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● *Review*

TELE-ULTRASOUND IN THE ERA OF COVID-19: A PRACTICAL GUIDE

Christopher Uschnig,[*,#] Florian Recker,[†,#] Michael Blaivas,[‡] Yi Dong,[§] and Christoph F. Dietrich[*]

[*] Department of Internal Medicine, Clinics Beau-Site, Salem and Permanence, Bern, Switzerland; [†] Department of Obstetrics and Prenatal Medicine, University Hospital Bonn, Venusberg Campus, Germany; [‡] Department of Emergency Medicine, St. Francis Hospital, University of South Carolina School of Medicine, Columbus, Georgia, USA; and [§] Department of Ultrasound, Zhongshan Hospital, Fudan University, Shanghai, China

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Abstract—Telemedicine has evolved over the past 50 years, with video consultations and telehealth (TH) mobile apps that are now widely used to support care in the management of chronic conditions, but are infrequently used in acute conditions such as emergencies. In the wake of the COVID-19 pandemic, demand is growing for video consultations as they minimize health provider−patient interactions and thereby the risk of infection. Advanced applications such as tele-ultrasound (TUS) have not yet gained a foothold despite their achieving technical maturity and the availability of software from numerous companies for TUS for their respective portable ultrasound devices. However, ultrasound is indispensable for triage in emergencies and also offers distinct advantages in the diagnosis of COVID-19 pneumonia for certain patient populations such as pregnant women, children and immobilized patients. Additionally, recent work suggests lung ultrasound can accurately risk stratify patients for likely infection when immediate polymerase chain reaction (PCR) testing is not available and has prognostic utility for positive patients with respect to the need for admission and intensive care unit (ICU) treatment. Though currently underutilized, a wider implementation of TUS in TH applications and processes may be an important stepping-stone for telemedicine. The addition of ultrasound to TH may allow it to cross the barrier from being an application used mainly for primary care and chronic conditions to an indispensable tool used in emergency care, disaster situations, remote areas and low-income countries where it is difficult to obtain high-quality diagnostic imaging. The objective of this review was to provide an overview of the current state of telemedicine, insights into current and future use scenarios, its practical application as well as current TUS uses and their potential value with an overview of currently available portable and handheld ultrasound devices. In the wake of the COVID-19 pandemic we point out an unmet need and use case of TUS as a supportive tool for health care providers and organizations in the management of affected patients. (E-mail: c.f.dietrich@googlemail.com) **© 2022 World Federation for Ultrasound in Medicine & Biology. All rights reserved.**

Key Words: **Tele-ultrasound, Telemedicine, COVID-19, Handheld ultrasound device, Lung ultrasound.**

TELEMEDICINE IN ITS HISTORIC CONTEXT

Telemedicine, a concept that originated in the late 1800s and early 1900s, is broadly understood as a means to exchange information for diagnosis, treatment and prevention of disease and injuries for patients, but also for research and evaluation as well as continuous education of health care providers (World Health Organization WHO 1998; Strehle and Shabde 2006). In contrast to traditional face-to-face or telephone consultations, telemedicine consultations, also known as virtual consultations, are increasing in demand. They allow the provision of remote medical care with specialized medical mobile apps or more recently video chat−capable apps including WhatsApp, Skype and FaceTime in certain countries (Armfield et al. 2015; Greenhalgh et al. 2016).

In 1957, a Canadian doctor constructed a teleradiology system in Montreal by which radiographic images were sent from one hospital to another 5 miles away through coaxial cable. In the early 2000s, the first remote ultrasound scans were done by astronauts with remote guidance from experts at Mission Control Center (Sargsyan et al. 2005). Those ultrasound systems were capable of high-definition sonographic imaging of

Address correspondence to: Christoph F. Dietrich, Department Allgemeine Innere Medizin (DAIM), Kliniken Beau Site, Salem und Permanence, Hirslanden, 3036 Bern, Switzerland. E-mail: c.f.dietrich@googlemail.com
[#] These authors contributed equally.

cardiac, vascular, general, abdominal, thoracic, and musculoskeletal systems. Arbeille et al. (2003, 2005, 2007) developed and tested a robotic arm to which an echographic probe was fixed, on a population located in rural areas. The system was used on various adult pathologies (gallbladder lithiasis, renal cavity distension, appendicitis, superficial and deep vessels), as well as gynecology and fetal development.

The technology remains relevant in aeronautics. The National Aeronautics and Space Administration continued to generate studies on the use of ultrasound by non-physician crew members at the International Space Station, which entailed prior training in ultrasound (Sargsyan et al. 2005; Kwon et al. 2007; Law and Macbeth 2011; Marsh-Feiley et al. 2018).

Currently, for routine ultrasound onboard the International Space Station, a system with motorized probe sensors (titling rotating) controlled from the ground is in use that solely requires the astronaut to maintain a motorized probe motionless on himself for the duration of the examination (Arbeille et al. 2018). Before being sent to the space station, the echo with motorized probe was successfully tested on 100 isolated patients on earth (Arbeille et al. 2016).

Often used complementarily with traditional face-to-face primary care, virtual consultations offer distinct advantages; they are considered to be more patient centered and are perceived as being high quality by patients (McGrail et al. 2017). Additionally, the diagnostic accuracy of consultations is not inferior to traditional in-person visits (Ohta et al. 2017; Sept et al. 2020) though even shorter (Ignatowicz et al. 2019). Finally, virtual consultations are also popular with health care providers (Shaw et al. 2018).

Telehealth solutions are widely used in the management of chronic conditions such as diabetes, hypertension, asthma, and chronic obstructive pulmonary disease (Car et al. 2020).

In obstetrics and gynecology, several successful prenatal tele-ultrasound projects have been completed (Chan et al. 1999; Ferlin et al. 2012). Many regions have only a limited number of qualified fetal medicine specialists who are capable of prenatal ultrasound imaging. Thus, few physicians do not adequately cover demand for imaging that is critical for diagnosing and preventing potential birth defects. Studies mainly from remote areas such as rural Australia have documented the need for fetal therapy and the impact of tele-ultrasound (TUS) (Soong et al. 2002). Recently, a TUS system was also successfully tested in Peru that can be deployed to improve access to diagnostic imaging in low-resource areas (Marini et al. 2021).

In acute conditions such as in emergency or disaster situations, however, telemedicine is used to a much lesser extent, although it can add value as part of triage protocols and management for patients who may benefit from immediate transportation. This includes triage of severe burn victims (Gacto-Sanchez et al. 2020), ocular emergencies (Car et al. 2020) or stroke victims (Wilcock et al. 2021). Some reports suggest that the use of telemedicine improves diagnosis and management, but has less impact on mortality and complications in trauma patients (Lapointe et al. 2020). However, a more recent large-scale representative study found that a telemedical consultation had significant impact on patients treated for stroke, resulting in a lower mortality rate, with the largest benefit seen in smaller hospitals, among rural residents and in patients older than 85 years (Wilcock et al. 2021).

Telehealth solutions may be used more in acute conditions if diagnostic imaging capabilities are expanded and embedded in telemedicine solutions. Here, we consider two scenarios offering distinct advantages by combining TH and advanced medical diagnostics, specifically ultrasound imaging. First, we examine use in trauma patients, for whom ultrasound examinations are already standard procedure for triage. Second, we look at COVID-19 patients for assessing disease progression with lung ultrasound where computerized tomography (CT) or chest X-rays are not an available or a viable option such as in remote areas, not medically indicated (such as in pregnancy) or unfeasible because of immobility, among other reasons.

We received approval from our institutional review board, and all studies cited in this article had institutional review board approval.

MEDICAL IMAGING

According to the WHO, medical imaging is needed to make a diagnosis in 20% to 30% of clinical cases, and ultrasound and/or conventional radiography are sufficient for 80% to 90% of those cases, yet two-thirds of the world population have no access to medical imaging (Smith and Brebner 2002). As telemedicine has evolved over the last few decades, medical imaging and therefore ultrasound technology have matured in parallel (Wootton 2001). Ultrasound can be used at the patient's bedside and is more portable than other imaging technologies such as X-rays, CT or magnetic resonance imaging (MRI).

TELE-ULTRASOUND, A USE SCENARIO OF TELEMEDICINE

Tele-ultrasound is defined as the use of ultrasound with voice and video and an additional instructor, such as an ultrasound-certified physician, who is remotely connected to it (Chimiak et al. 1995). The utilization of TUS has been increasing globally over the last 20 y, and various systems for remote ultrasound have been developed with the objective of providing ultrasound diagnosis to remote patient populations as well as in hostile environments. Ultrasound can be performed using the "remote guidance" method, where an ultrasound expert guides and assists through voice commands a medical doctor or patient to orient the probe (Hamilton et al. 2011). More recently, echography with probe orientation and echograph setting and function controlled from away allow for quicker ultrasound investigation and images of higher quality (Arbeille et al. 2016, 2018).

Tele-ultrasound is most frequently used for emergency, abdominal and obstetrical ultrasound by general practitioners in remote areas where it has proven most successful. However, much of the available data focuses on emergency ultrasound (Su et al. 2008) and other point-of-care ultrasound (POCUS) uses. TUS performed in resource-limited settings had diagnostically satisfactory image quality, which has an impact on medical treatment and outcome (Britton et al. 2019). Use scenarios of TUS include rural pre-hospital settings, geographically remote areas, areas restricted by political conflict, refugee camps, regions with limited medical professionals and areas with physicians not trained in ultrasound imaging (Adhikari et al. 2014). The technology itself has matured over the years, coincidentally with improved access to high-bandwidth networks globally, thereby allowing high-quality live-image transmission. Favorably for TUS, high-bandwidth infrastructure is now often available even in many low-income countries. However, readily available technology and regulatory challenges regarding data sharing and storage of patient data are still a major concern in many locations.

Strengths and weaknesses of TUS

Although TUS has distinct advantages and use scenarios, we wanted to provide a comparison table of its strengths, weaknesses, opportunities and threats, created through an exploratory SWOT analysis (analysis with research into current literature, practical experience in TH and testing of a series of portable and handheld ultrasound devices) (Table 1). Here, we narrowed our scope to more practical aspects such as portability of the ultrasound device, ease of use, acquisition and ongoing costs, availability and technical advances. Generally considered as one of the biggest strengths of TUS is the fact that no expert knowledge is required to start and operate an ultrasound device to generate an image that can be transmitted live and accurately interpreted by an ultrasound-trained medical professional. Another limitation is that even experts who daily perform ultrasound examinations on site may need twice as long for TUS compared with conventional ultrasound. This is because of the additional software needed to establish a remote connection, configurate the device remotely and instruct and guide the distant operator. This may place an additional burden on the health care system from a financial perspective.

A matter of bandwidth?

Major advances in telecommunication technology have paved the way for TUS in mobile (Levine et al. 2016) and web-based applications (Yoo et al. 2004). Commercially available video chat software can transmit high-quality and clinically useful ultrasound images, but may not guarantee compliance with local data safety and privacy rules. Studies indicate that images obtained are not inferior to images captured with a stationary ultrasound device (Barreiros et al. 2014, 2019). Some mobile ultrasound applications go beyond solely projecting a live image but have built-in tools to grade images captured, allowing evaluation if the operator failed or passed in completing a proper image acquisition. Comparatively, more than two decades ago when bandwidth was limited to about 2 Mbit/s, TUS could already be used successfully in obstetrics (Chan et al. 1999). Ten years ago, transmission of real-time ultrasound video footage to a remote phone was reported to be feasible even with inexpensive equipment without sacrificing image quality on 3G networks (Liteplo et al. 2010). Today, availability and wide coverage of 4G networks are considered standard in many countries and certainly in developed countries, where 5G is currently being rolled out more widely. However, low-bandwidth requirements are certainly an advantage, particularly in remote and isolated areas, as well as in countries that lack the financial resources to expand and/or maintain high-bandwidth networks.

Improving image quality with TUS

To further improve TUS images in sonographic evaluation, a quality assessment tool was developed to standardize the quality of images obtained (Bahner et al. 2011). An important feature of the tool is quantification of the sonographer's influence with respect to the final image quality. This approach can also be adopted for TUS. In addition, more recently, software-based applications have been introduced that support the teaching of knobology and handling of the probe (Kirkpatrick et al. 2016).

In many cases, optimizing imaging quality requires fine adjustments of the probe such as a two- or three-degree tilt or movement of the probe by just half a centimeter, which can often be difficult to communicate verbally. With the aforementioned "remote guidance" method, the remote operator is required to go through various steps to better ensure that.

Another method requires the operator to manually perform a tilt movement with the probe ($\pm 45^\circ$) whereby

Table 1. SWOT analysis of tele-ultrasound with a scope

Strengths	Weaknesses
• Bandwidth requirements are low for satisfactory image quality • Quality assessment tools are available for grading images • Access to imaging is possible in areas with limited health care infrastructure • Patients at home who are immobilized or with reduced mobility can be examined • There is no need for additional commuting to imaging facilities for patients • Uninterrupted end-to-end health care is available at a single-point location • Android/iOS compatibility allows imaging on vast majority of mobile phones • Handheld portable devices work as stand-alone devices without relying on additional computer hardware • Mobile apps are more user friendly compared with traditional ultrasound software • Some devices allow immediate sharing, saving and storing of images to a cloud storage • A selection of different ultrasound heads is available for different examinations (cost savings)	• Acquisition costs are high for individual practitioners • Software updates and compatibility are not guaranteed • Handheld devices often require an internet connection for full functionality • There are subscription fees for some services • Different ultrasound heads drive up the price • There are high battery drains for devices that are USB powered • USB-OTG (On-The-Go) port is needed for some handheld devices • Screen size is comparatively small for adjustments on mobile phones and smaller tablets • Cloud storage without multiple backup systems can result in the loss of data • Devices are more easily lost or stolen because of their small size
Opportunities	**Threats**
• Multiple expert opinions are available through sharing, recorded examinations or live-streaming • Health care systems save because of reduced costs for dedicated imaging centers • Diagnostic imaging capacity in underdeveloped countries is improved • Usage of ultrasound is expanded globally • Teaching in ultrasound imaging is expanded globally • Deployability is easy in disaster situations	• Legal regulations may restrict sharing of patient data/images • Regulations for telehealth do not exist or are vague in many countries • Android/iOS based handheld devices require high-end mobile devices for full compatibility of apps • Acquisition costs of devices may not allow for mass adoption in low-income countries • Purchase of ultrasound devices may be limited to licensed physicians/clinics • Whether devices are prone to error long-term under rough environmental conditions (such as high/low humidity, temperature fluctuations) is unknown

SWOT = Strengths, weaknesses, opportunities and threats.

all images of the organs below are captured and reconstruction in 3-D at the expert center (Arbeille et al 2014).

Moreover, robotic systems have been developed that allow the examiner to remotely control the orientation of the probe with a robotic arm (Vieyres et al. 2003; Arbeille et al. 2003, 2005, 2007; Courreges et al. 2005; Avgousti et al. 2016a, 2016b) for reliable echographic and echocardiographic imaging (Arbeille et al. 2014; Georgescu et al. 2016). Lastly, the echograph with probe orientation and echograph setting and function controlled from afar allow real-time tele-echography in a more comfortable manner, as the motorized probe volume is similar to a 3-D probe and thus much smaller than the robotic arm (Arbeille et al. 2016, 2018).

Storage of data and data safety

In a tele-guided setting, there are several ways to record and save images obtained and examination results. Various ultrasound documentation programs on portable devices and guidelines on how to appropriately document an ultrasound examination are available (Dormagen et al. 2015). Moreover, cloud-based monitoring systems are able to circumvent the requirement for bedside supervision and documentation, which may expand the supervision capacity of physicians studying and documenting ultrasound images (Canty et al. 2018). However, data security is a major concern with respect to cloud-based documentation applications though recent cloud-based products comply with EU laws on data protection and privacy.

A major threat for telemedicine in general is how patient data are stored and processed. As the value of personalized data increases and cheap data storage is abundantly available, telemedicine companies are able to record and analyze an entire set of parameters longitudinally in real time whereby patients' access to and control over these stored data are not guaranteed. These developments should spark an intense public discourse, which seems to, at best, lag behind the staggering pace of technological advancement.

Small number of ultrasound-trained medical professionals

A lack of health care professionals trained in ultrasound imaging remains a substantial challenge to be addressed. This is particularly true for low-income countries, especially in rural areas and/or areas with a low population density, where ultrasound-trained physicians are critically needed because of a general lack of other accessible advanced medical imaging diagnostics such as MR and CT imaging (LaGrone et al. 2012; Parker and Harrison 2015).

Costs and flexibility

Rapid technical development and competition in the field of medical software engineering have made costs manageable although prices vary significantly for devices and services offered (see Table 1) (Nascimento et al. 2016). However, a cost-efficient alternative is readily available tools such as web interfaces and commercial messenger tools. They can be used for telesupported ultrasound with the additional advantage of being independent of any specialized setting and having the flexibility to perform ultrasound (Robertson et al. 2017). However, consideration should be given to regulatory and data security concerns as indicated locally.

PORTABLE ULTRASOUND DEVICES

Depending on the setting, different ultrasound devices offer various advantages, yet to our knowledge, no detailed overview is available. Table 2 summarizes important tele-ultrasound aspects and is populated with more widely available handheld and portable ultrasound devices including specifications and details as provided on manufacturer websites in March 2021. Portable ultrasound devices are categorized as follows: handheld devices are solely the size of a traditional probe but therefore require an external device such as a mobile phone or tablet to depict the ultrasound image, whereby other portable devices resemble traditional laptops but often with special ports to connect to the probes (European Society of Radiology [ESR] 2019).

The provided overview of devices does not claim to be exhaustive with respect to neither the devices under consideration nor in terms of applied criteria. As an indicator of "portability," the weight, size and number of probes needed for different ultrasound examinations were included, allowing for a more accurate estimation of the overall acquisition costs as well as total size and weight of the equipment. Other indicators such as "ease of use" and "versatility" are reflected in connectivity, available applications and software supporting the device. Though image quality was not compared between devices, technical capabilities are listed within the technical features column, probe functionality and tools. For a wide rollout of those devices, total acquisition costs and longevity of the device, which includes free and long-term support of the software and mobile devices, are crucial, but are beyond the scope of this review, and were not taken into account as there were no data.

USE SCENARIOS OF TELE-ULTRASOUND

Trauma medicine

In the 1990s, ultrasound developed into a bedside application that was used in particular by emergency physicians for its ability to provide fast, accurate and critical information during initial patient evaluation and working diagnosis (Jehle et al. 1993). For the detection and characterization of pleural fluid, POCUS is more sensitive than physical examination and chest X-rays. FAST (focused assessment with sonography for trauma) has replaced peritoneal lavage as diagnostic tool of choice for abdominal trauma and is now considered standard practice (Song et al. 2013). One study reported that participants could perform a FAST scan in less than 6 min and were able to obtain good-quality images at the end of a 5-h course. It was concluded that even a small number of teleguided teaching sessions could significantly improve physician ultrasound skills in handling trauma patients. As ultrasound is widely used in emergency medicine, POCUS examinations such as FAST have been one of the first modalities successfully taught in TUS education (Song et al. 2013). Though promising in studies, TUS as a tool is underutilized in trauma medicine but may have a significant impact on mortality and the prevention of long term-disability. Moreover, studies have found that under remote guidance by an emergency physician, even ultrasound-naïve medical professionals are able to obtain interpretable FAST TUS images within 5 min that can be accurately assessed remotely (Boniface et al. 2011; Song et al. 2013; Marsh-Feiley et al. 2018). Even in a highly complex simulated disaster scenario with limited resources, commercially available mobile phones were adequate for physicians to accurately interpret FAST tele-ultrasound images within 90 s of video transmission (Boniface et al. 2011).

COVID-19

Over the last year, telehealth solutions in general became significantly more widely available and used in health systems globally as an infection control method in the COVID-19 pandemic to minimize health provider−patient interactions to the most necessary procedures (Adans-Dester et al. 2020). In agreement with previous reports, we strongly suggest the promotion of lung TUS to reduce nosocomial outbreaks as it reduces exposure of health care workers to patients and restricts patient movement (Buonsenso et al. 2020). Caution must be exercised when using ultrasound to examine patients with pneumonia. Depending on the stage and progression of pneumonia, trapped air could cause potential unknown damage, and caution must be exercised as there is no comprehensive evidence-based study in this area. Hence, it is recommended that the mechanical and thermal index levels be maintained as low as possible during the examination. Table 3 summarizes some advantages of lung ultrasound as it relates to COVID-19.

Standardization of lung ultrasound in COVID-19 pandemic

Interstitial lung diseases are among the most common consequences of COVID-19, and can cause acute respiratory distress syndrome (ARDS). To establish a

Table 2. **A and B** This table provides an overview of portable and handheld ultrasound devices with key technical features, integration of telemedicine software for tele-ultrasound, acquisition costs (RSVP), and available options to connect the ultrasound device. Connectivity for Android and iOS indicates that the supported mobile phones are using Android or iOS as operating system (usually only high-end devices are guaranteed to be fully supported); the display of the phones is used as the imaging display for the ultrasound examination whereby usually the mobile application needs to be downloaded and installed first through an app store (internet required). Rows with N/A (not available) indicate that there was no data available (or not by the manufacturer) or were not able to confirm the data such as the initial release date of a device. The "✓" sign indicates that the device does have the given feature, whereby "-" indicates that it does not have that feature to our knowledge. (✓) indicates that the technical feature is available.

Device	Company (release date)	Handheld device	Availability	Software	Telemedicine software	Connectivity			number of probes	Wireless probe
						Android	iOS	Other		
ACUSON P300	Siemens (2012)	-	Worldwide	Based on Windows XP	-	-	-	-	13	-
ACUSON P500	Siemens (2015)	-	Worldwide	N/A	(✓)(eSie-Link)	-	-	-	13	-
Butterfly iQ	Butterfly (2018)	✓	Worldwide	ButterflyIQ	✓(Built-in)	✓	✓	-	1	-(Wireless charging)
Clarius HD	Clarius (2019)	✓	Canada, EU, UK, USA	Clarius octal beam forming	✓(Clarius live)	✓	✓	-	8	✓
CX50	PHILIPS (2009)	-	Worldwide	QLAP quantification software	-	-	-	-	5	-
GE Vivid iq	GE Healthcare (2016)	-	Worldwide	N/A	-	-	-	-	11	-
iViz	FUJIFILM (2015)	✓	N/A	N/A	-	-	-	-	4	-
LOGIQ e	GE Healthcare (2014)	-	Worldwide	(Windows 10 based security system)	-	-	-	-	13	-
Lumify	PHILIPS (2015)	✓	Worldwide	N/A	✓(REACTS)	✓	✓	-	3	-
MicrUs Pro-L40S	Telemed Medical Systems	✓	Worldwide	N/A	✓	✓	-	Windows	3	-
SIFULTRAS-5.42	SIFSOF	✓	Worldwide	N/A	-	✓	✓	Windows (announced)	1	✓
Sonon 300L/300C	Healcerion	✓	EU, South Korea	N/A	-	✓	✓	-	2	✓
Vave health	Vave	✓	Worldwide	N/A	✓(Vave assist)	✓	✓	-	1	✓
Viamo sv7	Canon; Toshiba (2018)	✓	EU, UK	N/A	-	-	-	-	N/A	-
Vscan Extend	GE Health-care (2017)	✓	Worldwide	Self-built	-	-	-	-	2	-

Device	Technical Features							Tools	Probes	Size	Weight	Battery life	Price
	B-mode	M-Mode	Color-Doppler	2D	3D	other	DICOM						
ACUSON P300	✓	✓	✓	✓	-	CW, PDI,PW	✓	DTI, Panoramic imaging, SRI, Stress echo, THI	Convex, linear endocavity, intraoperative, laparoscopic, phased	15" screen	9 kg	1,5 h	~30.000 USD
ACUSON P500	✓	✓	✓	✓	-	CW, CFM, PDI, PW	✓	Auto flash artifact suppression technology, Cross-XBeam, DTI, ICE, panoramic imaging, SRI, stress echo	Convex, linear, endocavity, laparoscopic, phased, intracardiac	402 x 374 × 715 mm	7,2 kg	1 h	~32.000 USD
Butterfly iQ	✓	✓	✓	✓	-	PDI	✓	Ellipse measurement, linear, Midline marker, OB Calculations	Convex, linear, phased (one probe; Ultra-sound-on-Chip)	163 x 56 × 35 mm	309 g	> 2 h**	2.000 USD
Clarius HD	✓	✓	✓	-	-	(PW)	(✓)	Clarius AI = deep-learning-tool, veterinarian scanner	Cardial, endocavity micro convex, linear, multifunction	164 x 78 × 38 mm	392 g	1 h**	€ 4.450
CX50	✓	✓	✓	✓	(✓)		✓	CMQ, I SCAN, IMT, Sono CT, MVN, ROI, "support require button"	Cardiac sector, convex, linear, microcon-vex, sector TEE	15" screen, 86 × 413 × 356 mm	7,3 kg	N/A	~22.000 USD
GE Vivid iq	✓	✓	✓	✓	-	CW, PDI, PW	✓	4D imaging, anatomical M-Mode, AI-tools, SRI, (Stress echo), triplex imaging	Cardiac sector, convex, linear, endo cavity, micro convex, non-imaging Doppler, TEE	15.6" touch LCD, 64 × 390 × 362 mm	5,2 kg	1 h	~34.000 USD
iViz	-	✓	✓	✓	-	CW, PW	✓	Color HD technology, distance calipers, THI	Convex, linear, phased	7" screen, 183 × 117 × 27 mm	570 g	1 h**	N/A
LOGIQ e	✓	✓	✓	✓	(✓)	(CFM), PDI, (PW)	✓	Anatomical M-Mode, CHI, CrossXBeam, Panoramic screen, smart screen, split screen, SRI	Convex, linear, microconvex, phased, TEE	15"screen, 61 × 340 × 287 mm	4,6 kg	2 h	N/A
Lumify	✓	✓	✓	✓	-	-	✓	AutoSCAN, CrossXBeam, SonoCT, SRI, THI, vol-ume mode	Convex, linear, phased	***	96 g-135 g*	N/A	€ 6.500 (probe) € 100 (cable)
MicrUs Pro-L40S	✓	✓	-		(✓)	-	-	Panoramic imaging	Convex, linear, multifunction	***	200 g	N/A	€ 3.900
SIFULTRAS-5.42	✓	-	✓	-	-	PDI, PW	-	Area, distance, obstetrics measurements, puncture assist function	Multifunction (exchangeable head)	156 × 60 × 20mm	308 g	3 h	5.000 USD
Sonon 300L/300C	✓/✓	-	✓/-	-	-	-	✓	-	Convex, linear	78 × 223/216 × 41 mm	370g	3 h**	5.000 USD

(*continued on next page*)

Table 2 (***Continued***)

Device	Technical Features							Tools	Probes	Size	Weight	Battery life	Price
	B-mode	M-Mode	Color-Doppler	2D	3D	other	DICOM						
Vave health	✓	✓	✓	-	-	-	✓	Area and linear measurement, streams to multiple devices	Multifunction	169 × 54 × 38 mm	340 g	1 h**	99 USD / month (subscription)
Viamo sv7	✓	-	✓	-	-	-	✓	Built-in camera, Precision and ApliPure+, THI, TwinView	Frequency range: 1,5 - 12 MHz	12″ screen	N/A	3 h	N/A
Vscan Extend	✓	✓	✓	-	-	-	✓	Apps for protocols and measurements (Distance, volume, EF), TGC	Linear, phased	15″ screen, 168 × 76 × 22 mm (display)	321 g screen, 85 -120 g*	1 h**	4.995 USD

*weight depending on probe, **continuous scanning, *** size depending on probe.

Abbreviations: CFM (Color flow M-Mode), CHI (Code Harmonic Imaging), CMQ (Cardiac Motion Quantification), CW (Continuous Wave Doppler), EF (Ejection Fraction), DICOM (Digital Imaging and Communications in Medicine; a nonproprietary standard to facilitate the exchange of medical images and related data), ICE (Intra-Cardiac Echo), IMT (Intima-Media Thickness), MVN (Mitral Valve Navigator), OB (Obstetrics), PW (Pulsed Wave Doppler), PDI (Power Doppler Imaging), ROI (Region of Interest), SRI (Speckle Reduction Imaging), TEE (Transesophageal Echocardiogram), THI (Tissue Harmonic Imaging), TGC (Time Gain compensation).

Table 3. Advantages of ultrasound and tele-ultrasound in the examination and evaluation of patients with confirmed and/or suspected SARS-CoV-2 infection

- Evaluation of disease progression in pregnancy (Porpora et al. 2021)
- Confirmation of diagnosis in children (Gregori and Sacchetti 2020; Sainz et al. 2021)
- Much safer management procedures feasible for evaluation of suspected cases (Buonsenso et al. 2020)
- Prognostication and assessment of response to COVID-19 therapy without point-of-care ultrasound experts on site (Kulkarni et al. 2020)
- Remote assessment by experts of multiple recorded or live sessions and service for a much wider population
- Medical imaging in refugee camps and remote and not easily accessible areas (Adler et al. 2008; Leiner et al. 2020)
- Significantly lower cost compared with computed tomography scans (Kulkarni et al. 2020)

diagnosis for those diseases and evaluate the course and progression of the disease, but also to guide treatment, imaging, usually in the form of a CT scan of the chest, is required (Bernheim et al. 2020). The German professional societies for intensive care recommend systematic bedside examinations with ultrasound for severe COVID-19 patients who require intensive care.

Currently, it is suggested that lung ultrasound examinations be performed systematically by scanning the lung from medial to lateral or dividing the thorax into left and right (hemithorax) and subdividing each side into four additional quadrants (Volpicelli et al. 2012; Gargani and Volpicelli 2014; Kluge et al. 2020; Soldati et al. 2020). A standardized examination approach has been proposed by the ultrasound societies of Austria, Germany and Switzerland. It is suggested that chest CT-suspected lung changes caused by COVID-19 should be confirmed and compared by lung and thoracic sonography of the suspected areas (Ai et al. 2020).

CT: The gold standard for COVID-19 pneumonia?

Though by no means a portable solution, currently chest CT scans represent the gold standard in assessment of COVID-19 pneumonia and disease progression at this point (Kwee and Kwee 2020). However, lung ultrasound is considered a highly valuable alternative in many settings, and being portable, it offers a completely different set of opportunities for diagnosis and/or treatment. However, expert knowledge in assessing COVID-19 pneumonia is less widespread compared with chest X-ray or CT scans for various reasons (Borakati et al. 2020). Previous studies confirmed the accuracy of lung ultrasound in detecting the occurrence and development of lung inflammation in bacterial and viral pneumonia, as well as in acute respiratory distress syndrome. It was reported to be not inferior to chest X-ray and to have value in disease follow-up (Dietrich et al. 2015). In particular, POCUS was reported to be useful for the diagnosis of a SARS-CoV-2 infection (Gil-Rodrigo et al. 2020).

Lung ultrasound: A valuable alternative to CT scans

Lung ultrasound already has a dedicated niche, one that may expand. In immobilized patients, imaging already heavily relies on ultrasound in general as CT scans are not feasible because of the bulk and size of the device, which is not portable. Similarly, in pregnant women and children, CT scans are not routinely used because of the high radiation exposure (Wu et al. 2020). In those cases, the only meaningful option for imaging COVID lung manifestation is ultrasound and, thus, TUS. A recent study indicated that in women infected with SARS-CoV-2 during pregnancy and examined with lung ultrasound prior to giving birth and afterward with a CT for lung manifestations, a significant positive correlation between the two techniques was observed, and lung ultrasound is considered a safe alternative in pregnancy (Porpora et al. 2021). In children, the accuracy of lung ultrasound in detecting pediatric pneumonia of any etiology seems to be comparable in the context of COVID-19 and is limited. Further studies are needed to assess the usefulness of POCUS in children with COVID-19 (Sainz et al. 2021).

Safety measures for the examiner

Safe management procedures for the evaluation of suspected COVID-19 cases were suggested for lung ultrasound imaging at the bedside with standard personal protections per WHO indications. Those procedures can be similarly applied with health professionals executing lung TUS with a video consultation (Buonsenso et al. 2020). A more recent study found that robot-assisted TUS over 5G is feasible and offers a significant advantage, as it also protects the examiner, who is not necessarily a physician in TUS, entirely from SARS-CoV-2 infection. However, such sophisticated devices are out of reach for the majority of health care systems because of high acquisition costs, lack of portability and high requirements on mobile networks to operate optimally (Wu et al. 2020). Given the advantages of TUS, we consider imaging of COVID-19 a highly valuable tool in diverse settings, particularly in under-resourced health care systems and restricted and/or remote areas such as refugee camps, where portable ultrasound combined with a TH application may be the only viable option for accurate assessment and/or confirmation of COVID-19 pneumonia and imaging, respectively.

CONCLUSIONS

Telehealth is a valuable and valued tool for patients and providers alike. It has matured technologically to a point where its current theoretical limitations are now centered mostly on legal, regulatory and data privacy concerns. The COVID-19 pandemic has stimulated all areas of health care to identify ways to limit the spread of infection, and TH was naturally adopted early on in the pandemic as a tool for infection control that limits contact between patient and provider. As a result, TH saw a huge increase in demand and access to a wider medical audience and patients than ever before. Integrating TUS into TH, as a technologically sound tool in terms of diagnostic accuracy and image quality that is not inferior to traditional ultrasound examinations, is a logical progression to enhance TH capabilities. Consequently, adding ultrasound to the list of TH services offered by practitioners, clinics and mobile health companies might be a natural advancement of telemedicine. With respect to devices offering the greatest TUS value, multiple different aspects need to be considered, and purchasing decisions will depend on clinical setting and actual intended use. In the case of COVID-19 lung TUS, we anticipate that remote areas or areas with limited access to a functioning health care infrastructure, such as a refugee camp, may greatly benefit from its use. In this particular use case, a handheld ultrasound device supporting multiple mobile operating systems with low acquisition costs, a long battery life and included TH software for video consultations might be best equipped to deal with such a diverse patient population as found in refugee camps. Though studies have reported the benefits of TUS in general, large-scale studies are needed in the field to further explore weaknesses and strengths in different use scenarios, obstacles with the equipment and acceptance by patients and providers. For wider adoption of TUS, private TH companies and clinics need to find a common standard that would allow different TUS devices to live stream and capture ultrasound images instead of proprietary software solutions from individual ultrasound device manufacturers.

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