Journal of Digital Imaging (2019) 32:841–848
https://doi.org/10.1007/s10278-018-0157-9

Remote Real-Time Ultrasound Supervision via Commercially Available and Low-Cost Tele-Ultrasound: a Mixed Methods Study of the Practical Feasibility and Users' Acceptability in an Emergency Department

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Published online: 26 November 2018

Abstract
Minor emergency departments (ED) struggle to access sufficient expertise to supervise learners of lung and cardiac point-of-care ultrasound (POCUS). Using tele-ultrasound (tele-US) for remote supervision may remedy this situation. We aimed to evaluate the feasibility of real-time supervision via tele-US when applied to an everyday ED clinic. We conducted a mixed methods study that assessed practical feasibility, determined performance, and explored users' acceptability of supervision via tele-US. Technical performance was assessed quantitatively by the ratio in mean gray value between images on site and as received by the supervisor, and by after-compression frame rate. Qualitatively, 12 exploratory semi-structured interviews were conducted with exposed junior doctors and supervisors. Remote supervision via tele-US was performed with 10 junior doctors scanning 45 included patients. During performance assessment, neither alternating internet connection nor software significantly changed the mean gray value ratio. The lowest median frame rate of 4.6 (interquartile range [IQR]: 3.1–5.0) was found by using a 4G internet connection; the highest of 28.5 (IQR: 28.5–29.0) was found with alternative computer and local area network internet connection. In interviews, supervisors stressed the importance of preserving frame rate, and junior doctors emphasized a need for shared ultrasound terminology. In the qualitative analysis, setup mobility, accessibility, and time consumption were emphasized as being of key importance for future clinical implementations. Remote supervision via a commercially available and low-cost tele-US setup is operational for both junior doctors and supervisors when applied to lung and cardiac POCUS scans of hospitalized patients.

Keywords Point-of-care ultrasound · Tele-ultrasound

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10278-018-0157-9) contains supplementary material, which is available to authorized users.

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Introduction

Lung and cardiac point-of-care ultrasound (POCUS) is considered beneficial for initial evaluation of patients with dyspnea, shock, chest pain, cardiac trauma, and cardiac arrest in the emergency department (ED) [1, 2]. Due to high operator dependency, appropriate training is necessary to ensure quality in this discipline [3]. However, lack of experienced personnel impedes minor hospitals from providing sufficient supervision.

Audio-visual conferencing of ultrasound (US) examinations, referred to as tele-ultrasound (tele-US), has recently been described as a remote outreach with limitless potential, and this may hold the future remedy for remote teaching, mentoring, and diagnosing in real time [4].

Previous studies have demonstrated the feasibility of tele-US in a trauma setting, in fetal scans, and in a pediatric population. Resuscitating doctors, particularly residents, in the trauma setting were satisfied when receiving real-time supervision for the Extended Focused Assessment with Sonography for Trauma (EFAST) protocol. Remotely supervised ED pediatricians also produced reliable and timely diagnoses when compared with pediatric radiologists in abdominal ultrasound [5, 6]. However, to our knowledge, no prior studies have evaluated real-time supervision of junior doctors performing lung and cardiac POCUS in the ED.

The current study's aim was twofold:

1) to quantitatively describe the technical performance of tele-US in the ED using commercially available, low-cost equipment; and
2) to qualitatively explore supervisors' and junior doctors' acceptability of supervision via tele-US.

Methods

To embrace technical, practical, and acceptance aspects of feasibility, we employed a mixed methods approach following the reporting recommendations of O'Cathain et al., an EQUATOR Network reporting guideline [7]. The study's two aims are reported separately, and equally emphasized, in the "Methods" and "Results" sections. Finally, both are integrated in a joint discussion.

Quantitative

Practical Feasibility A tele-US setup was established and temporarily implemented to include junior doctors in their first 6 months of postgraduate employment, in the emergency department of the Regional Hospital West Jutland in the Central Denmark Region region. This ED receives approximately 40,000 patients per year.

Before inclusion, doctors, first, attended a two-day US course of basic US physics, focused assessment with sonography for trauma (FAST), peripheral US-guided vascular access, and cardiac, lung, and abdominal POCUS; second, performed 60 or more US examinations; and third, got certified in the course-modalities. Then included doctors performed lung and cardiac POCUS scans on ED patients under remote supervision from one of two supervisors with an US experience exceeding 500 examinations, 5 years of clinical experience and extensive US teaching experience. During supervision, the supervisors were located at a different hospital or at home. All lung and cardiac POCUS scans followed the same protocol including four cardiac views (subcostal four-chamber, parasternal long and short axis, and apical four-chamber views) and eight lung views as described by Volpicelli et al. [2].

Commercial and low-cost equipment was prioritized in the decision about the technical solution. The final solution, concerning equipment connections, is illustrated in Fig. 1, and the specifications are described in Table 1. The supervisor's view, with a two-angle overview video and US image, is shown in Fig. 2.

Of all components, internet connection, on-site laptop, and software were expected to influence setup performance and were regarded as practically changeable. Hence, these three were changed for various alternatives and the outcomes were measured on five different days while keeping other components constant; alternative on-site laptops and software are presented in Table 1, internet connection in Table 2. To quantify the transmitted video quality, we measured frames per second (FPS) and mean gray value (MGV) difference. FPS was manually counted as the mean frames per second during 10 s of remote computer screen-recordings. MGV difference is a surrogate for the amount of lost information between before and after image compression [8]. MGV estimates were measured using ImageJ (National Institutes of Health, USA) and reported as a ratio between the MGV of remote screenshots and US system screenshots' MGV (the closer to zero, the more information is lost during compression) [9].

Statistics All data were reported as median values with 25 and 75% quartiles (interquartile range [IQR]) and were compared using the Kruskal–Wallis one-way analysis of variance. Data analysis was performed using Stata 14 (Statacorp, Texas, USA).

Qualitative

Acceptability Junior doctors' and supervisors' acceptability were unfolded by exploratory semi-structured interviews addressing their impression, satisfaction, and perceived benefits [10]. Interview guides, for doctors and supervisors respectively, were developed based on first author's experiences during remotely supervised US examinations (for interview guides, see

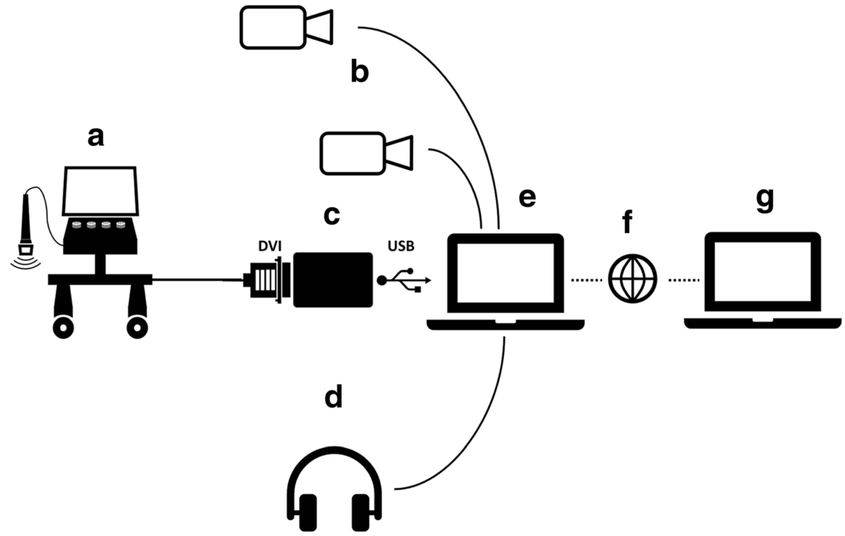


Fig. 1 Tele-ultrasound setup: (**a**) ultrasound system, (**b**) web cameras, (**c**) video grabber, (**d**) headset, (**e**) on-site laptop, (**f**) internet connection, and (**g**) remote laptop

online resource 1); in addition to using interview guides, interviewees were encouraged to discuss additional topics important to them. All doctors and supervisors participating were given study information, guaranteed anonymization, and consented to participate before the first author interviewed doctors by telephone or face to face. Based on these interviews, the interview guide for supervisors was modified, and in-depth supervisor interviews were conducted. All interviews were recorded, transcribed verbatim, and independently examined by the first and second author. Subsequently, based on the first author's previous tele-US experiences and tendencies emerging during analysis, all statements were coded into four topics: a) technical solution, b) learning perspective, c) patient–doctor communication, and d) supervisor–doctor communication. Statements

Table 1 Equipment specifications: USB (universal serial bus), RAM (random-access memory), and VoIP (Voice over Internet Protocol)

Function	Name	Company
Ultrasound system	Vivid S6 M4S Phased Array Transducer, 1.5–4.5 MHz	GE Healthcare, Chicago, Illinois, USA
USB video grabber	DVI2USB 3.0	Epiphan Video, Ottawa, Canada
Onsite laptops	MacBook Pro 2,7 GHz Intel Core i5 processor, 8 GB 1867 MHz DDR3 RAM, macOS Sierra (Version 10.12)	Apple, California, USA
	Vision B-Series B7520 Intel Core i7 4712MQ CPU 2.3 GHz processor, 8 GB RAM, Windows 10	MM Vision A/S, Slagelse, Denmark
	Lenovo P50 laptop 2.8 GHz Intel Xeon processor, 32 GB RAM, Windows 10	Lenovo Group, Morrisville, North Carolina, USA
Web cameras	Logitech HD Pro C920	Logitech, Romanel-sur-Morges, Schwitzerland
	Logitech HD Webcam C525	—‖—
Headset	Major II Bluetooth	Marshall, Bletchley, Milton Keynes, England
Software	Manycam Studio Version Webcam software	Visicom Media, Inc., Brossard, Quebec, Canada
	Skype VoIP software	Skype Technologies, Luxembourg, Luxembourg
	Epiphan Capture Recording software	Epiphan Video, Ottawa, Canada
Remote laptop	MacBook Pro 2.4 GHz Intel Core i5 processor, 8 GB 1600 MHz DDR3 RAM, macOS Sierra (Version 10.12)	Apple, California, USA
	Lenovo ThinkPad T440 1.6 GHz Intel Core i5 processor, 4 GB RAM, Windows 10	Lenovo Group, Morrisville, North Carolina, USA

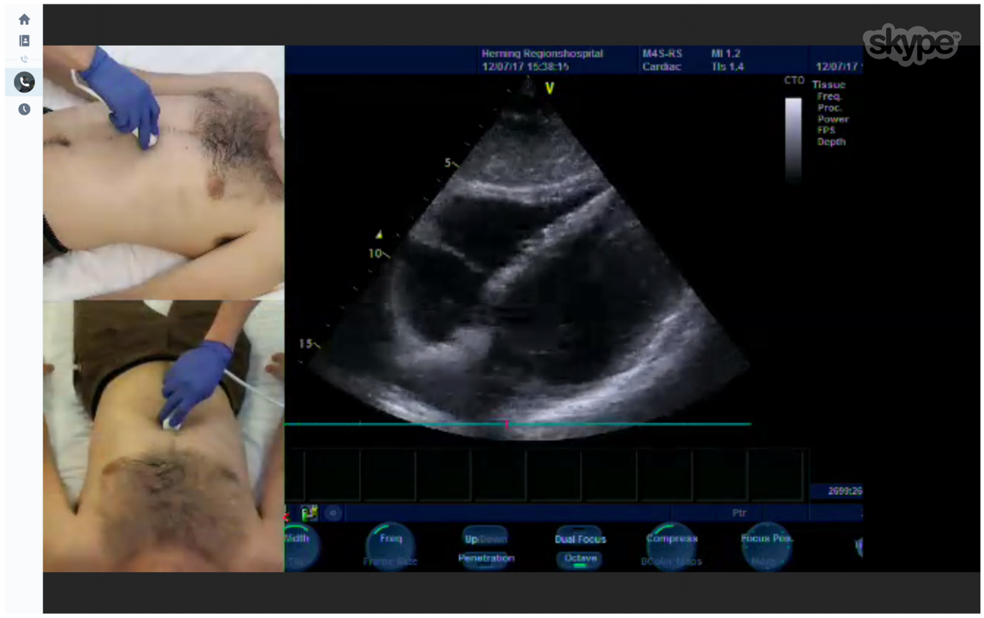


Fig. 2 Supervisor's view: two-angled overview video (left) and US image (right)

were only included if there was agreement between SHJ and ID regarding relevance and topic. Based on citations, SHJ and ID drew conclusions by consensus and reported the results.

Ethics

The study was exempted from the informed consent requirements by the Regional Ethics Committee, Central Denmark Region (inquiry 153/2016). The Danish Data Protection Agency approved data handling (case no. 1-16-02-175-16). Before enrolment, all participants gave oral informed consent, and patients were free to exit the project at any time. Additional informed consent was obtained from all individual participants for whom identifying information is included in this article.

Results

Quantitative

Practical Feasibility From October 2016 to January 2017, 10 junior doctors (six male) were included; performing 3–5 lung and cardiac POCUS scans each. Two supervisors supervised 20 and 23 examinations, respectively. Of 58 included patients, 45 were scanned by a tele-supervised doctor. One patient was lost, specifically due to the unavailability of a supervisor. Similarly, one other supervised examination was canceled due to the urgent need of the US system elsewhere. The remaining 11 screened patients were hindered from inclusion by unexpected changes in patient management or doctor unavailability.

As illustrated in Fig. 3, FPS was significantly lower for the screen of the tele-supervisor with 4G remote Internet connection (4.6; IQR: 3.1–5.0) when compared to local area network (LAN) (9.5; IQR: 7.1–9.7). Frame rates performed by each of the alternate computers significantly outperformed the default computer (MacBook Pro) ($p < 0.01$). FPS significantly increased as a direct consequence of lowering the number of running software applications ($p < 0.01$).

Figure 4 illustrates that neither alternating the Internet connection nor the software significantly changed the MGV ratio. The Skype-only solution showed a tendency toward less information loss due to compression. Exchanging the default

Table 2 Internet speed: Internet speed was measured using speedtest.com by Ookla and presented as median with interquartile range (IQR). ms (milliseconds), Mbps (megabit per second), LAN (local area network), Wi-Fi (wireless local area network), and 4G (mobile telecommunications technology)

Internet connection	Network	Ping (ms)	Download (Mbps)	Upload (Mbps)
Onsite Internet connection	LAN	8 (7; 12)	327 (251; 361)	316 (303; 359)
Remote Internet connection	LAN	7 (7; 8)	94 (94; 94)	94 (94; 94)
	WiFi	12 (12; 13)	57 (56; 57)	11 (11; 11)
	4G	39 (32; 51)	13 (4; 26)	2 (1; 8)

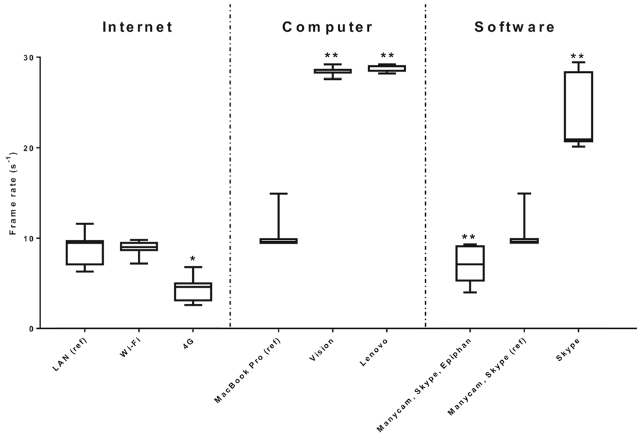


Fig. 3 Frames per second: Median, IQR, minimum, and maximum. ref.: equipment used in the clinical implementation, and the reference used in statistical comparison. * = $p < 0.05$, ** = $p < 0.01$ from Kruskall–Wallis one-way analysis of variance

computer (MacBook Pro) for each of the two alternatives resulted in a significantly higher MGV ratio.

Qualitative

Acceptability Interviews were conducted with all 10 junior doctors from November 2016 to February 2017, after their final exposure to tele-US, and with the two supervisors in April 2017. On average, doctor interviews lasted 11 min, ranging from 7 to 16; supervisor interviews lasted 35 and 47 min.

In the following, main findings from the semi-structured interviews are reported within the four topics: (a) technical solution, (b) learning perspective, (c) patient–doctor communication, and (d) supervisor–doctor communication.

a) Technical solution

In general, the present setup was perceived as operational. The audio was clear, and the two-angle video stream helped the supervisors guide the probe and the patient into the right positions. Our expected primary learning objective for the doctors was image acquisition, but interpretation quickly became an issue. Supervisors found it difficult to interpret the images, especially cardiac contractility due to limited frame rates:

> "When frame rate was poor, it was extremely difficult (…) I could not see the dynamics in the picture, and that made it difficult to assess whether it was a proper image and also to appraise pathologies in the image." (Supervisor)

For future clinical implementation, accessibility, time consumption, and mobility were regarded as being of key importance:

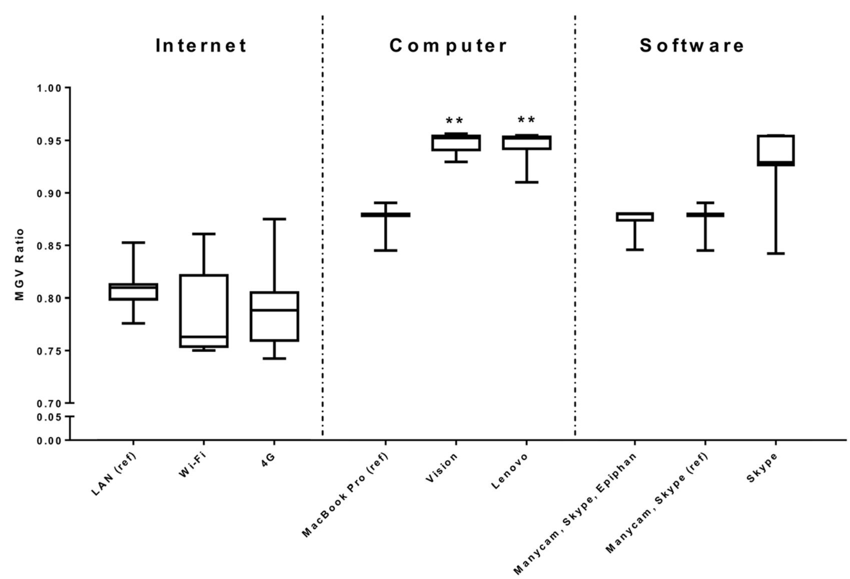
> "It must be fairly accessible to get started; that, I think, is the most important." (Doctor)

b) Learning perspective

The doctors expressed a lack of confidence in their ability to perform US scans, but they seemed to feel more confident when using tele-US:

> "In my own opinion, I struggled to obtain the correct images and felt like: 'Oh, is this good enough, and can I

Fig. 4 Mean gray value (MGV) ratio: Median, IQR, minimum, and maximum. ref.: equipment used in the clinical implementation, and the reference used in statistical comparison. * = $p < 0.05$, ** = $p < 0.01$ from Kruskall–Wallis one-way analysis of variance



depend on my own findings?' Then, I think, it worked really fine to be tele-supervised." (Doctor)

In terms of learning effect, the doctors perceived the use of tele-US as support, refinements, and minor improvements. The supervisors echoed this view by expressing that they found it hard to detect major improvements in the doctors' ability.

A recurring theme in the interviews was interpretation and potential pathology. In the direct context of an examination, this discussion was much appreciated:

"…discussing what you actually saw on the images and not just the part of achieving the optimal image, but also discussing what you saw and why and how and what you could think of it." (Doctor)

c) Patient–doctor communication

The addition of a physically absent supervisor influenced the relation between the doctor and the patient. Some doctors felt that the headset limited their communication with the patient:

"…you probably compromise the actual communication with the patient when you feel you have one in the ears to talk to also." (Doctor)

Other doctors argued that communication was not their focus during the examination anyway. Despite potential limitations, the doctors were unanimous that headsets were preferred over a speakerphone due to discretion involved in any discussion of pathology.

d) Supervisor–doctor communication

For both supervisors and doctors, agreement of terminology stood out as fundamental for successful remote supervision.

"You easily get confused; when it's (the supervisor) on the phone, there has to be definite instructions for what tilt means, what rotation means, and which views." (Doctor)

However, besides terminology, a surprisingly large variety of perspectives was expressed about supervisor–doctor communication.

In the comparison of on-site and remote communication, interviewees expressed advantages and disadvantages of both. Overall, on-site communication was preferred over remote. One supervisor explained an advantage of on-site communication:

"There are also all sorts of other communication taking place at a subconscious level instinctively." (Supervisor)

Being unable to use nonverbal communication is a downside of remote communication; for instance, supervisors indicate understanding during on-site supervision by gesticulating with their hands.

In contrast, in relation to knobology and probe manipulation, both supervisors described how they would normally try to keep their hands in their pockets, but still regularly fail to do so, during on-site supervision. Relating to that dilemma, some interviewees argued that remote supervision could be an advantage:

"…the advantage of tele-supervision is that the supervisor does not take the probe out of your hands. By that, you do not learn anything. So that is the advantage." (Doctor)

Another challenge in remote communication compared to on-site communication is the inevitable time lapse in the conversation. During the inclusion process, the supervisors experienced a need for changing their approach in order to address this challenge:

"If the instructor is to help optimizing an image, it can sometimes be beneficial to issue an instruction by saying, 'Keep the probe still as it is now, and then…'" (Supervisor)

A second perspective that influences supervisor–doctor communication, includes the personal characteristics of supervisors and doctors. A doctor discovered a difference in the supervisors' general approach to supervision:

"The two ways [of the different supervisors] were different. One had sort of a certain image in mind of a system you should go through. Whereas, the other, he let one search a bit longer." (Doctor)

In addition, patience was underlined as a determinant for effective communication when supervisors were asked about doctor characteristics.

Finally, the relation between the doctor and supervisor also affected the communication. One supervisor elaborated on the relation's impact:

"When they (the doctors) discovered, during the two first times, that it was quite friendly, they were more relaxed, I think. Maybe we communicated more easily because they gave me, as a supervisor, more of their feedback, too." (Supervisor)

Discussion

This mixed methods study demonstrated a functional tele-US setup with satisfied users who perceived it as operational and beneficial. Integration of the results revealed that frame-rate preservation is important for remote supervisors to interpret cardiac scans. Furthermore, we did find advantages, challenges, and future improvements to consider in tele-US implementations.

According to the interviews, supervisors felt unable to interpret cardiac motion in transmissions with inferior frame rates. In performance measurements, frame rates were estimated to be a median of 9.6 FPS (IQR: 9.5–9.9). In contrast to our findings, McBeth et al. found a 3G connection sufficient for supervision and interpretation of the EFAST protocol [11]. In our opinion, this finding reflects different interpretational dependency on motion and resolution for US modalities. Interpretation of cardiac US is more dependent on motion than the EFAST exam.

When using a Skype-only solution, we found a higher frame-rate preservation (20.9 FPS; IQR: 20.7–28.3). The drawback of this solution is the loss of scene views, which were found helpful during supervision. However, Boniface et al. reported scene views unnecessary when applied to supervision of FAST examinations [12]. We interpret this discrepancy as a result of using different examinations. The probe placement in the FAST protocol is strict, whereas the cardiac examination is more complex, and visualization of the probe and patient are necessary for the supervisor to guide.

An alternative future solution for cardiac imaging could be the application of a half real-time, half asynchronous system, where supervision of image acquisition is performed in real time and image interpretation is performed afterwards.

Doctors identified mobility, accessibility, and time consumption as challenges. Determinants of tele-US mobility include the US system, Internet connection, web camera, and headset connectivity. To avoid connection dropouts, we decided to use cable-based solutions, such as universal serial bus (USB)-connected web cameras and to maximize on-site Internet speed, we used LAN Internet connection. These two factors were mostly responsible for the setup being immobile. In retrospect, our performance measurements indicate that WiFi may provide frame rates as high as LAN. In addition, smaller mobile US systems than the one applied in the present study are available; McBeth et al. applied such an US system and a head-mounted web camera in remote and out-of-hospital settings and found it easy to implement [13]. WiFi Internet should be preferred over LAN in future implementations.

Doctors found that supervision via tele-US is a good alternative to on-site supervision in instances where on-site supervision was not feasible. Tele-US and on-site supervision require the same net workload, but tele-US has potential to increase the pool of competent supervisors. Another advantage mentioned was the inability of supervisors to take the probe out of the doctors' hands; in contrast, supervisors were unable to use nonverbal communication and hand gestures. Verbal communication plays a major role within remote supervision, and the shared terminology instruction made prior to supervision was important for doctors and supervisors. Equally, Dyer et al. found that their supervision recipients appreciated instructions given sequentially in simple nontechnical language [5]. This calls for future studies and tele-US implementations to explicitly instruct participants in the use of clear command-based communication and to focus on speaking-rights and pauses. Several questions remain unanswered at present. Further work is needed to evaluate the effect on actual patient care, provide cost analyses, and to explore whether it can be used clinically or only for educational purposes.

The strengths of the present study are mainly attributed to the applied study design, allowing a wide scope with various feasibility agendas. The pragmatic temporary implementation within the clinic further heightens the external validity and reduces the knowledge gap in clinical decision-making.

Our study has some limitations. A more precise picture could have been drawn of the technical performance by doing measurements during each actual clinical implementation. The qualitative results might have been skewed by interviewees curbing their criticism due to a collegiate interviewer–interviewee relation. With this in mind, interview guides were prepared in a manner that encouraged interviewees to relate to potentially negative topics. Some degree of interviewee recall bias might also have been present.

Conclusion

Remote supervision via a commercially available and low-cost tele-US setup is operational for both junior doctors and supervisors when applied to lung and cardiac POCUS scans of hospitalized patients. Frame-rate preservation, clear communication, and mobility and availability of the technical setup were identified as key features and should receive attention in future tele-US implementations.

Acknowledgements The authors thank the Emergency Department, Regional Hospital West Jutland and doctors and patients participating in the study. The authors especially want to thank Professor Bo Løfgren and Associate Professor Lars Bolvig for participation in project discussions.

Author Contribution All authors contributed in the planning of the work described. SHJ, RA, and JW conducted the quantitative data collection, and SHJ and ID conducted the qualitative data collection. SHJ, ID, and JW analyzed and interpreted the results. All authors critically revised the content and approved the final manuscript.

Funding This work was supported by the Holger & Ruth Hesse's Mindefond and the Knud og Edith Eriksens Mindefond. The funders had no role in the design and conduct of the study; collection, management, analyses, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

Compliance with Ethical Standards

Conflict of Interest The authors declare that there are no conflicts of interest. This research was not sponsored by any company. None of the authors have any financial relationship with Apple; Lenovo; MM Vision; Visicom Media; Logitech; GE Healthcare; Marshall; Epiphan Video; Skype; National Institutes of Health, USA; Ookla; or any of their products. The authors have full control of data.

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