Study to determine the repeatability of supra-sternal Doppler (ultrasound cardiac output monitor) during general anaesthesia: effects of scan quality, flow volume, and increasing age

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Editor’s key points

- This study found that the supra-sternal ultrasound cardiac output monitor (USCOM) scan can be used during anaesthesia.
- Repeatability data with a precision of <10% support the use of the USCOM to guide therapeutic interventions such as fluid optimization.
- The experience of the operator is crucial to capture good-quality USCOM signals.
- Age >50 has a significant effect on the ability to obtain good-quality and reliable scans.

Background. The ultrasound cardiac output monitor (USCOM) is a continuous wave Doppler system designed to measure cardiac output (CO) non-invasively and intermittently either from the pulmonary or from the aortic valve. USCOM scan quality is critical to obtaining reliable data and during anaesthesia it is said to deteriorate with increasing age. The aim of this study was to investigate the effect of age on supra-sternal USCOM scan repeatability during anaesthesia.

Methods. We performed a series of 6 USCOM scans in 180 patients of all ages after induction for routine surgery. A 12-point Cattermole (CS) score and 10-point insonation (IS) score were used to evaluate scan quality and ease of insonation. The coefficients of variation (CVs) of USCOM variables [CO, peak velocity, stroke volume index (SVI) and the corrected flow time] were derived from the series of six readings.

Results. In >95% of young patients (age <50 yr), it was easy to obtain a good-quality USCOM scan (CS > 8). In these patients, repeatability of serial readings was good with CVs <5% and precision of less than ±10%. In older patients (>50 yr), scan quality and ease of insonation declined, with >25% of patients >60 yr having unreliable USCOM scans (CS < 5). In these patients, the CV was >5–10%. In several elderly patients (>65 yr), we failed to locate the USCOM signal. Average scan time increased with age (30 to >60 s). SVI was also strongly correlated with scan quality (R² = 0.77).

Conclusions. Increasing age has a significant effect on USCOM scan quality and data reliability.

Keywords: age; cardiac output; Doppler; repeatability

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A simple and reliable method of assessing changes in cardiac output (CO) and related flow parameters during general anaesthesia is currently being sought.1 The ultrasound cardiac output monitor (USCOM) (USCOM Ltd, Sydney, Australia) is a continuous wave Doppler system designed to measure CO intermittently either from the pulmonary or from the aortic valve.2 It uses a 2.2 MHz external hand-held probe. During anaesthesia, the supra-sternal aortic valve route is more convenient. It is estimated that 20 patient USCOM examinations are required to gain competence with the technique.1 The USCOM is able to obtain good-quality signals that can track changes in CO and guide therapy, fluid or inotrope, in most patients. However, unlike most other CO monitoring systems, the quality of USCOM data is very operator dependent. Thus, in addition to accuracy or reliability, reproducibility or repeatability becomes a factor in evaluation of the technique especially when it is used to track changes in CO during anaesthesia. Furthermore, the quality and repeatability of the USCOM scan appears to decrease with the patient’s age during anaesthesia. Several scoring systems have been developed to categorize the quality of USCOM scans, the most well-known being the six-point Fremanlce score and the more recently described 12-point Cattermole score.3,4 The objective of this study was to determine at what level of scan quality the USCOM is reliable during
anaesthesia in terms of its repeatability and ability to show changes in CO and related variables. Secondly, to document the effect of age on the quality of USCOM scans recorded during anaesthesia, albeit in Chinese Hong Kong patients. The Cattermole scoring system was used in preference to Fremantle because it provided a more sensitive evaluation.

**Methods**

Approval for the study was obtained from the Joint Chinese University of Hong Kong and New Territories East Cluster Ethics Committee. Written informed consent was obtained from all participants. Patients of all ages presenting for surgery under general anaesthesia in the operating theatres at the Prince of Wales Hospital were recruited. They were divided into 9 age groups of 20 patients each: <18, 19–29, 30–39, 40–49, 50–54, 55–59, 60–64, 65–69, and >70 yr. A previous pilot study had shown that USCOM signal reliability decreased above the age of 50 yr so the age range of patient groupings was reduced from 10 to 5 yr above this age to improve the discriminative power of the study. Patients were not randomized but studied as they presented at the hospital for surgery with capping once sufficient cases in each age group had been collected. There were no specific medical conditions that resulted in exclusion from the study. However, there were types of surgery where access to the supra-sternal notch would be limited such as head and neck cases, ear nose and throat, and neurosurgery.

All patients studied received general anaesthesia. The choice of anaesthetic agents was left up to the attending anaesthetist, as was the decision to manage the airway with a tracheal tube or laryngeal mask airway. Standard patient monitoring including heart rate and non-invasive arterial pressure was applied. After induction of anaesthesia and during a period of haemodynamic stability when heart rate and CO did not fluctuate, a series of six consecutive USCOM readings were made. Data were rejected if the heart rate drifted or fluctuated by >5 beats min⁻¹. USCOM measurements were performed by one of the two authors (L.H. and L.C.), both of whom were proficient in its use. A third investigator (C.C.: see Acknowledgements) helped later with scoring the scans. To ensure that each of the six readings was new and individually performed, the probe was removed, new ultrasonic gel applied and then the probe re-applied to the sternal notch. The new reading was performed with the full focusing technique described by the USCOM Company. The probe was then held in its optimal position and a full screen’s worth of data was collected (7.5 s: Fig. 1).

The USCOM measures a number of variables from the Doppler flow profiles, which are averaged from selected profiles present in each saved screen shot. Thus, aberrant flow profile outlines on visual inspection can be rejected. Important variables included (a) the peak flow velocity (Vpk), (b) the flow time corrected to a heart rate of 60 per minute (FTc), (c) heart rate, (d) stroke volume index (SVI), indexed to body surface area, and (e) CO. The USCOM software determines the Doppler flow at the aortic valve over one cycle and multiplies by an estimate of valve cross-sectional area. The USCOM assumes a near-unity value for the cosine of the angle of insonation (i.e. parallel and \( \theta = 0^\circ \)) of the flow with the ultrasound beam [i.e. \( \cos(\theta) = 1 \)] . Multiplication by heart rate gives CO. The cross-sectional area of the aortic valve is determined from an algorithm based on the patient’s height.

Ease with which insonation of the flow across the aortic valve could be detected was assessed using a 10-point in-house-developed insonation score (Table 1).

The quality of each saved USCOM flow profile image was assessed using the Fremantle and Cattermole scoring systems. After data collection, the series of six screen images were reviewed by one of the authors (L.H.). The three best quality profiles from each image were selected. Profiles were scored according to definition of the outline, apex, and overall density, and also the presence of well-recognized auxiliary features. The scores were later reconfirmed by the third investigator (C.C.).

A data collection form was used that recorded patient characteristics including age and insonation score. We also recorded four haemodynamic variables, CO, SVI, Vpk, and FTc. The coefficient of variation (CV), where CV=standard

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**Table 1** 10-point insonation score

<table>
<thead>
<tr>
<th>Insonation score</th>
<th>Assessment</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neck position</td>
<td>Flexed or neutral/extend</td>
<td>1</td>
</tr>
<tr>
<td>Probe insertion</td>
<td>Easy/moderate/difficult/impossible</td>
<td>3</td>
</tr>
<tr>
<td>Ability to locate signal</td>
<td>Easy/moderate/difficult/impossible</td>
<td>3</td>
</tr>
<tr>
<td>Two-axis focusing</td>
<td>Easy/difficult/not done</td>
<td>2</td>
</tr>
<tr>
<td>Fine focus</td>
<td>Yes/no</td>
<td>1</td>
</tr>
</tbody>
</table>

**Fig 1** Typical screen image of a well-focused optimum aortic valve Doppler flow profile held steady for a 7.5 s sweep and saved on the USCOM’s screen. Each flow profile is automatically outlined and Doppler flow variables calculated. Lower windows show four selected variables and a trend plot of previously saved CO readings. The Cattermole score of these flow profiles is 9 of 12.
deviation (SD) over the mean (as a percentage) of the six serial readings was calculated for each variable.

IBM SPSS Statistics (version 18) was used for statistical analyses. Data were presented as mean (SD or range) and P < 0.05 was considered significant.

Repeatability defined by CV was based on a series of six readings, which provided sufficient statistic variability to calculate the SD, yet was sufficiently short in duration to permit stable haemodynamics for the measurements. According to Bland, the sample size for a repeatability study should be based on (a) the within-subject SD for the measured variable (SDw), (b) the number of serial readings (m), and (c) the number of subjects (n). Using the equation, 95% confidence intervals \( \frac{1.96 \times SDw}{\sqrt{2n(m-1)}} \), 20 patients in each group was sufficient for the USCOM to provide a precision of ± 10% when six serial readings were performed.7 8 The threshold for SDw was set at 5%. In hospital practice for a haemodynamic measurement such as stroke volume to be useful in the clinical setting, it needs to be measured to a precision of less than ± 10%.

Multiple linear regression was used to investigate the effects on our assessment when using the USCOM (i.e. Cattermole and insonation scores) of patient characteristic factors such as age, gender, weight, height, and BMI and co-factors on age such as the Doppler flow profile variables, CO, SVI, Vpk, and FTc. Because patient age was not distributed evenly with twice as many patients recruited between 50 and 70 yr, data from patients with the same age were averaged to provide a single data set. This reduced the number of data sets for this part of the analysis.

**Results**

One hundred and eighty patients were recruited. They were divided into nine groups according to age. The patient characteristic data for each age group are given in Table 2. When children and adolescents were excluded (age < 18 yr), there was a slight mal-distribution of female to male patients across the age range (P = 0.043). Whereas all the younger adult patients (age < 49 yr) were ASA I, older patients tended to have some co-morbidity and were mainly ASA II. Height decreased with increasing age (P = 0.003), but weight and BMI had no effect (P > 0.05).

Types of surgical patients recruited were 20 paediatric surgery (11%), 28 general abdominal surgery (16%), 38 orthopaedic (21%), 57 gynaecology (32%), and 37 urology (21%). The type of surgery performed varied with the age of the patient. In 51 patients, the airway was maintained using a laryngeal mask. In the remaining 129 patients, a tracheal tube was used. Age did not affect the choice of airway (P = 0.3).

The Fremantle and Cattermole scores were strongly correlated \( R^2 = 0.85; P < 0.001 \). The Cattermole score was used in the study because its more detailed scale provided greater sensitivity when assessing USCOM scans. The insonation assessment score showed good correlation with the Cattermole score \( R^2 = 0.85 \) (Fig. 2). In 7 of the 180 patients USCOM scanned, it was not possible to achieve a focused Doppler profile signal and the Cattermole score was not completed. These patients received a zero score. Two of these patients

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**Table 2** Patient characteristic data [mean (SD) or incidence] stratified according to age

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (yr)</th>
<th>Gender (F/M)</th>
<th>ASA (I/II/III)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>BMI (kg m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 18 yr</td>
<td>9 (5)</td>
<td>4/16</td>
<td>20/0/0</td>
<td>133 (30)</td>
<td>32 (15)</td>
<td>17 (2)</td>
</tr>
<tr>
<td>18–29 yr</td>
<td>24 (3)</td>
<td>10/10</td>
<td>20/0/0</td>
<td>168 (10)</td>
<td>66 (16)</td>
<td>23 (4)</td>
</tr>
<tr>
<td>30–39 yr</td>
<td>34 (3)</td>
<td>13/7</td>
<td>20/0/0</td>
<td>164 (7)</td>
<td>62 (12)</td>
<td>23 (3)</td>
</tr>
<tr>
<td>40–49 yr</td>
<td>46 (3)</td>
<td>15/5</td>
<td>20/0/0</td>
<td>162 (10)</td>
<td>63 (11)</td>
<td>24 (3)</td>
</tr>
<tr>
<td>50–54 yr</td>
<td>52 (1)</td>
<td>15/5</td>
<td>18/2/0</td>
<td>161 (9)</td>
<td>61 (8)</td>
<td>24 (3)</td>
</tr>
<tr>
<td>55–59 yr</td>
<td>57 (1)</td>
<td>12/8</td>
<td>0/20/0</td>
<td>157 (9)</td>
<td>63 (13)</td>
<td>26 (5)</td>
</tr>
<tr>
<td>60–64 yr</td>
<td>62 (1)</td>
<td>8/12</td>
<td>0/20/0</td>
<td>160 (6)</td>
<td>62 (7)</td>
<td>24 (3)</td>
</tr>
<tr>
<td>65–69 yr</td>
<td>67 (1)</td>
<td>11/9</td>
<td>0/20/0</td>
<td>159 (8)</td>
<td>62 (10)</td>
<td>24 (3)</td>
</tr>
<tr>
<td>≥ 70 yr</td>
<td>77 (5)</td>
<td>6/14</td>
<td>0/16/4</td>
<td>158 (8)</td>
<td>58 (8)</td>
<td>23 (3)</td>
</tr>
<tr>
<td>All patients</td>
<td>48 (21)</td>
<td>94/86</td>
<td>98/78/4</td>
<td>158 (16)</td>
<td>59 (15)</td>
<td>24 (4)</td>
</tr>
</tbody>
</table>
came from the 65 to 69 yr age group and 5 came from the >70 yr age group (75, 78, 84, 88, and 91 yr).

The CV data based on the series of six scan readings were plotted according to their Cattermole scores (Fig. 3). Data from the four Doppler flow variables studied, CO, SVI, Vpk, and FTc, are shown. For all the four variables studied, the CV, and thus repeatability of the USCOM scan data, during periods of stable haemodynamics increased in percentage as the Cattermole score decreased (Fig. 3: x-axis left to right). The repeatability of these measurements, shown by the CV, was slightly worse for FTc compared with CO, SVI, and Vpk. Of note, 95% of the CV data points were <5% when the Cattermole score was ≥8. The CV was further grouped according to the Cattermole score (Table 3). When the average Cattermole score for the six readings was ≥10, the upper 95% confidence limit for the CV was 4.4%; between 8 and 10 was 6.3%; between 5 and 8 was 9.0%; and <5 was 16.8%. The average of CV percentages from the four variables was used for this part of the analysis.

Age was found to have a significant effect on the quality and Cattermole scores of USCOM scans (Fig. 4). The insonation assessment score was also adversely affected by increasing age (Table 4). Below 30 yr of age, all patients had an insonation score of ≥8, below 40 yr ≥7, and the score diminished above 60 yr ranging from 0 to 9 (Table 4).

The proportion of patients where the USCOM scan was considered unreliable with a failed or unaccepted Cattermole score (<5) also increased with age. Above the age of 55 yr, 25% of patients had unacceptable USCOM scans (i.e. score <5) and even less had a good to excellent scan of ≥8 (Fig. 4 and Table 4). Above the age of 65 yr, it sometimes proved impossible to obtain an acceptable scan of the aortic valve flow signal.

Gender and BMI had no demonstrable effect on scan quality ($R^2=0.06; P>0.05$). Patients with an ASA status of I and II had better scans than those of ASA III ($P<0.01$), but there was no demonstrable difference between ASA I and II patients ($P>0.05$).

The time required to perform each USCOM scan also increased with age (Table 4).

The volume of blood that flowed through the aortic valve had a positive effect on the Cattermole score (Fig. 5A: open circles). The quality of the Doppler signal was improved with larger aortic valve flows. Of the four Doppler flow variables studied, SVI was the most predictive.
For multiple linear regression analysis, the 180 sets of study data were condensed to 55 that represented most ages. Subsequent analysis using CO, SVI, Vpk, and FTc as co-factors in the model of the Cattermole score (dependent variable) against age generated $R^2$ values of 0.68, 0.77, 0.74, and 0.64, respectively. SVI with a $R^2$ value of 0.77 was the most predictive co-factor ($P<0.001$). A formula was then derived using multiple linear regression that predicted the Cattermole score from age and SVI data:

$$\text{Predicted score} = 9.007 - (0.084) \times \text{age} + (0.071) \times \text{SVI}.$$ 

This formula, which utilized SVI, improved the correlation between age and the Cattermole score from $R^2=0.74$ (original data) to $R^2=0.93$ (formula predicted data) (Fig. 5b). It implied that (a) an increase in SVI by 14 ml m$^{-2}$ would result in an increase in the Cattermole score by 1 point and (b) an increase in age by 12 yr would result in a decrease in the Cattermole score by 1 point.

### Discussion

The study addressed two key issues regarding the use of the USCOM during general anaesthesia: (a) the repeatability of its readings and (b) the effects on readings of patient factors such as age. The main findings of the study were that: (a) the Fremantle and Cattermole scores from USCOM scans were strongly correlated ($R^2=0.86; P<0.001$); (b) the Cattermole score was strongly correlated with the ability to insonate the aortic valve flow ($R^2=0.85; P<0.001$) (Fig. 2); (c) USCOM flow profiles with a Cattermole assessment score of $\geq 8$ had a CV of $<5\%$ and precision error $<10\%$ (Table 3 and Fig. 3); (d) increasing age adversely affected the quality of USCOM scans with $>50\%$ of Hong Kong Chinese patients having Cattermole scores $<8$ when they were above 50 yr of age (Fig. 4); and (e) higher SVI readings were associated with increased signal intensity, better Cattermole scores, and thus greater repeatability of the USCOM and ability to measure changes in flow-based haemodynamic variables (Fig. 5).

Our assessment of repeatability of USCOM readings was based on a series of six consecutive measurements. It was important that these measurements were performed during a period of constant haemodynamic conditions to avoid any drift between readings. This was achieved by performing the measurements shortly after induction when the patient’s haemodynamic status had settled, when there was minimal surgical stimulation, and by checking that heart rate remained constant throughout the period of data collection. The CV was used as the method of determining variability, or random

### Table 3: CV percentages [mean (SD)] for the four Doppler flow variables, CO, Vpk, SVI, and FTc, grouped according to their Cattermole scores. The time to perform one USCOM scan measurement is also shown.

<table>
<thead>
<tr>
<th>Cattermole score rating</th>
<th>Above 10 (excellent)</th>
<th>8.0–9.9 (good)</th>
<th>5.0–7.9 (acceptable)</th>
<th>Below 4.9 (poor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients (n)</td>
<td>47</td>
<td>63</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>CV data</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO (%)</td>
<td>1.7 (0.8)</td>
<td>2.7 (1.3)</td>
<td>4.5 (2.1)</td>
<td>9.1 (4.7)</td>
</tr>
<tr>
<td>Vpk (%)</td>
<td>2.4 (1.5)</td>
<td>3.2 (1.8)</td>
<td>4.9 (2.0)</td>
<td>8.3 (4.0)</td>
</tr>
<tr>
<td>SVI (%)</td>
<td>2.2 (0.9)</td>
<td>3.2 (1.3)</td>
<td>5.0 (1.8)</td>
<td>7.8 (3.8)</td>
</tr>
<tr>
<td>FTc (%)</td>
<td>2.5 (1.1)</td>
<td>3.7 (1.8)</td>
<td>5.1 (2.4)</td>
<td>7.6 (4.7)</td>
</tr>
<tr>
<td>Time taken (s)</td>
<td>27 (8)</td>
<td>36 (9)</td>
<td>54 (13)</td>
<td>80 (28)</td>
</tr>
</tbody>
</table>

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**Fig 4**: Box plot showing the decrease in Cattermole score with increasing age.
measurement error, between individual readings, and it enabled us to predict the 95% confidence limits (i.e. precision) for USCOM readings in each patient. Previous work had shown that to detect a clinically relevant change of a patient’s condition one needed to be able to define with 95% certainty a 10–15% change.9 Thus, when analysing our CVdata, we set a 5% repeatability (Fig. 3 and Table 3) as our threshold for acceptable quality scans (Table 3).

Very little has been published previously on the significance of USCOM scan quality and data repeatability. The Fremantle criteria have been used since 2005 to visually assess scan quality, which are based on scoring six aspects of the flow profile.3 In 2009, Cattermole and colleagues4 published a more elaborate visual scoring system. Rather than scoring just the base and peak of the flow profile, four features of the flow profile are assessed, which are scored using a 2- rather than a 1-point scale. Thus, a total of eight rather than two points are awarded and this helps grade the quality of the scan. The Cattermole score also uses a more discerning 2-point assessment of the signal in diastole and the presence of aortic valve opening and closing snaps. A Cattermole score of ≥8 was considered acceptable. Our series of six USCOM scans repeatability data confirms that when the Cattermole score is ≥8, the precision of the data lies within ±10% limits for all the four haemodynamic variables studied: CO, Vpk, SVI, and FTc (Table 3 and Fig. 3).

More contentious are Cattermole scores between 5 and 8 points. Our repeatability data would suggest that USCOM variables still have an acceptable precision of between ±10 to 15%, but clearly the USCOM is less reliable (i.e. grey zone) than when the Cattermole score is >8 points. Below 8 points, the flow profile becomes blurred along its edges and less dense and its outline becomes more difficult to define accurately, so readings will be less reliable. However, what is clear from our repeatability data is that below a Cattermole score of 5 the USCOM data become totally unreliable with precisions

<table>
<thead>
<tr>
<th>Age group</th>
<th>Insonation score</th>
<th>Scan time (s)</th>
<th>Fremantle score</th>
<th>Cattermole score</th>
<th>Score&lt;5 (unreliable)</th>
<th>Scan failed</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;18 yr</td>
<td>9.4 (0.7)</td>
<td>27 (7)</td>
<td>5.9 (0.3)</td>
<td>10.2 (0.6)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>18–29 yr</td>
<td>8.9 (0.9)</td>
<td>33 (10)</td>
<td>5.9 (0.3)</td>
<td>10.1 (0.6)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>30–39 yr</td>
<td>8.7 (1.1)</td>
<td>32 (9)</td>
<td>5.6 (0.5)</td>
<td>9.8 (0.9)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>40–49 yr</td>
<td>7.5 (1.8)</td>
<td>41 (16)</td>
<td>5.2 (0.8)</td>
<td>8.7 (1.8)</td>
<td>5%</td>
<td>0</td>
</tr>
<tr>
<td>50–54 yr</td>
<td>6.4 (1.8)</td>
<td>49 (19)</td>
<td>5.1 (0.9)</td>
<td>7.8 (1.8)</td>
<td>5%</td>
<td>0</td>
</tr>
<tr>
<td>55–59 yr</td>
<td>5.6 (2.2)</td>
<td>51 (15)</td>
<td>4.8 (0.9)</td>
<td>7.0 (2.1)</td>
<td>20%</td>
<td>0</td>
</tr>
<tr>
<td>60–64 yr</td>
<td>5.6 (2.1)</td>
<td>52 (18)</td>
<td>4.5 (0.7)</td>
<td>6.7 (2.2)</td>
<td>25%</td>
<td>0</td>
</tr>
<tr>
<td>65–69 yr</td>
<td>4.9 (2.4)</td>
<td>55 (21)</td>
<td>3.5 (1.5)</td>
<td>5.6 (2.7)</td>
<td>35%</td>
<td>2</td>
</tr>
<tr>
<td>≥70 yr</td>
<td>4.5 (2.4)</td>
<td>71 (37)</td>
<td>2.9 (1.9)</td>
<td>4.6 (3.3)</td>
<td>60%</td>
<td>5</td>
</tr>
</tbody>
</table>

Fig 5 Scatter plot (a) of Cattermole scores against the patient’s age (filled circles) and SVI (open circles). As SVI increases, the Cattermole score improves, whereas the score becomes worse with increasing age. Regression plot (a) shows predicted Cattermole scores from derived age-SVI formula against the patient’s age.

Table 4 The effect of age on insonation score (0–10), Fremantle score (0–6), and Cattermole score (0–12), reliability of readings, and time to perform one USCOM scan. Mean (so). n=20 patient per age group

AB
10
8
6
4
2
12
10
8
6
4
2
20 30 40 50 60 70 80
Patient's age/SVI
Relationships between the Cattermole score and age and SVI

Derived equation:
Score=9.01–(0.08)×age+(0.07)×SVI
(n=55 data points: R²=0.93)
greater than $\pm 15\%$. When the Cattermole score is $< 5$ points, the USCOM does not capture fully the blood flow across the aortic valve. Thus, it is no surprise that the USCOM method gives falsely low readings. Use of the Cattermole scoring system helps the operator determine when this is happening so that unreliable scan data are rejected appropriately.

The time taken to perform each USCOM reading also provides one with an indication of USCOM reliability. We found that when the patient was easy to insonate and Cattermole scores were $> 8$, it took on average 30 s to perform the USCOM scan (Table 3). However, in those patients that were difficult to insonate and had low Cattermole scores, it took $> 1$ min. Data from these patients also had low repeatability data with CVs of $> 5\%$. Thus, our data suggests that if scanning takes $> 1$ min to perform then the data it provides are likely to be unreliable.

Our insonation score (Table 1) correlated well with Cattermole scores (Fig. 3; $R^2 = 0.85$). Assessment of insonation was based on two main factors: (a) ability to position the probe in the sternal notch; and (b) ability to locate the aortic valve signal and perform two-axis and fine focusing. In many of our patients, probe placement proved difficult because the trachea was situated very anterior in the thoracic inlet. We found that extending the neck sometimes helped. Whether morphological differences exist between our Asian Hong Kong Chinese patient population and other larger build ethnic races is unclear at present, but the suggestion is that Europeans may be easier to insonate, and a further study is planned to address this question.

Increasing age had a major effect on the success of using supra-sternal USCOM in anaesthetized patients. Our data showed that above the age of 50 yr the reliability of the USCOM decreased, albeit in our Hong Kong Chinese patient cohort (Table 4 and box plot Fig. 4). For the age range 55–59 yr, 25% of cases had USCOM scans rated as poor according to Cattermole scoring. Furthermore, in patients over the age of 65 yr, the USCOM became unreliable with $> 50\%$ of cases having USCOM scans rated less than good. Over the age of 80 yr, it became unusable (i.e. no signal) in many patients. This finding is unfortunate because elderly surgical patients tend to have multiple co-morbidities and they are the very patients in whom reliable minimally invasive CO monitoring would be most useful.

Previous studies suggest that failure rates when using the USCOM are not high. However, all these studies were conducted on relatively healthy and awake emergency room or paediatric ward patients. Furthermore, they were mostly European patients. USCOM use during anaesthesia is a different situation. Patients are unconscious, their airways are managed with a tracheal tube, or laryngeal mask airway, they may be ventilated, access to the chest and pulmonary valve is limited because of surgical draping and repositioning of the patients to improve the signal is difficult. Thus, little can be inferred from these studies to our study findings.

Several factors may account for this decrease in USCOM scan reliability observed in our study as patients become older: (a) the bony sternum elevates with age and this may obstruct the path of the ultrasound beam. Partial obstruction of the USCOM probe certainly does occur in some patients, which then attenuates the strength of the Doppler signal and the pixel density of the USCOM scan, leading to poor signal enveloping and thus reduced reliability. This problem seems to be more common in patients with a prominent trachea as difficulty is often experienced placing the probe sufficiently deep into the supra-sternal notch. (b) The aorta is known to elongate and unfold with increasing age. This is well known to radiologists but less well known to doctors from other fields. The pathological mechanism is related to the loss of elastic tissue from the wall of the aorta. Unfolding of the aorta appears to alter the positions of relevant structure with respect to insonation, in particular the ascending aorta and the aortic valve during supra-sternal examination. This appears to have a profound effect on the reflected component of the USCOM signal as presumably tissues that cause greater signal attenuation have to be traversed. It is very noticeable that many of the chest X-rays from patients in our study with poorer scans show significant mediastinal enlargement with aortic unfolding. This is an aspect of the use of USCOM that we have only recently identified and we are currently in the process of investigating. (c) The echogenicity of the thoracic inlet and mediastinal structures also increases with age. The amount of fat in mediastinum increases as the thymus is replaced by fatty tissue. Below the age of 20 yr, the thymus is almost completely parenchyma tissue. However, $> 40$ yr, 75% of the thymus is replaced by more echogenic fatty tissue. Furthermore, calcification of tissues, particularly of lymph nodes, is found in older patients. (d) The position of the heart and thus the aorta within the thorax is known to change with the patient’s age. This is a little different from unfolding and elongation of the aorta mentioned in point (b). Heart size is also known to increase with age, which alters the position of the aortic valve. During many types of surgery, such as laparoscopy, the ability of the USCOM to insonate the heart is noted to change with body position and manoeuvres that affect the position of the diaphragm. (e) Finally, many older patients develop aortic calcification. Below 45 yr of age, the percentage of patients with aortic calcification is $< 0.5\%$, but this percentage increases sharply: $> 60$ yr to 15%, and $> 80$ yr to 50%. The volume of aortic blood flow and SVI was also found to correlate well with scan quality (Fig. 5a). The clinical significance of this finding is that as SVI increases the ability to detect the USCOM signal and thus scan reliability improves. For every 14 ml m$^{-2}$ increase in SVI, a 1-point increase in the Cattermole score was predicted.

The study had some limitations: measurements were performed after induction of anaesthesia when the patient’s CO and SVI were at their lowest values. Choosing this period when data can be at its most difficult to collect could provide readers with a false impression of the utility of the USCOM intra-operatively. Our impression is that the USCOM becomes more easy to use as surgery progresses and CO increases. However, we did not study the effects on repeatability of treatments that would change CO such as before and after an i.v. fluid bolus challenge. Additionally, two very experienced USCOM operators conducted the research, although their
inter-rater variability was not assessed. However, when the USCOM signal was difficult to locate, the second operator usually rechecked the measurement. The reproducibility of scan images by the two operators in difficult cases was very high. Furthermore, the scanning endpoint was to achieve the best possible signal with highest peak velocity, investigator bias was minimized. Previous studies have confirmed that the variability between different operators is acceptable in both children and adults. However, less experienced operators cannot be expected to achieve such good results in the elderly patient. Also, the USCOM estimates cross-sectional valve area from the patient's height using an algorithm, which introduces systematic error that affects the accuracy of CO and SVI readings, though the ability to track changes in CO by the USCOM is not affected. Measuring valve diameter directly using transthoracic echocardiography (TTE) or transoesophageal echocardiography (TOE) could arguably be a better option. However, compared with the USCOM, both TTE and TOE would be much less convenient to use during surgery because these techniques involve bulky machines. Besides, when using TTE, access to the anterior chest wall is needed and the patient needs to be turned to a lateral position, and the alternative TOE requires insertion of a large-diameter oesophageal probe. Smaller diameter alternatives such as the CardiQ (Deltex Medical Ltd, Chichester, UK) do not have imaging capability and also use an algorithm to indirectly estimate vessel area. Furthermore, compared with TTE and TOE, USCOM is much easier to learn. However, pre-induction measurement of the valve diameter by TTE could be useful. Another limitation is that the direction of the Doppler beam to the aortic flow is critical to calculating accurately SVI and the angle of insonation may vary between patients, users, and times during surgery. To address these issues and overcome the need to measure the insonation angle, the USCOM, unlike conventional pulsed Doppler, uses a wide-angled beam so alignment of the probe is always parallel. Furthermore, provided that the direction of the Doppler beam to the aortic flow is critical, it has very little effect on the cosine (i.e. \(\cos 20^\circ = 0.94\)). Finally, the study protocol did not specify the choice and dose of anaesthetic drugs and this may have affected the mean SVI and the statistical variation between different patient groups with respect to age and Cattermole scores. The study was conducted on Hong Kong Chinese patients. Owing to anthropomorphic difference between races, particularly body size, our results may not apply to all ethnic groups of patients.

The USCOM is a non-continuous monitor and samples CO and SVI at the discretion of its operator. Therefore, sudden and unexpected circulatory changes may be missed. However, more continuous CO monitors such as oesophageal Doppler (which still needs to be focused), pulse contour analysis, and bioelectrical impedance are more invasive, expensive to use, and in some cases much less reliable. Although the USCOM reportedly takes 20 scans to gain proficiency with the technique, learning can vary between individuals. Furthermore, our study suggests that reliable USCOM data can be more difficult to gather in elderly anaesthetized patients and probably a high degree of proficiency with using the USCOM in this setting is needed. Currently, CO monitoring is not routinely performed during high-risk anaesthesia by many centres worldwide and thus clinical information about the patient’s ‘flow haemodynamic’ is not always available. The USCOM can certainly provide this type of information, but proficiency in the technique would be needed.

In conclusion, the USCOM can be used during anaesthesia via the supra-sternal route in most patients. Repeatability data with a precision of \(<10\%\) support the use of the USCOM to guide therapeutic interventions such as fluid optimization. Assessing the quality of the USCOM scan using a sensitive scoring system such as Cattermole is advised. The experience and ability of the operator to capture good-quality USCOM signals (i.e. Cattermole scores of \(\geq 8\)) is important if USCOM is to be used to best effect. Scanning should take \(<1\) min or be abandoned because it is too difficult. Age has a very significant effect on the ability to obtain good-quality and reliable scans. Above the age of 50 yr, when-age related anthropomorphic changes occur, USCOM scanning becomes more difficult in some patients. The patient’s SVI and CO also play an important role with low CO states being more difficult to measure reliably. However, SVI and CO normally increase during surgery, making USCOM scans more reliable and easier to obtain. Further studies are needed to determine whether our findings can (a) be extended to non-Chinese patients and (b) to patients in other areas of the hospital, such as the intensive care unit.

Authors’ contributions
L.H. was involved in all aspects of the study from conception and design, to data collection and analysis, to preparation of the manuscript. L.A.H.C. was also involved in all aspects of the study as senior author from conception and design, to data collection and analysis, to preparation of the manuscript.

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None declared.

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Effects of scan quality, flow volume, and increasing age


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