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Diagnostic ability of hand-held echocardiography in ventilated critically ill patients

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Abstract

Study objectives To compare the diagnostic capability of recently available hand-held echocardiography (HHE) and of conventional transthoracic echocardiography (TTE) used as a gold standard in critically ill patients under mechanical ventilation.

Design A prospective and descriptive study.

Setting The general intensive care unit of a teaching hospital.

Patients All mechanically ventilated patients requiring a TTE study with a full-feature echocardiographic platform (Sonos 5500®; Philips Medical Systems, Andover, MA, USA) also underwent an echocardiographic examination using a small battery-operated device ($33 \times 23\,cm^2$, 3.5 kg) (Optigo®; Philips Medical Systems).

Interventions Each examination was performed independently by two intensivists experienced in echocardiography and was interpreted online. For each patient, the TTE videotape was reviewed by a cardiologist experienced in echocardiography and the final interpretation was used as a reference diagnosis.

Results During the study period, 106 TTE procedures were performed in 103 consecutive patients (age, 59 ± 18 years; Simplified Acute Physiology Score, 46 ± 14; body mass index, $26 \pm 9\,kg/m^2$; positive end-expiratory pressure, $8 \pm 4\,cmH_2O$). The number of acoustic windows was comparable using HHE and TTE (233/318 versus 238/318, $P = 0.72$). HHE had a lower overall diagnostic capacity than TTE (199/251 versus 223/251 clinical questions solved, $P = 0.005$), mainly due to its lack of spectral Doppler capability. In contrast, diagnostic capacity based on two-dimensional imaging was comparable for both approaches (129/155 versus 135/155 clinical questions solved, $P = 0.4$). In addition, HHE and TTE had a similar therapeutic impact in 45 and 47 patients, respectively (44% versus 46%, $P = 0.9$).

Conclusions HHE appears to have a narrower diagnostic field when compared with conventional TTE, but promises to accurately identify diagnoses based on two-dimensional imaging in ventilated critically ill patients.

Keywords critical care, diagnostic techniques and procedures, echocardiography, echocardiography Doppler, therapeutics

HHE = hand-held echocardiography; ICU = intensive care unit; TEE = transesophageal echocardiography; TTE = transthoracic echocardiography.

Introduction

Echocardiography has become a powerful noninvasive imaging modality for the assessment of critically ill patients over the past few years. This technique provides unparalleled morphological and hemodynamic information that leads to frequent therapeutic changes in the acute management of patients hospitalized in the intensive care unit (ICU) [1–3].

Most recently, progress in electronics enabled the emergence of echocardiographic systems the size of a laptop computer. These compact, battery-operated echocardiography machines can be hand-held and easily used by physicians at the patient's bedside, even in a crowded ICU setting. The ease of performance and relatively low cost of emergent portable echocardiography systems allow one to potentially use these devices in various circumstances, whenever patient condition abruptly deteriorates. In addition, portable ultrasound units have the potential to extend the physical examination, allowing a more rapid assessment of cardiovascular anatomy, function and physiology, and may be adequately suited for routine use in emerging strategies of focused ultrasound examination [4].

Hand-held echocardiography (HHE) has mostly been tested against advanced feature echocardiographic platforms in spontaneously breathing cardiology outpatients or during hospital rounds, and in coronary care units [5–13]. Little information is yet available in critically ill patients who are mechanically ventilated. Accordingly, we sought to evaluate the diagnostic capability and potential therapeutic impact of HHE in ventilated patients hospitalized in a general ICU, compared with standard conventional transthoracic echocardiography (TTE).

Methods

Patients

During a 6-month period, all consecutive patients who were under ventilation and required a TTE study in the general ICU of our institution were eligible. In each patient, the precise indication(s) for performing an echocardiogram was recorded (e.g. evaluation of left ventricular systolic function, pericardial effusion, acute valvular regurgitation, etc.).

The reason for admission, the Simplified Acute Physiology Score, the body mass index, and the presence of factors other than mechanical ventilation known to interfere with image acquisition (i.e. supine position, tube drainage, bandage, chest deformity, abdominal meteorism, subcutaneous emphysema) were noted for all patients.

Transthoracic echocardiography

Each patient underwent successively two TTE studies within 30 min of each other, according to the availability of imaging systems and operators: the first using a hand-held device (Optigo®; Philips Medical Systems, Andover, MA, USA), and the other TTE study using a full-feature echocardiographic platform (Sonos 5500®; Philips Ultrasons). Ongoing treatment was not changed between both echocardiographic examinations. A transesophageal echocardiography (TEE) was performed whenever required to solve clinical problems [14]; namely, when TTE was inconclusive or when TTE yielded a negative result contrasting with a high clinical index of suspicion. This observational study was accepted by the Ethics Committee of the Société de Réanimation de Langue Française (Paris, France), which waived the need for informed consent.

Figure 1

Photograph of the Optigo® device (Philips Medical Systems, Andover, MA, USA), the hand-held ultrasound system used in the present study. A 20 cm ruler is shown at the bottom of the device.

A single investigator (PV) performed all portable echocardiograms. The portable system is a small battery-operated device ($33.0 \times 22.8 \times 8.9\,cm^3$, 3.5 kg) connected to a 2.5 MHz phased array transducer (Fig. 1). This system provides two-dimensional and color Doppler echocardiographic images on a $14 \times 10.5\,cm^2$ screen. An electrocardiogram, and M-mode, pulsed-wave and continuous Doppler are not available. Imaging gain and depth controls can be adjusted, and measurements can be performed on two-dimensional images using electronic calipers. Images can be frozen and scrolled for review, and still frames (but not loops) can be digitally stored on a flashcard. Another investigator (CC) independently performed a conventional TTE study that was recorded on videotape.

Both investigators are intensivists with level 3 training in echocardiography [15]. They were not aware of the findings yielded by the alternative imaging modality, but both investigators were provided with the clinical history and available results of first-line tests (e.g. biology, chest X-ray). No preset imaging protocol was followed, but the three standard transthoracic windows (i.e. parasternal, apical and subcostal) were systematically screened in each patient.

Echocardiographic studies were mainly focused on solving the raised clinical problems, but a complete examination was concisely performed according to imaging quality. Both pleural spaces were also assessed when indicated, using a previously described technique [16]. In each patient, the duration of the echocardiographic study required to answer clinical questions (excluding installation time and study report), the number of acoustic windows available (0–3 per patient) and therapeutic changes related to the results of the examination were noted.

Analysis and definitions

As a common practice in our institution, all echocardiograms were interpreted online by the operators. However, the results of conventional TTE were only given to the attending physician at the bedside and were potentially used to alter ongoing therapy. Trivial valvular regurgitations identified using color Doppler mapping were not considered clinically relevant in the data analysis. Pulmonary hypertension was deemed significant when systolic pulmonary pressure estimated from the maximal Doppler velocity of the tricuspid regurgitation during conventional TTE examination exceeded 40 mmHg.

For the purposes of the present study, conventional TTE was considered the reference diagnostic method. All the videotapes of TTE studies were independently reviewed by a cardiologist with level 3 training in echocardiography [15] who was not directly involved in the study. When the cardiologist's interpretation differed from that obtained at the patient's bedside by the investigator who performed the TTE study, the videotape was reviewed by both physicians until a consensus was reached.

In the analysis, each response to clinical problems was considered positive, negative, or undetermined (i.e. no response) when the imaging quality or the device technology failed to provide a definite diagnosis. Diagnostic capability was defined by the percentage of solved clinical problems (i.e. the number of true positive or true negative responses/the number of clinical questions). Additional diagnoses yielded by echocardiography were defined as findings fortuitously observed and indirectly related or unrelated with the clinical indication. This additional information was classified as major or minor diagnoses according to their clinical relevance. Typically, major diagnoses resulted in definite changes in patient management (treatment, diagnostic evaluation) or prognosis, whereas minor diagnoses had no substantial impact. The therapeutic impact corresponded to actual changes in acute care that resulted directly from TTE studies, or to potential changes following HHE.

Statistics

The results of HHE and conventional TTE were compared in each patient. The number of acoustic windows available, the duration of the study, the diagnostic capability, the frequency of additional diagnoses and the therapeutic impact provided by both echocardiographic approaches were compared. Quantitative parameters were compared using a paired *t* test or a Wilcoxon signed rank test in the absence of a normal distribution. Qualitative variables were compared using the chi-squared test, with Yates' correction for continuity when necessary. Results are expressed as means ± standard deviation, and $P < 0.05$ was considered significant.

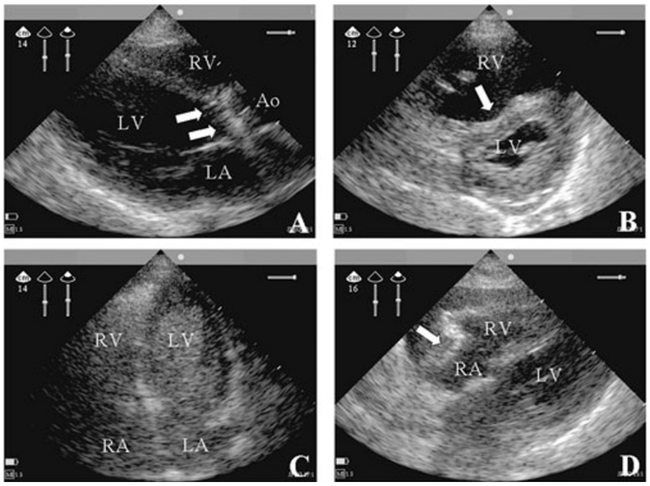
Results

During the study period, 154 out of 448 consecutive patients (34%) hospitalized in the ICU of our institution underwent a TTE. Among them, 36 spontaneously breathing patients were excluded from the analysis and 15 ventilated patients were not enrolled in the study due to the absence of one of the investigators. Finally, 106 echocardiographic studies were performed in 103 mechanically ventilated patients (age, 59 ± 18 years; males/females, 57/47; Simplified Acute Physiology Score, 46 ± 14; body mass index, 26 ± 9 kg/m^2; positive end-expiratory pressure, 8 ± 4 cmH_2O), with three of the patients undergoing two examinations. Sixty-four patients (62%) were admitted to the ICU for a medical condition, 24 patients (23%) for complicated surgery, and the remaining 16 patients (15%) for multisystem trauma. The clinical settings that led to performance of a transthoracic echocardiography were an acute respiratory failure associated or not with acute circulatory failure ($n = 34$), a shock ($n = 31$), a chest trauma ($n = 13$), a cardiac arrest ($n = 8$), potential cardiac donors ($n = 9$), a suspected endocarditis ($n = 8$), or a systemic arterial embolism ($n = 3$).

Despite the presence of factors known to substantially alter the imaging quality in the study population (mean, 1.7 ± 0.9 factors; range, 1–4), the number of acoustic windows deemed adequate for image interpretation was comparable using HHE and conventional TTE (233/318 versus 238/318, $P = 0.72$). No image was obtained in only 14 patients examined using the hand-held device (13%), and in 13 of them during the conventional TTE examination. Examples of two-dimensional and color Doppler still frames obtained using the portable system are shown in Figs 2 and 3.

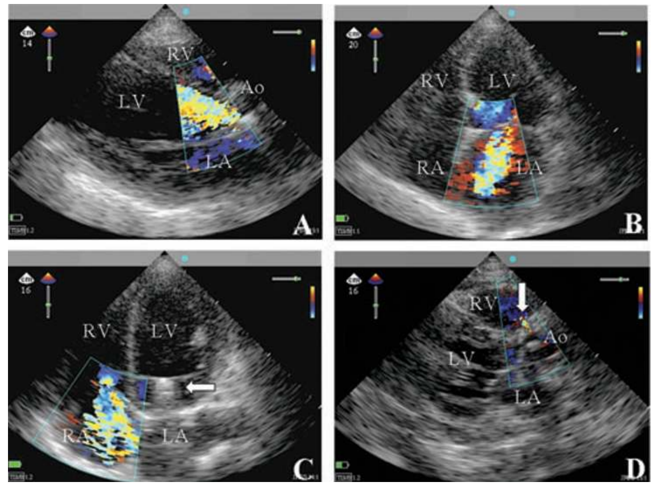
The mean time required for completing the examination was consistently shorter with the portable device when compared with the advanced feature system (5 ± 4 min versus 9 ± 5 min, $P = 0.001$). In addition to the 229 clinical questions that indicated echocardiography, the miniaturized system and TTE allowed 13 and 22 additional diagnoses, respectively. The overall diagnostic capability of HHE (i.e. clinical queries and additional diagnoses) was lower than that of conventional TTE (199/251 versus 223/251 clinical questions solved, $P = 0.005$), reaching 79% and 88%, respectively. Both

Figure 2



Examples of two-dimensional still frames obtained from hand-held echocardiographic examinations of four distinct patients. **(A)** Parasternal long axis view obtained from a patient admitted for septic shock secondary to a severe aortic endocarditis (arrows indicate vegetations) associated with a massive regurgitation and dilated left ventricle. **(B)** Parasternal short axis view obtained from a patient with an acute respiratory distress syndrome and associated cor pulmonale. The right ventricle was markedly enlarged and the ventricular septum bulged towards the left ventricular cavity at end systole, due to severe pulmonary hypertension (arrow). **(C)** Apical four-chamber view obtained from a ventilated patient with refractory hypoxemia. The contrast study (intravenous injection of saline microbubbles) revealed a large interatrial right-to-left shunt through a patent foramen ovale, which participated to persistent hypoxemia: left cardiac cavities were filled up by the microbubbles within two cardiac cycles. **(D)** Subcostal view obtained from a patient presenting with shock and pulsus paradoxus. A mild pericardial effusion responsible for prolonged right atrial collapse during the cardiac cycle (arrow) was consistent with a tamponade, and the patient underwent successful pericardotomy. LV, left ventricle; RV, right ventricle; LA, left atrium; RA, right atrium; Ao, ascending aorta.

Figure 3



Examples of color Doppler mapping still frames obtained from hand-held echocardiographic examinations of four distinct patients. **(A)** Parasternal long axis view obtained from the same patient as in Fig. 2A. A large regurgitant jet was consistent with massive aortic insufficiency. **(B)** Apical four-chamber view obtained from a patient ventilated for an acute pulmonary edema and associated systolic murmur. Color Doppler mapping disclosed a severe mitral regurgitation associated with extended regional wall motion abnormality consistent with an ischemic cardiopathy. **(C)** Apical four-chamber view obtained from a ventilated patient with shock. Hand-held echocardiography revealed a severe left ventricular systolic dysfunction. Color Doppler mapping depicted a massive tricuspid regurgitation reflecting a severe pulmonary hypertension (arrow indicates mitral valve prosthesis). **(D)** Parasternal long axis view obtained from a patient presenting with septic shock and new onset systolic murmur. Color Doppler identified an aorto-right ventricular fistula (arrow) associated with aortic regurgitation. Two-dimensional examination showed large aortic vegetations and blood cultures yielded *Streptococcus bovis*. LV, left ventricle; RV, right ventricle; LA, left atrium; RA, right atrium; Ao, ascending aorta.

approaches yielded similar diagnostic accuracy for the assessment of left ventricular function, pericardial and pleural effusions, volume status, endocarditis and cardiac trauma, and for the identification of a potential source of arterial embolism (Table 1). In contrast, HHE missed the diagnosis of significant pulmonary hypertension in 10 patients, four relevant valvulopathies (moderate-to-severe mitral regurgitation [$n=2$] and aortic stenosis [$n=2$]), a left ventricular outflow tract obstruction in three patients receiving vasopressor agents (Fig. 4), and an atrial septum defect with trivial left-to-right shunt and no pulmonary hypertension in another patient (Table 1). When only considering diagnoses mainly based on two-dimensional echocardiography, both HHE and conventional TTE had similar diagnostic accuracy (129/155 versus 135/155 clinical questions solved, $P=0.4$), reaching 83% and 87%, respectively.

HHE allowed seven major additional diagnoses and the identification of six minor findings, whereas conventional TTE yielded 15 major and seven minor additional diagnoses. In addition, TTE allowed the quantification of pulmonary hypertension in 10 of 13 patients diagnosed with cor pulmonale using HHE (Table 1). Conventional TTE also confirmed the presence and objectively evaluated the severity of an aortic stenosis that was only suspected in two patients using the HHE device.

The potential therapeutic impact of HHE was similar to that of conventional TTE in 45 and 47 patients, respectively (44% versus 46%, $P=0.9$), seven patients having more than one therapeutic change. Alterations in ongoing therapy consisted of fluid challenge ($n=14$), inotropic agents ($n=14$), vasoactive drugs ($n=8$), anticoagulation or thrombolysis ($n=5$), diuretics ($n=3$), antibiotics for an endocarditis ($n=2$), discontinuation of inotropic support ($n=3$), and thoracocentesis ($n=5$). In addition, seven patients (7%) underwent rapid surgery after diagnostic confirmation by TEE in all cases (Fig. 5). Finally, seven brain-dead patients were deemed eligi-

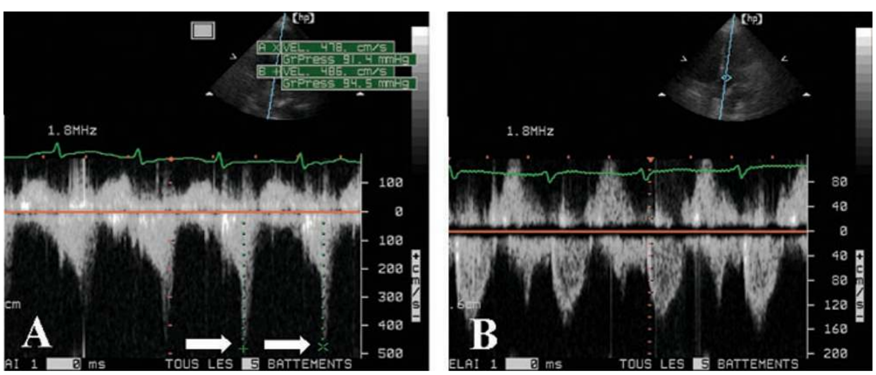
Table 1

Diagnostic capability of hand-held echocardiography and conventional transthoracic echocardiography, according to clinical problems ($n = 229$) and additional diagnoses ($n = 22$) assessed in 103 consecutive ventilated patients

	Hand-held echocardiography				Transthoracic echocardiography			
Clinical problem	No response (*n*)	Present (*n*)	Absent (*n*)	Diagnostic capability (%)	No response (*n*)	Present (*n*)	Absent (*n*)	Diagnostic capability (%)
Left ventricular systolic dysfunction (*n*=88)	10	31	47	82	10	35	43	89
Cor pulmonale/pulmonary hypertension (*n*=42)	2	13	27	71	2	23	17	95
Valvulopathy/valvular prosthesis assessment (*n*=29)	1	8	20	83	1	12	16	96
Pericardial effusion/tamponade (*n*=20)	4	7	9[a]	75	4	7	9[a]	75
Pleural effusion (*n*=13)	0	11	2	100	0	11	2	100
Volume status assessment (*n*=18)	4	10	4	78	4	10	4	78
Cardiac trauma (*n*=10)	3	2	5	70	3	2	5	70
Intracardiac shunt (*n*=9)	1	4	4	78	1	5	3	89
Endocarditis (*n*=8)	0	2	6[a]	87	0	2	6[a]	87
Source of arterial embolism (*n*=8)	1	3	4	87	1	3	4	87
Left ventricular outflow tract obstruction (*n*=3)	0	0	3	–	0	3	0	–
Acute aortic condition (*n*=3)	0	1	2	–	0	1	2	–

[a] Includes one false-negative result compared with transesophageal echocardiography.

Figure 4



Continuous-wave Doppler findings obtained with a full-feature echocardiographic platform from a ventilated patient receiving high doses of inotropes for a suspected cardiogenic shock after cardiac surgery. **(A)** Conventional transthoracic echocardiography revealed a systolic left ventricular obstruction with a dynamic pressure gradient up to 94 mmHg, whereas hand-held echocardiography only showed a hyperkinetic left ventricle. **(B)** The hemodynamics improved after repeated fluid challenges and rapid tapering of positive inotrope doses, as reflected by the absence of Doppler detectable dynamic obstruction.

ble as heart donors based only on transthoracic echocardiograms, and heart transplantation was successfully performed in all cases.

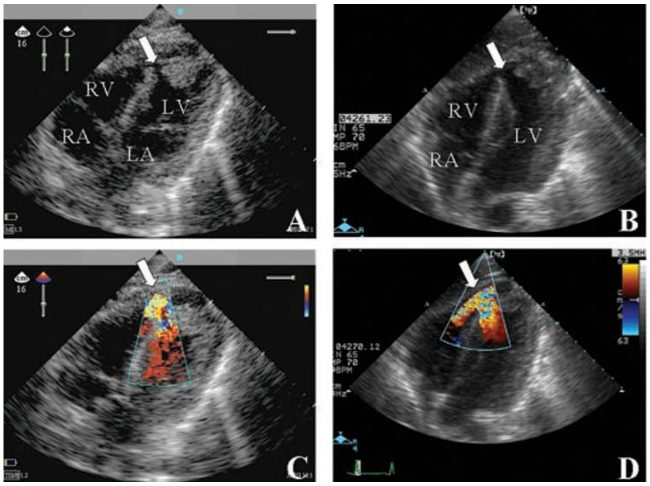
Multiplane TEE (mean duration, 14 ± 6 min) was performed in addition to 59/106 TTE studies (56%) because of an inadequate imaging quality (*n*=6), because of the absence of acoustic windows (*n*=14) or considering its superior sensitivity to confidently rule out a diagnostic hypothesis (*n*=39). TEE solved clinical questions in all cases and led to additional medical therapeutic changes in 14 patients.

Discussion

Feasibility of HHE in the ICU

Despite the presence of numerous factors known to interfere with the imaging quality in the study population (e.g. mechanical ventilation), the compact ultrasound system provided a number of acoustic windows similar to that obtained with the

Figure 5



Subcostal view in a ventilated patient sustaining severe multisystem trauma and a circulatory failure: **(A)**, **(C)** using hand-held echocardiography, and **(B)**, **(D)** using a full-feature echocardiographic platform. Two-dimensional echocardiography in both cases revealed a large ventricular septal defect ((A) and (B), arrow). Color Doppler mapping confirmed the presence of a large left-to-right shunt ((C) and (D), arrow). The patient underwent immediate surgical repair, which confirmed the diagnosis. LV, left ventricle; RV, right ventricle; LA, left atrium; RA, right atrium; Ao, ascending aorta.

full-feature echocardiographic unit (Fig. 5). This undoubtedly contributed to the diagnostic ability of HHE in our ventilated patients.

As previously reported in cardiology outpatients or inpatients [8,9,12], HHE was consistently more rapidly performed than conventional TTE. The short examination time was explained by focused echocardiographic studies to answer clinical questions by experienced operators. The versatility and ease of use of this small portable device constitutes a definite advantage in the settings of crowded ICUs or emergency rooms.

Diagnostic capability of HHE in ventilated patients

In the present study, the portable device had a lower overall diagnostic accuracy when compared with conventional TTE. Importantly, false-negative results were predominantly attributable to the lack of spectral Doppler capability of the portable device (Table 1). In a cohort of 80 critically ill patients, Goodkin and colleagues [5] showed that portable echocardiography provided important anatomic information but was unable to answer 15% of clinical questions because of its lack of spectral Doppler capability. Similar false-negative results have been previously reported in other studies [6,9,12], which have shown that miniaturized ultrasound units were less accurate than advanced feature platforms for both the detection and quantification of valvular regurgitations, of pulmonary hypertension, or of dynamic left ventricular outflow tract obstruction (Fig. 4).

In the present study, we confirmed that relevant pulmonary hypertension may be missed by the miniaturized system (Table 1), especially in the absence of significant right ventricular enlargement as observed in a substantial proportion of acute cor pulmonales [17]. In contrast, in most of our patients, HHE allowed the diagnosis of relevant valvular regurgitations and intracardiac shunts using color Doppler mapping (Figs 2, 3 and 5). This is presumably attributable to its true color flow Doppler imaging capability [9], as opposed to other portable devices [5]. In our experience, however, excentric regurgitations and trivial shunts may not be depicted by the miniaturized ultrasound unit (Table 1).

Due to its two-dimensional imaging capability, the new portable device allowed the evaluation of global and regional systolic function of both ventricles, the assessment of cardiac chamber size and intracardiac masses, and the accurate detection of pericardial or pleural effusions in most of our patients (Fig. 2). These results are in keeping with those reported in most previous studies [8–13] but differ from Goodkin and colleagues' experience [5], who described several false-negative findings of HHE related to inadequate two-dimensional imaging quality. This discrepancy may be related to differences in image processing between miniaturized ultrasound systems.

Potential therapeutic impact of HHE

The therapeutic changes following conventional TTE involved nearly 50% of the study population, including prompted surgery in seven patients (7%) and the selection of seven potential cardiac donors among brain-dead patients [1]. Despite its lack of spectral Doppler, HHE would potentially have led to a similar therapeutic impact in our ventilated patients. This is presumably accounted for by the predominance of relevant findings that can be adequately obtained by two-dimensional echocardiography and color flow Doppler mapping [9], and that have been interpretated by operators highly trained in echocardiography. Accordingly, the present results should not be extrapolated to the clinical practice of intensivists without experience in cardiovascular ultrasound.

Clinical field of use of HHE in ventilated patients

Miniaturized ultrasound imaging systems and the context of goal-directed studies do not currently fulfill the criteria for a state-of-the-art comprehensive echocardiographic study [18]. Specifically, the lack of spectral Doppler capability constitutes a major limitation to the widespread use of HHE, particularly in assessing hemodynamics. The portable devices should be used with caution in the setting of patients presenting with shock, with suspected valvulopathy and/or with pulmonary hypertension, in whom a full non-invasive evaluation of the hemodynamic status is crucial [4–6]. An additional TEE study remains advocated in complex ventilated critically ill patients [1–3], especially after cardiac surgery or multisystem trauma, or in patients with a known cardiopathy.

In contrast, HHE appears adequately suited for the evaluation of left ventricular systolic function [7–12] and cardiac chamber size [7,9], the identification of pericardial or pleural effusion (Table 1), and for diagnoses based on two-dimensional imaging and color Doppler mapping [8,9,12]. Several studies have recently shown that, after limited training, the routine use of HHE improves clinical diagnosis of heart failure and allows an accurate evaluation of left ventricular systolic function [8,10,11]. Accordingly, HHE may be used as a screening imaging modality to address specific clinical questions during a goal-oriented examination at a patient's bedside, thus extending the physical examination and potentially improving patient care [6,7,18,19]. The efficacy and safety of tailored ultrasound training to specific needs remains to be tested using HHE in the ICU setting [12,13].

Study limitations

In the present study, operators performing HHE and conventional TTE were not randomized. Since the most experienced investigator always performed the portable examinations, the influence of expertise cannot be separated from HHE technology in the observed diagnostic capability. The study was purposefully designed to evaluate the optimal diagnostic capability of HHE when used in experienced hands. To reduce the potential bias related to operator experience, all conventional TTE studies were independently reviewed by a cardiologist working full-time in echocardiography.

Conventional TTE was considered the gold standard for the purpose of the study, whereas TEE is widely accepted as the reference ultrasound imaging modality for the assessment of mechanically ventilated patients [1–3,14]. However, the goal of the present study was to compare the diagnostic field of two distinct transthoracic approaches and to test a newly developed portable unit against a commercially available, full-featured system.

Conclusions

In the present study, HHE provided adequate echocardiographic windows in the majority of ventilated critically ill patients. Due to the lack of spectral Doppler capability, the portable device yielded a lower diagnostic capability compared with conventional TTE. However, in experienced hands, HHE allowed the accurate identification of diagnoses based on two-dimensional imaging and color Doppler mapping. This presumably explain the similar therapeutic impact of both approaches in a substantial proportion of patients.

At its present stage of development HHE may be considered a screening imaging modality that extends the clinical evaluation of ventilated patients at bedside, but may not be considered an alternative to conventional echocardiography, especially in hemodynamically unstable patients. Further studies are needed to compare the diagnostic capability of different portable systems, and to determine the field of application of goal-directed HHE performed by intensivists after limited ultrasound training.

Key messages

- HHE allows the evaluation of left ventricular function and the identification of pericardial or pleural effusion in ventilated patient.
- HHE has a lower diagnostic ability when compared to conventional TTE due to its lack of spectral Doppler capability.
- Conventional echocardiography using a full-feature system remains crucial for a comprehensive hemodynamic assessment in patients with circulatory failure

Competing interests

None declared.

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