Improved consistency in interpretation and management of cardiovascular variables by intensive care staff using a computerised decision-support system

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Cardiovascular monitoring is a cornerstone in the management of critically ill patients in the intensive care unit, but no form of monitoring, however sophisticated, will change patient outcome unless coupled with appropriate therapeutic interventions. For example, the wealth of haemodynamic data obtained from the pulmonary artery catheter has not been shown to lead to outcome benefit.[1] One possible reason is the complexity of transforming data into management strategies.

The function of the cardiovascular system depends on three interactive variables: intravascular volume, cardiac efficiency and vascular resistances. These correlate with the most common interventions applied to treat circulatory compromise: administration or removal of fluid, and cardio-active and vasoactive agents.

Methods to appraise intravascular volume, and perhaps more importantly volume responsiveness, have been widely investigated.[2] In the bedside situation, intravascular volume is typically estimated with limited data that may not necessarily measure volume responsiveness.[3] The mean systemic filling pressure (P_{ms}), which is the mean distending pressure of the volume in the systemic circulation, is the physiologically precise variable to gauge volume status, but is only measurable after cessation of circulation. Instead, the P_{ms} analogue (P_{msa}) is used and is based on mathematical modelling of the circulation.[4] Heart efficiency (E_h) refers to the variable ability of the heart to maintain a low right atrial filling pressure (measured as central venous pressure [CVP]) in the face of a rising P_{ms}. The venous return, driven by the pressure gradient between P_{ms} and CVP, determines cardiac output (CO). Finally, the resistance of the vasculature (systemic vascular resistance [SVR]) controls the mean arterial pressure (MAP) generated on ejection of the stroke volume.

A computerised decision-support system (CDSS) has been developed based on the circulatory variables described above. A graphic interface shows the present haemodynamic status in relation to a target area based on clinician-set values for MAP, CO and oxygen delivery.[5] Haemodynamic therapy guided by the CDSS has been shown not to be inferior to standard postoperative intensive care therapy after cardiac surgery.[6] A high level of concordance was found intraoperatively between the CDSS and the actions of experienced anaesthetists during high-risk surgery.[7]

ABSTRACT

Objective: To investigate the potential of a computerised decision-support system (CDSS) to improve consistency of haemodynamic evaluation and treatment suggestions by intensive care unit clinical staff with different levels of expertise and experience.

Design, setting and participants: Prospective observational study in a tertiary general ICU, of 20 patients admitted after elective cardiac surgery and assessed by staff specialists, senior registrars, registrars and nurses.

Main outcome measures: A CDSS was used to display key cardiovascular variables, including mean systemic filling pressure analogue (P_{msa}), heart efficiency (E_h) and vascular resistance (SVR). Staff were asked to score P_{msa}, E_h and SVR ranging from –5 (grossly subnormal) through 0 (normal) to 5 (grossly supranormal), first without and then with access to the CDSS. Recommendations for therapeutic interventions were recorded. Maximal differences ($diff_{max}$) and the proportion of minimal disagreement ($diff_{min}$) between staff were evaluated.

Results: Without use of the CDSS, P_{msa} was commonly underestimated, E_h was overestimated, and there was no clear trend for SVR, compared with estimations using the CDSS. $Diff_{max}$ was reduced and $diff_{min}$ was increased after access to the CDSS. Agreement between all categories of staff on therapeutic interventions increased from four to 18 patients after access to the CDSS.

Conclusion: Use of a CDSS significantly improved the consistency between categories of clinical ICU staff in assessing the cardiovascular status and making management decisions in postoperative cardiac surgery patients.

The various levels of expertise and experience among members of the ICU team may lead to inconsistencies in identifying the cause of and appropriate therapeutic action for haemodynamic instability. The potential of the CDSS to improve the concordance of cardiovascular assessments and management decisions in this setting has not been reported.

Variable	−CDSS agreement ($n = 20$)	−CDSS diff$_{max}$* (median [IQR])	−CDSS diff$_{min}$† ($n = 120$)	+CDSS agreement ($n = 20$)	P	+CDSS diff$_{max}$* (median [IQR])	P	+CDSS diff$_{min}$† ($n = 120$)	P
P$_{ms}$	6	2.5 (2–3.75)	65	17‡	0.001	2 (1–2)‡	0.014	84‡	0.016
E$_h$	6	2 (1–3)	79	17‡	0.001	1 (0–1)‡	<0.0001	101‡	0.003
SVR	8	2 (1–2.75)	87	16‡	0.023	1 (1–1.75)‡	0.024	90	0.769
Intervention	4	na	na	18‡	< 0.0001	na	na	na	na

Table 1. Assessments of haemodynamic variables by staff blinded and unblinded to the CDSS

P$_{ms}$ = mean systemic filling pressure. E$_h$ = heart efficiency. SVR = systemic vascular resistance. CDSS = computerised decision-support system. IQR = interquartile range. −CDSS = blinded to the CDSS. +CDSS = unblinded to the CDSS. Diff$_{max}$ = maximum difference in scores. Diff$_{min}$ = minimum difference in scores. * Maximum difference in scores between any staff categories. † Proportion of assessments within a 0, 1 or −1 difference, comparing all scores by all staff categories. ‡ Significantly different ($P < 0.05$), +CDSS v −CDSS. na = not applicable.

Our aim was to investigate the impact of the CDSS in aligning haemodynamic evaluation and treatment by ICU nurses, registrars and specialists in patients after elective cardiac surgery. It was hypothesised that the CDSS display of P$_{msa}$, E$_h$ and SVR in relation to a set target area would improve agreement on cardiovascular status and therapy.

Methods

Twenty sedated, mechanically ventilated patients admitted to the ICU after elective cardiac surgery were included in the study, which was approved by the local ethics and research governance office (LNR/12/LPOOL/281). The sample size of 16 was estimated after a pilot study showing a baseline SD for haemodynamic scoring (see below) of 1; ie, 16 patients would need to be investigated to detect a change in score of 1. Four patients were added to allow for dropouts as a result of incomplete or missing data.

Routine perioperative monitoring included insertion of arterial, central venous and pulmonary artery catheters. All patients were stable when investigated within 6 hours of admission to the ICU and all haemodynamic information was displayed on an ICU patient monitor (IntelliVue MP70, Philips) serially connected to the CDSS (Navigator, Applied Physiology). MAP, CO, CVP and oxygen saturation by pulse oximetry were transmitted to the CDSS. The weight, height and age of the patient (which were necessary for the Navigator algorithm to calculate P$_{msa}$) were manually entered, as well as the haemoglobin (Hb) level, enabling the CDSS to display the oxygen delivery. Other relevant information, such as the medical history and results of echocardiographic investigations and blood gas analyses were available at the bedside.

Four categories of ICU staff participated in the study: nine staff specialists with a median of 15 years' ICU experience (range, 9–28 years), eight senior registrars with a median of 7 years' ICU experience (range, 3–15 years), nine registrars

with a median of 2 years' ICU experience (range, 0.5–12 years) and 11 registered nurses with a median of 10 years' ICU experience (range, 2–27 years).

All staff were given at least 1 hour of education to explain the concepts and working principles of the Navigator CDSS before the monitor was implemented clinically. The study protocol comprised three sections, with access to the CDSS display only provided during the last section. One participant from each category of staff simultaneously assessed each patient. First, participants were asked to specify the haemodynamic goals for the patient, specifically heart rate, arterial pressure, cardiac output and the adequacy of oxygen delivery. Second, participants (while blinded to the CDSS) were asked to score the P$_{msa}$, E$_h$ and SVR, on a scale from −5 to 5, with discrete steps of one. A score of −5 denoted a grossly subnormal state, 5 denoted a grossly supranormal state and 0 denoted an adequate or normal state. Any interventions that the participants thought should be instituted were also documented. Third, the participants were given access to the CDSS display and were asked to repeat an unblinded score of P$_{msa}$, E$_h$ and SVR and to state whether they agreed with the CDSS information and whether they would make any changes to their proposed interventions. The scores reflected subjective assessments rather than any numerical difference between an anticipated and measured value and were hence equally applicable with and without access to the CDSS. The protocol was completed within 30 minutes in all patients so any significant haemodynamic changes between assessments could be excluded.

We defined "agreement" between categories of staff in assessing haemodynamic variables as scores with a maximum deviation of 2 and a range including 0 unless at one end of the scale (eg, −4 to −2, 1 to 3, or −1 to 1). We defined "disagreement" as any deviation of more than 2 or the inclusion of 0 at one end of the score range (eg, −5 to −2, 0 to 2, or 1 to 4). The maximum difference in scores

Figure 1. Frequency distribution of differences in scores for P_{ms}, all staff categories
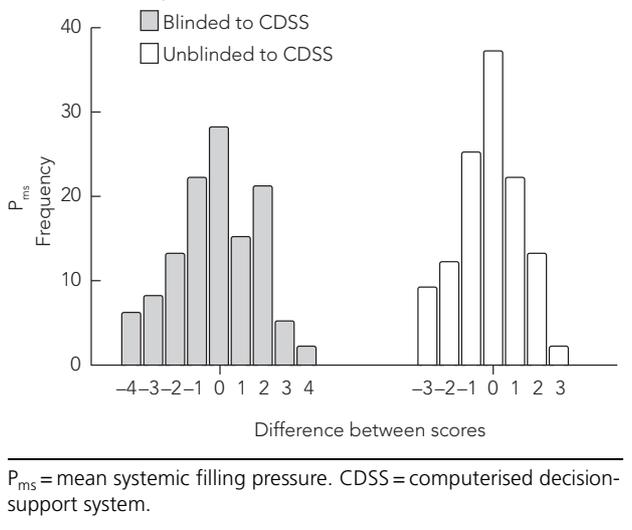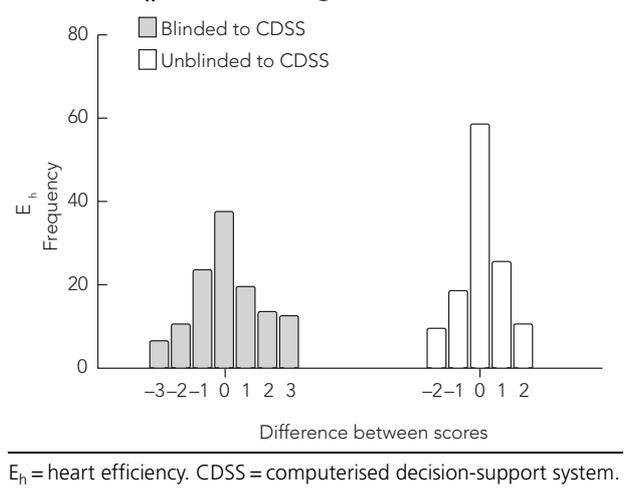

P_{ms} = mean systemic filling pressure. CDSS = computerised decision-support system.

Figure 2. Frequency distribution of differences in scores for E_h, all staff categories

E_h = heart efficiency. CDSS = computerised decision-support system.

(diff$_{max}$) between any staff categories was noted. All scores were also compared numerically between all staff categories to give a total of six differences for each assessment (a total of 120 for all 20 patients). The minimum difference in scores (diff$_{min}$) between staff categories (ie, 0, 1 or −1) were also recorded to reflect concordance in assessment.

We defined "agreement" in therapeutic interventions as any interventions that would change P_{msa}, E_h and SVR in similar directions (eg, diuretics, increased fluid removal on dialysis, or reduced administration of fluids). Conversely, we defined "disagreement" as interventions with opposite

effects (eg, decreased and increased rates of inotropes or vasopressors, diuretics and fluid boluses).

Since all results were non-normally distributed, we described and analysed them using non-parametric statistics. We have reported results as medians with interquartile ranges (IQRs). Scores were analysed with the Mann–Whitney t test. Proportions of staff members as well as proportions of diff$_{min}$ values were analysed with the Fisher exact test. Prism version 6.0b (GraphPad) was used for all statistical analyses. Statistical significance was set at a $P < 0.05$.
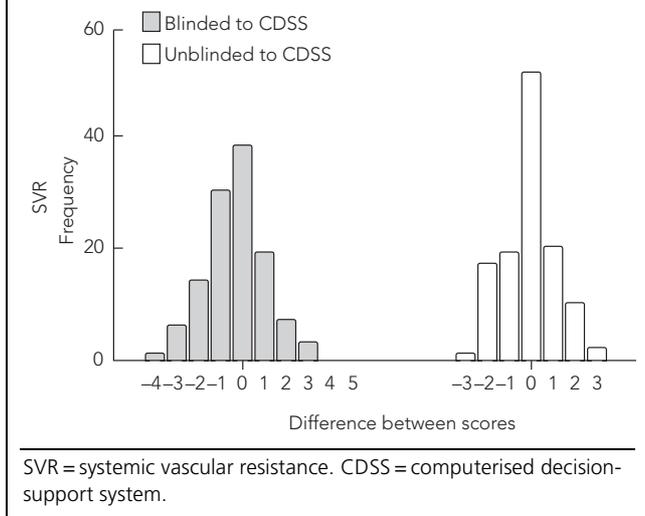
Results

The median age of patients was 58 years (IQR, 52–68 years) and the median Hb level was 103 g/L (IQR, 88–117 g/L). The baseline haemodynamic variables were stable with any ongoing vasoactive support and after volume expansion by fluid boluses when assessed by participants. The medians of baseline haemodynamic variables were as follows: heart rate, 89 beats/min (IQR, 75–104 beats/min); MAP, 76 mmHg (IQR, 69–82 mmHg); CVP, 12 mmHg (IQR, 10–16 mmHg); CO, 5.5 L/min (IQR, 4.8–6.2 L/min); P_{msa}, 20 mmHg (IQR, 16–22 mmHg); E_h, 0.35 (IQR, 0.27–0.41); and SVR, 945 dyn·s/cm^5 (IQR, 730–1115 dyn·s/cm^5).

There was broad agreement between staff categories on haemodynamic targets, for an MAP of 65–70 mmHg and a CO of > 5 L/min. The agreement was consistent in 13 of 20 patients for MAP, and in 16 of 20 patients for CO. The target for heart rate was 60–90 beats/min, with agreement consistent in 13 of 20 patients. Central filling pressures (CVP or pulmonary artery wedge pressure) were only targeted (mainly by nurses) in five patients. Oxygen delivery was specifically targeted by staff specialists in seven patients and by senior registrars in two patients. No registrars or nurses commented on oxygen delivery.

For blinded assessment of P_{msa}, there was agreement between staff categories in a minority of patients. This was reflected by a diff$_{max}$ > 2 on the scoring scale (Table 1). The frequency distribution of differences in scores for P_{msa} is shown in Figure 1, with about 50% of assessments within the diff$_{min}$ range (Table 1). Most participants typically underestimated P_{msa}, with no significant differences between staff categories. There was agreement for the blinded assessment of E_h in a minority of patients, similar to P_{msa}, with a slightly reduced median diff$_{max}$ compared with P_{msa}. Two-thirds of assessments were within diff$_{min}$ range. The frequency distribution of differences in scores for E_h is shown in Figure 2. E_h was commonly overestimated, with no significant differences between staff categories. A non-significant increased level of agreement for eight of 20 patients was observed for SVR scoring, with a lower median diff$_{max}$. SVR was significantly under-

Figure 3. Frequency distribution of differences in scores for SVR, all staff categories

SVR = systemic vascular resistance. CDSS = computerised decision-support system.

made in all but two patients, when staff were unblinded to the CDSS.

Discussion

Our study shows the potential of a CDSS to significantly improve the consistency of assessments and decisions involving the haemodynamic status of postoperative cardiac surgery patients, among intensive care team members with varying levels of experience and expertise. This feature of a haemodynamic monitoring system is important since it can provide a nexus between diagnosis and treatment that has until now largely been absent.

The algorithm to calculate P_{msa} is unique to the Navigator. It provides a physiologically robust quantitative measure of the effective circulating blood volume that can be used for therapeutic guidance.[8] This algorithm has recently been shown to correlate well with other independent measures of intravascular volume status in mechanically ventilated postoperative cardiac patients.[9] It is interesting to note that the P_{msa} was commonly underestimated by all categories of clinical ICU staff, with significant variability. The median P_{msa} of 20 mmHg was significantly higher than the normal P_{ms} of 7 mmHg,[10] but similar to the P_{msa} of 19.7 mmHg reported in comparable patients.[9] The failure to recognise a more than adequate intravascular volume state led many clinicians to suggest further fluid boluses, and overzealous fluid loading has been identified as one important contributing factor to postoperative morbidity.[11,12] Introducing the CDSS reduced the overall variability of volume state assessment and resulted in a markedly increased level of agreement. Staff specialists and senior registrars, in particular, re-evaluated P_{msa}, giving it a higher score, hence accepting an appropriate circulating blood volume, while registrars and nurses did not significantly downgrade their scores. It seems likely that fluid management guided by P_{msa} would result in less fluid being given, as a result of a more uniform appreciation of the effective circulating volume.

In contrast to P_{msa} estimates, clinical staff commonly overestimated the E_h, with no significant differences between categories of participants. The CDSS introduced a reduction in the variability of assessments of E_h (down to a deviation of only 1) that was associated with a significantly increased level of agreement across categories of staff. The concept of E_h, a dimensionless ratio of the pressure gradient for venous return divided by P_{ms}, follows the concept of Guytonian circulatory control[10] which is characteristic of the Navigator design. E_h may be affected by extracardiac factors, eg, tension pneumothorax, pericardial tamponade and intra-abdominal hypertension, as well as factors intrinsic to the heart, ie, rate, rhythm, inotropy and lusitropy. E_h is therefore a powerful tool to assess heart function beyond

estimated by registrars and nurses, compared with staff specialists and senior registrars. The frequency distribution of differences in scores for SVR is shown in Figure 3, with slightly more than 70% of observations in the $diff_{min}$ range. Agreement between suggested interventions, between all categories of staff, was only observed in four of 20 patients.

In contrast, there was agreement between staff categories in unblinded assessment of P_{msa} using the CDSS in most patients, with a reduced median $diff_{max}$ (Table 1), an increased proportion within the $diff_{min}$ range (70%), and a more narrow frequency distribution of differences (Figure 1). The results of the unblinded vs blinded assessment were significantly different for staff specialists and senior registrars. The results of the unblinded assessment of E_h were similarly in agreement between staff categories for most patients, with a reduced median $diff_{max}$ and an increased proportion of scores within the $diff_{min}$ range at 84%. There were no significant differences between different categories of staff before and after access to the CDSS. Agreement in unblinded assessment of SVR was observed for most patients with a reduced median $diff_{max}$ but with no change in the proportion of assessments within the $diff_{min}$ range. Staff specialists and registrars made significantly different assessments of SVR. Staff specialists stated that they agreed with the haemodynamic state displayed by the CDSS in 19 of 20 patients. The corresponding numbers for senior registrars, registrars and nurses were 16 of 20, 16 of 20 and 19 of 20, respectively.

Finally, an increased level of agreement was observed for interventions, so that similar management decisions were

the concept of generating an adequate cardiac output. The "clinically acceptable" CO observed in the patients in our study might have erroneously implied "normal" heart function. Thus, the CDSS provided useful information to separate the function of the heart as a pump from the venous return function governing CO. The precision of the CVP measurement, while useless to assess intravascular volume,[13] is crucial to the measurement of E_h. During the education sessions before starting the study, we emphasised the importance of appropriately levelling and zeroing the CVP pressure transducer to the phlebostatic axis.

The significantly increased level of agreement on haemodynamic management that was associated with the CDSS was largely the result of all categories of staff suggesting less fluid and increased inotropic support.

The level of agreement between categories of staff when blinded to the CDSS was highest for SVR. This is perhaps not surprising since the necessary haemodynamic information was already accessible from the standard clinical monitor, as opposed to P_{msa} and E_h that only the CDSS displayed. Nevertheless, the level of agreement increased further by unblinding participants to the CDSS, with staff specialists and registrars making significant adjustments to their SVR scores, resulting in a reduced level of divergence. The reason for the change in SVR scoring might relate to the way the CDSS displayed SVR. It was shown *together* with P_{msa} and E_h, hence the appropriate step in a patient with acceptable P_{msa} and E_h might be to decrease SVR in order to move into the desired MAP target area, even if MAP was not excessively increased to begin with.

All staff reported a high level of acceptance of the CDSS results in most patients. This indicates that compliance with the CDSS, if applied in the clinical routine, is likely to be high. The improved level of agreement (as proportions within categories of clinical staff as well as the reduced maximal range of difference when scoring pivotal haemodynamic variables) make it plausible that a clinical treatment protocol based on the CDSS could provide the important link between cardiovascular assessment and therapy lacking in most ICU monitors.

Our study did not include or permit any changes to ICU care solely based on the CDSS. The next step in evaluating the CDSS should focus on patient-centred outcomes as well as induced changes in management, eg, volumes of fluids and doses of inotropes or vasopressors as well as the time to reach haemodynamic targets and the time spent within the target area. The CDSS has previously been shown to perform with excellent concordance with expert intensivist and anaesthetist opinion,[6,7] but none of the previous studies was powered to analyse morbidity or mortality.

Our study has several important limitations. Only stable cardiac surgery patients were included in this single-centre, observational study. The ICU had well established clinical policies and protocols for postoperative management that might have reduced variability. A greater variability in haemodynamic targets and assessments may have been shown in another patient population, eg, patients with septic shock admitted on an acute basis to ICU, on whom the impact of the CDSS cannot be directly inferred. Furthermore, participants evaluated the patients over a limited period of time, so variability over time (eg, from admission to the first postoperative day) remains unknown. It could be significantly higher, given the involvement of more clinical staff members.

Variability was investigated between different categories of ICU clinical staff, who were asked individually to perform two sets of haemodynamic assessments, while blinded and unblinded to the CDSS. This highlights the interindividual variability. It might be equally important to investigate the intraindividual variability, ie, to study the consistency of one clinician over time. We decided, for practical reasons, not to include any intraindividual data, since independent changes in the haemodynamic status of the patients in the early postoperative period might have confounded the results. This would have necessitated the study of a significantly larger patient population over extended periods of time.

Conclusion

Use of a CDSS in postoperative cardiac surgery patients significantly improved the consistency between staff specialists, registrars and nurses in assessment of cardiovascular status and in decision making for patient management.

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Competing interests

None declared.

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