic (Epic Systems), Zoom (Zoom Video Communications), Skype (Microsoft), and WebEx (Cisco Systems), are now available to reach patients in many diverse locations.

However, several concerns exist regarding coverage when the crisis ends. Service parity and payment across insurers can vary. Many providers have struggled with network capacities and broadband access when trying to connect for virtual visits. The Federal Communications Commission announced it is increasing funding for its rural health care program to US$802.7 million this year, as rural providers' applications for high-speed broadband during the pandemic have exceeded the programs US$604.7 million funding cap [48].

Introduced in 2013, Australian Medicare reimbursement for telemedicine services was limited to video-based consultations for geographically remote or indigenous patients, with limited exceptions. In March 2020, the COVID-19 pandemic prompted the temporary introduction of a greater range of Australian Medicare item numbers for telephone and video-based telemedicine, available for all equivalent consultation services delivered by a range of medical, nursing, and allied health practitioners and reimbursed at the same rate (see Table 4). This pandemic telehealth program has been extended as the pandemic impact has continued [49,50]. As of March 2021, more than 51 million telehealth services were reported by the Australian Government as having been delivered to 13 million patients, with almost AU$2.6 billion (US$1.9 billion) paid to more than 82,000 health care providers [51].

The role of telemedicine in vascular surgery has been recognized and used during this pandemic, becoming a mainstream form of communication. A survey among 535 vascular surgeons in more than 45 states showed that 91.7% had significant cancellations to elective surgical procedures during the COVID-19 era [52]. The majority (89.2%) of vascular surgeons reported disruption to their outpatient clinic/ambulatory center schedules. Ambulatory or clinic hours were limited in 71% of responders, with 81.1% reporting use of telehealth services in their practice. Many vascular surgeons have used and embraced telemedicine during this crisis. The pressure of patient demand and shortage of vascular surgeons in an aging population makes an even greater case for acceptance with or without the presence of a pandemic.

It is estimated that the number of surgeons needed to meet population demand for care suggests an undersupply of US surgeons between 10% and 30%, particularly in rural areas [53]. Also, vascular patients are a vulnerable population due to multiple comorbidities and advanced age. Telemedicine is a practical way to bridge the gap between supply and demand in an otherwise demanding patient population.

3. Digital health tools and digital therapeutics

Digital health solutions, particularly mobile and app-based patient engagement methodologies, have seen increasing implementation over recent years as research tools, clinical outcome measures [54], and interventional strategies [55,56]. This has been fueled further by patient acceptance and physician adoption during the pandemic of mobile, app-based contact-tracing initiatives [57].

Before the advent of portable electronic computing devices and personal "smartphones" the concept of patient-based engagement in personal health care was rudimentary—primarily reliant on static information delivered verbally or on paper by the clinician during face-to-face encounters, and observations collected between visits either through formal investigations, or measures that were, at most, collected by the patient and recorded in a patient diary. The introduction of automated blood pressure monitoring alone is a surprisingly

Table 4 – Australian COVID-19 Temporary Medical Benefits Schedule Telehealth Items for surgical specialists introduced March 13, 2020 and April 20, 2020.[a]

Service	Existing items (face to face)	Existing remote-health items[b] (video-conference)	Telehealth items (via videoconference)	Telephone items (for when videoconferencing is not available)
Specialist				
Initial attendance	104 (76.80)	>10 min: 99+104 (115.20) ≤10 min: 113 (57.65)	91822 (76.80)	91832 (76.80)
Subsequent attendance	105 (38.60)	>10 min: 99+105 (57.90) ≤10 min: 113 (57.65)	91823 (38.60)	91833 (38.60)
Neurosurgeon				
Initial attendance	6007 (116.35)	>10 min: 6016+6007 (174.52) ≤10 min: 6004 (87.30)	92610 (116.35)	92617 (116.35)
Minor attendance	6009 (38.60)	>10 min: 6016+6009 (57.90) ≤10 min: 6004 (87.30)	92611 (38.60)	92618 (38.60)
Subsequent attendance, 15–30 min	6011 (76.80)	>10 min: 6016+6011 (115.20) ≤10 min: 6004 (87.30)	92612 (76.80)	92619 (76.80)
Subsequent attendance 30–45 min	6013 (106.40)	>10 min: 6016+6013 (159.60) ≤10 min: 6004 (87.30)	92613 (106.40)	92620 (106.40)
Subsequent attendance, more than 45 min	6015 (135.45)	>10 min: 6016+6015 (203.17) ≤10 min: 6004 (87.30)	92614 (135.45)	92621 (135.45)

[a] Values in parentheses are reimbursement in AU$ represents 85% of the standard Commonwealth Medical Benefits Schedule (CMBS) fee. Data accurate as at July 39, 2021 via CMBS website (mbsonline.gov.au).

[b] Conditions of pre-existing Australian Medical Benefits Schedule telehealth numbers introduced January 1, 2013: not an admitted patient; and not a patient of an emergency department; and located in a telehealth eligible area at the time of the attendance; and located at least 15km by road from the specialist; or a care recipient of a residential aged care facility (located anywhere in Australia); or a patient of an eligible Aboriginal Medical Service (located anywhere in Australia).

recent development and is symbolic of data collection outside of the hospital or clinic environment [58].

Modern personal smartphones or digital devices now possess more than 100,000 times the computing power of the Apollo Guidance Computer used on the Apollo 11 Moon Landing Mission [59]. Even in low socioeconomic settings and developing countries, personal app-capable mobile phone ownership is in excess of 80% [60]. Historically, clinical research data collection was reliant on statistical sampling of a large population, we now live in an age of “big data” when it is now possible to collect large datasets using digital devices for analysis using traditional statistical, data science, or artificial intelligence techniques [61]. Because the availability of affordable, network-connected consumer smartphones, the proliferation of electronic health (eHealth) and mobile health (mHealth) applications has been significant [62].

Common implementations of digital health are discussed below.

3.1. *Digital health for patient and practitioner education and engagement*

One of the most straightforward implementations of digital health is the delivery of health information in an electronic format, such as an electronic textbook, patient brochure, or consumer health information. This removes the need to physically attend a location to obtain written information or for a physical booklet to be delivered to the patient. Material can be sent via SMS (short message service) text delivery, electronic mail, or on internet-based webpages accessed via standard URL (uniform resource locators) or even QR (quick response) codes. The targeting and scheduled delivery of this material can be finely tuned and personalized to the recipient and their situation, such as through bite-sized journal abstract subscriptions, “health tips” for patients with known conditions [63], or notifications of upcoming health care appointments or events, such as clinic appointments or surgery [64].

Mobile health technologies have been used to exchange health information and develop social communities at an academic level [65], a professional level, or a consumer-level via free-to-access social networking platforms, such as LinkedIn, Facebook, Twitter, or Instagram (owned by Facebook), or curated platforms through professional organizations such as the American College of Surgeons Member Communities service [66].

Increasing network and bandwidth capacity has made the connection to hospital clinical information systems a realistic prospect [67], facilitating the use of remote access for doctors to access health information systems and clinical results when in the field, or for patients to access portals to better engage in appointment management, attendances, and to improve patient autonomy and engagement [68].

3.2. *Digital reference tools and clinical decision-making aids*

The late 20th and early 21st centuries have seen significant growth in medical literature, with 218,734 serial articles tabulated in the US National Library of Medicine in 1957 [69], 8.1 million publications indexed in the US National Library of Medicine Medline database between 1978 and 2001 [70], and more than 28 million journal article references as of 2021 [71]. It has been estimated that it is growing exponentially, with a projected doubling time of 73 days in 2020, although both the source and veracity of this figure are highly questionable [72].

Such growth dramatically inhibits the ability of the average clinician to absorb and process contemporary medical knowledge. Dynamic, interactive online services accessible through phone-based internet browsers have also transformed the access to medical literature and consumer-oriented health information, especially at the point of care. This has given rise to numerous clinical reference tools, such as UpToDate (Wolters Kluwer Health), and numerous smartphone app-based clinical calculators [73].

With the uptake of clinical management protocols, point-of-care tools can act as decision support tools, improving the consistency of care [74], relieving the cognitive load on clinicians in high-stress situations, or permitting task substitution such that less experienced clinical staff can execute such protocols. Examples of mobile tools for clinical staging or decision making include phone-based field tools for ruptured abdominal aortic aneurysm recognition and triage by paramedics [75] and apps released by the Society for Vascular Surgery (SVS), including risk calculators and staging tools for mortality of critical limb threatening ischemia based on the Vascular Quality Initiative dataset, a WIfI (wound, ischemia, and foot infection) staging calculator for classification of the threatened limb, and a Global Limb Anatomic Staging System calculator [76].

3.3. *Digital health for data collection*

Clinical outcomes research has traditionally been reliant on the collection of case report forms at key time points and are a major source of stress, work, and error in data collection. Transition to electronic case report forms has dramatically improved the efficiency of data collection within clinical trials [77].

Electronic data capture systems can also be designed for direct patient entry, permitting large-scale data collection of patient-reported outcome measures and patient-reported experience measures [78]. These data can be used for clinical research, quality improvement, or to tailor the next step in a protocolized treatment algorithm for individual patients.

3.4. *Digital telemetry, remote monitoring, and wearable devices*

Although remote telemetry was initially conceived for use in long-distance, isolated environments, such as space travel, the ubiquity of portable, electronic medical monitoring has opened the door to a variety of home-based and mobile biotelemetry systems. The concept of “home telecare” is not entirely new [79,80]; however, amid the COVID-19 pandemic and resultant hospital-bed scarcity, the advantages of home-based self-administered physiological observations and basic investigations are clearly evident and have received renewed attention.

The development of ambulatory monitoring equipment for electrocardiographic rhythm recording and blood pressure monitoring has contributed significantly to the detection and diagnosis of cardiovascular disorders, and the availability of remote-monitoring devices, such as implantable loop monitors [81,82] or continuous glucose monitors [83] have transformed this field further. A new generation of wearable devices, such as noninvasive transdermal glucose monitoring sensors [84], use wireless technologies and mobile phone connectivity to communicate results to a remote monitoring station. The prospect of low-cost, home-based point-of-care monitoring and diagnostic equipment was a key attraction for investors of the ill-fated medical technology company Theranos [85].

Telemetry functions of commercially available wearable devices are another untapped resource in the digitalization of health care. Commercial wearable devices such as the Fitbit (Fitbit Inc) and Apple Watch (Apple Inc) already include functions such as monitoring of heart rate, oxygen saturation, skin temperature, and single-lead electrocardiography. With an estimated 20% of US residents currently owning a smart wearable device [86], there is much room for wearable data to be used telemetrically in the clinical workplace. Large-scale studies, such as the Apple Heart study [87], have demonstrated the excellent sensitivity of a commercial wearable device in the diagnosis of atrial fibrillation.

As with any new technology, funding and reimbursement pose significant challenges and, when combined with the potential for data to be transmitted to other countries or jurisdictions to providers subject to different regulations to the patient, medicolegal and regulatory problems arise [88]. Common Procedural Terminology codes for remote monitoring services are shown in Table 5.

3.5. *Digital therapeutics and gamification*

Digitalization of therapeutic interventions involves the transformation of care delivery using digital, electronic health, and mobile health technologies [89,90]. In part, this consists of the delivery of timely and targeted health care information to individual patients. Still, advanced digital therapeutics combine dynamic interactions that are responsive to feedback or input from the patient during the course of their treatment. Most examples of digital therapeutics have primarily focused on behavioral interventions [91], such as smoking cessation [92].

Many developers of digital therapeutics applications take inspiration from concepts in psychological and behavioral sciences used to enhance participation in electronic video games, known as “gamification” [56]. Key aspects of gamification include meaningful purpose (alignment of app goals with the user’s motivations and interests); meaningful choice (users have agency over how they achieve their goals); supporting player archetypes (app mechanics leverage individual user and player characteristics); feedback (progress is communicated, even if small and incremental); and visibility (the amount of progress so far and remaining progress to the next stage is made clear) [93].

The SVS Structured Exercise Training (SET) app is a novel app-based exercise therapy program for peripheral arterial disease [94]. SET is well-known as the most effective noninvasive therapy for improving pain-free walking distances in claudicants [95]. Despite the strong evidence for SET, there have been poor SET referral rates by medical providers, with only 50% of providers making a referral in a recent national SET utilization survey [96].

Table 5 – Common Procedural Terminology Coding for remote patient monitoring[a] and patient-generated health data.

CPT codes	Description
99453	Remote monitoring of physiologic parameters, initial; set-up and patient education on use of equipment
99454	Devices supply with daily recordings or programmed alerts transmission, each 30 d
99457	Remote physiologic monitoring treatment management services, clinical staff/physician/other qualified health care professional time in a calendar month requiring interactive communication with the patient/caregiver during the month; first 20 min
99458	Each additional 20 min
99091	Collection and interpretation of physiologic data digitally stored and/or transmitted by the patient and/or caregiver to the physician or other qualified health care professional, qualified by education, training, licensure/regulation.

[a] Remote patient monitoring: collecting and interpreting physiologic data digitally stored and/or caregiver to the physician or qualified health care professional.

The most common barriers stated were travel distance, lack of SET availability, lack of patient interest in SET, and cost. The mobile phone-based SVS SET app aims to address these barriers by delivering live SET coaching at scheduled times, eliminating the need to travel, and making it readily available. It is also highly scalable and potentially cost-effective and can also be modified for geriatric patients to be delivered in assisted-living settings.

In the current COVID pandemic climate, delivery of institution-based rehabilitation or SET programs pose an unjustifiable risk where home-based alternatives, such as SVS SET, are available. In addition, such digital therapies have the unique opportunity to create tailored, personalized programs in real time by incorporating user data and feedback in real time.

Despite lacking the "personal touch" of equivalent in-person programs, evidence already exists to support the efficacy of home-based exercise therapy in improving walking performance and preventing invasive surgical treatment [97–99]. By combining and incorporating real-time user feedback, gamification, and digital telemetry through wearable devices, dynamic, tailored, digital therapeutic programs might be even more effective than their traditional counterparts.

4. Three-dimensional technologies in vascular surgery

Anatomic visualization and three-dimensional (3D) correlation are critical in the planning and conduct of vascular procedures, especially endovascular surgery. The development of tomographic imaging has transformed the ability to appreciate the extent of vascular disease, and to prepare for surgery in a manner that has dramatically reduced perioperative risk and expanded the capability to undertake complex and minimally invasive surgery.

4.1. *3D visualization and virtual and augmented reality*

Improved volume-acquisition hardware and software processing systems have resulted in high-fidelity 3D computed tomography and magnetic resonance imaging datasets that are no longer possible to view and interpret on standard physical x-ray films. Instead, workstation-based scrolling or panning of axial image datasets, multiplanar, curved-planar, and volume-rendered 3D reconstructions are now standard image analysis techniques employed by radiologists and vascular surgeons alike.

Emerging technologies in the visualization of these complex datasets include the use of live fusion or overlay fluoroscopic imaging during endovascular procedures, and augmented reality overlays to supplement direct vision, which can be employed in a robotic display setting [100] or with head-mounted holographic imaging systems [101]. Outside of the clinical environment, virtual reality systems permit the visualization of tomographic data or 3D rendered anatomical models for preoperative planning, simulation, or surgical training.

4.2. *Virtual reality and 3D printing for teaching, training, and surgical planning*

In the reduced-contact environment of the COVID-19 pandemic, many face-to-face training and educational opportunities have been lost to surgical trainees. Open operative and anastomotic simulation models have established roles in surgical skills training, further supplemented by the use of physical and virtual endovascular simulators [102–104]. Although dedicated faculty instruction coupled with intensive simulation training provides better learning outcomes [105,106], pandemic-related lockdown measures have forced innovative training measures, such as distribution of low-fidelity skills trainers to students for home-based learning, coupled with video tutorials, as seen in the 24th European Vascular Course run by the European Society for Vascular Surgery during March 2021 [107].

Immersive distributed simulation [108] involves creation of a simulated environment around the trainee, together with a high-fidelity task simulator, or in order to simulate clinical decision making or interdisciplinary communication skills based on multisensory prompts [109]. Although virtual reality headsets might have limited fidelity and interactivity to teach operative skills, they are suitable for delivery of immersive 3D or point-of-view learning experiences from 360-degree intraoperative video recordings, or interactive teaching of nontechnical skills in a virtual environment [110,111]—all of which can be delivered remotely and without physical contact.

Segmentation of 3D datasets facilitates the extraction of specific structures for advanced reconstruction, and 3D printers have been used to create physical models of vascular structures, such as the aorta for education, training, or preoperative planning [112], including preparation of custom-manufactured or physician-modified endografts in complex endovascular aneurysm repair [113].

4.3. *3D printing for simulation and personalized and novel medical devices*

Direct 3D-printed implanted prostheses are becoming readily available, supporting the delivery of personalized medicine. Currently, the majority of these prostheses are for orthopedic [114], maxillofacial, or neurosurgical use, however, work is in progress to lend this technology to implantable vascular devices.

As highlighted in work by Coles-Black et al [115,116], 3D-printed models for endograft deployment and task training provide valuable adjuncts to surgical simulation and training. As 3D printing and material technology improve, increasingly high-fidelity operative simulation trainers show promise as substitutes for animal tissue and cadaveric models [117].

Biological 3D printing (or bioprinting) has the great potential to produce patient-specific, biocompatible or vascularized implants, however, despite steady progress and the tantalizing prospect of a 3D-printed, fully vascularized implantable solid organ, the technical challenges in this field are significant [118].

A key advantage to 3D printing technology is the ability to create highly customized, personalized devices and implants at small volume, and with a short turnaround time between design, prototyping, redesign, and manufacture—a capacity that has been put to extensive use during the COVID-19 pandemic to supplement the shortage of personal protective equipment [119]. This has prompted extensive debate and consideration of regulatory mechanisms for personalized and 3D-printed medical devices. Especially in an era of highly extensive biological and genetic manipulation, the ethical and medicolegal consequences of personalized medical devices and implants gain increasing prominence [120].

5. Conclusions

Despite having had a slow start with limited traction, digital telemedicine initiatives have soared ahead during the COVID-19 pandemic, complementing existing medical services and filling the gap created by pandemic-related clinic cancellations and contact minimization precautions. The implementation of telemedicine in vascular surgery is feasible and beneficial, although there are still risks related to exacerbation of health inequities and medicolegal and ethical challenges that require ongoing attention.

Current initiatives to support telemedicine have generally been temporary. However, there is little doubt that with growing clinician and community acceptance, telemedicine services will be a permanent fixture of vascular surgical practice even in a post-pandemic environment.

Digital and mobile technologies have facilitated radical transformations in the landscape of medical care, with direct applications in vascular surgery. Many of these changes are reliant on the proliferation of personal digital devices and increased consumer confidence in their use, along with data network infrastructure and the shift in information and communication platforms toward cloud-based and mobile-friendly interfaces. Nevertheless, these changes alone are not adequate to ensure high-quality and equitable health care delivery. Optimal utilization of these technologies will require a significant redesign of surgical care systems and changes in the paradigm of care.

3D advanced imaging and printing technologies are already making significant contributions toward improved vascular surgical education and clinical practice. These novel technologies hold great promise for future developments in procedural planning and implantable vascular devices.

In summary, we have presented our review of telemedicine, digital technologies, and 3D technologies in the practice of vascular surgery. The COVID-19 pandemic has seen emerging technologies become mainstream by forcing clinicians and institutions to revisit the standard paradigms of face-to-face medicine. Many of these changes will likely become embedded into common vascular surgical practice. Undoubtedly future crises will push us to embrace more and more technological changes, along with the usual drivers of convenience and efficiency in health care. It has never been truer that “necessity is the mother of invention.”

Regardless of the pace and disruptive nature of technological progress, it remains incumbent on us as vascular clinicians and specialists to assess these technologies carefully, reconsider our assumptions about standard paradigms of care, understand the ethical and medicolegal implications of these changes, and embrace them enthusiastically when they are of clear benefit to our profession and our patients.

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