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Reliable critical care: making it easy to do the right thing

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Sir Muir Gray, Director of the NHS Chief Knowledge Office, hypothesized that 'The application of what we know will have a bigger impact than any drug or technology likely to be introduced in the next decade.' He recognized that blind investment in new drugs and technologies that provide only a modest improvement in efficacy may cost more lives than it saves, because this investment will consume scarce resources needed for improved delivery of care. Therefore, it can be argued from a health, economic, and moral standpoint that we should spend less on new technology and new drugs and more on improving systems for delivery of care[1] and turning knowledge into action.

Whilst few of us would disagree that robust evidence from clinical trials should be implemented to improve patient care, it has become apparent that a gap exists and that the translation of evidence into routine practice is not as widespread and easily done as one would have expected. Evidence suggests that it takes on average 17 years for research evidence to reach clinical practice.[2] This is a remarkably slow and inefficient process. Indeed, it took 13 years for cardiologists to recommend thrombolysis for the treatment of acute myocardial infarction after the publication of randomized controlled trials showed therapeutic benefit.[3] Furthermore, Lomas and colleagues[4] calculated a 5 year gap between publication of guidelines and changes to routine practice in Western health-care systems. Although the paucity of robust and high-quality evidence in critical care used to be cited as a reason for the lack of change in practice, critical care research in the last 10 years has been inundated with a number of practice-changing headlines, leaving clinicians with the responsibility of ensuring that these are incorporated into everyday practice to enable patients to receive safe, effective, and person-centred care.

In 2000, the acute respiratory distress syndrome (ARDS) network study demonstrated conclusively and unarguably that limiting tidal volume to <6 ml kg^{-1} predicted body weight (PBW) and end-inspiratory pressure to not more than 30 cm H_2O, compared with patients ventilated with higher tidal volumes (>12 ml kg^{-1} PBW), significantly reduces mortality in acute lung injury and ARDS, with a number needed to treat of 11 patients to save one life.[5] No special equipment or expertise was required to achieve this benefit. Despite the perceived relative simplicity of implementing low-tidal volume ventilation, a number of studies published in the last 10 years reveal a disappointing failure of clinicians to adopt and implement this piece of evidence.[6–8]

In a simple yet elegantly designed and conducted service evaluation study in this issue of the *BJA*, Bourdeaux and colleagues[9] have demonstrated how a large screen configured to display information routinely collected from a clinical information system resulted in a significant and sustained improvement in the use of evidence-based ventilation practice and reduced unwarranted tidal volume variation with improved reliability. In a mixed medical and surgical intesive care unit in a UK teaching hospital, two similar cohorts of patients on controlled mechanical

ventilation in two 6 month periods were studied, and data regarding the delivered tidal volumes were recorded and analysed. The intervention was simple. Two large (48 inch) display screens, which were visible to most staff working in the unit, were configured to display a number of metrics derived from the clinical information system database, including the tidal volume in millilitres per kilogram PBW, with real-time alerts if targets were breached. The authors observed that there was a significant increase in the time spent with tidal volumes <6 ml kg^{-1} (from 17.5 to 28.6%). The introduction of a large visual display with real-time alerts appears to be more effective in improving compliance than conventional audit processes where clinicians are presented with retrospective data highlighting non-compliance with expected standards.

Consequently, it is not only the timeliness of getting evidence into practice that is a challenge; it is also the quality and the reliability of the care that is provided. A large study from the USA reported that the 'defect rate' in the technical quality of American health care is 45%; in other words, only 55% of patients received the recommended care.[10] In The Netherlands, it has likewise been estimated that 30–40% of health care is not based on best available scientific evidence.[11] Consequently, quality critical care and anaesthesia are dependent on two variables, namely knowledge into action and reliability.

Translating knowledge into action

Knowledge translation is the process by which results from research are put to use in routine practice. It is the use of knowledge in health-care decision making as outlined by Straus and colleagues,[12] namely creating, acquiring, and disseminating knowledge, to manage and expedite the flow of knowledge into practice. It helps to clarify the distinction between efficacy (demonstrated in clinical trials; i.e. results achieved in rigorously controlled conditions in carefully selected patients) and clinical effectiveness (experienced in day-to-day practice, where unselected patients are managed in variable conditions).

Translating knowledge into action is thus the provision of 'know-what' (i.e. validated evidence and guidance for safe and effective care) and 'know-how' (i.e. evidence about effective implementation methods). This combination of knowledge about interventions and about implementation helps to create more reliable health care that is safe, effective, and person-centred. Improved critical care outcomes depend as much on knowledge from practice and experience as on published research knowledge. 'Know-what' helps the physician to answer the question, 'Does this intervention work?' 'Know-how' answers the question, 'How do I make it work better here, for my patients?'

An interesting model proposed to ensure knowledge translation to improve health care in the USA is the '3Ts' road map.[13] The three steps are Translation 1 (T1), Translation 2 (T2), and Translation 3 (T3). Translation 1 comprises activities that test what works or clinical efficacy research to determine which intervention is effective, T2 consists of activities that focus on patient-specific evidence of clinical effectiveness or outcomes research, and finally, T3 consists of activities that test delivery of the intervention reliably and in all settings. Translation 3 includes measurement and evaluation of quality, implementation of interventions, and health-care redesign, scaling, and spread of effective designs.

There are many barriers to successful implementation, and these can be mapped into three main domains: knowledge; attitudes and behaviour, including lack of awareness of evidence, lack of familiarity, lack of agreement, lack of belief in self-efficacy, and lack of motivation; and organizational or environmental barriers. Rubenfield and colleagues[14] surveyed nurses and respiratory therapists in the institutions that participated in the ARDS network study[5] and identified barriers to both initiation and continuation once commenced. Barriers to initiation included physician reluctance to relinquish control over ventilator adjustments, failure of recognition of acute lung injury/ARDS, and difficulty with calculating low tidal volume based on PBW. Barriers to continuation included concerns over patient distress, permissive hypercapnia, and the permissive oxygenation (acceptance of oxygen saturations of 88%) observed with low-tidal volume ventilation.

The study by Bourdeaux and colleagues[9] perhaps addresses some of these barriers, namely the reluctance of physicians to relinquish control by allowing them to retain the reins of ventilator settings, simplification of the process of calculating 6 ml kg^{-1} tidal volumes based on PBW, and finally, removing a few steps from the recognition that the tidal volume is elevated in the decision-making process.

The crucial rate-limiting step in knowledge translation is the care delivery or implementation. Traditional processes, such as advice and feedback, care pathways, protocol use, or practice guidelines, are at best modestly effective in critical care because these initiatives target the problem too far downstream after the event. The critical care environment has been identified as a complex adaptive system, not unlike the stock market, where performance hinges more on the dynamic interactions of the adaptable elements (i.e. the team rather than the contribution of each individual). A complex adaptive system is an interactive structure with adaptable elements that have the freedom to act unpredictably and where the relationships of the elements are not the sum of individual static entities. The greatest strength of such a system is resilience in the face of adversity. Failure to adopt high-quality evidence can therefore be viewed through a systems thinking lens as an organizational problem rather than an individual problem. Solutions that focus on changing organizational factors, such as culture, communication, and the working environment, would consequently be more effective in implementation and ensuring reliability.

Reliable design

A good operational definition of reliability in health care is 'failure-free operation over time',[15] and this is something that we continually strive for in both anaesthesia and critical care. In fact, the critical care community has a proven track record with regard to the success of reliable health care, namely, the Ventilator Associated Pneumonia (VAP),[16] central line-associated bloodstream infection (CLABSI),[17] and Sepsis bundles.[18]

In the aforementioned article by Bourdeaux and colleagues,[9] the authors show a significant increase in compliance with evidence-based controlled mechanical ventilation, with the time spent with tidal volumes <6 ml kg^{-1} increasing from 17.5 to 28.6%. So, why is it, some 15 years after the publication of this landmark ARDS network trial,[5] that we are still achieving reliable protective lung ventilation only one in four times, even with the help of technology? Well, health care is increasingly complex; indeed, the Institute of Medicine described it as one of the 'most complex of human endeavours'.[19] Current performance improvement methods are highly dependent on training and education, with an over-reliance on vigilance and hard work. We have a tendency to focus on benchmarked outcomes, thereby exaggerating the reliability within health care, giving both clinicians and leadership a false sense of security. The evidence of

harm from not following lung-protective ventilation is not tangible, with the outcome not immediately linked to the process. Finally, we rarely use deliberate design to achieve reliability goals, making it easy to do the right thing and difficult to do the wrong thing.

The Institute for Healthcare Improvement has a three-step model for applying principles of reliability to health-care systems,[15] as follows: (i) prevent initial failure using intent and standardization (e.g. VAP bundle); (ii) identify failure when it occurs and intervene before harm is caused (e.g. World Health Organization Surgical Safety Checklist) or mitigate the harm caused by failures that are not intercepted with a back-up plan or contingency function (e.g. plan B in a failed intubation); and (iii) measure and then communicate learning from defects back into the design process (real-time assessment with root cause analysis).

The study by Bourdeaux and colleagues[9] is a potentially promising example of the first two steps of the Institute for Healthcare Improvement reliable design model. However, in order to achieve process reliability for lung-protective ventilation of 80–90% and above, further work needs to be done. The public and transparent display of clinical information, such as the one by Bourdeaux and colleagues,[9] in combination with computerized support decision making, real-time feedback of data, staff briefings, staff education as to the 'know-why' or 'know-what' of protective lung ventilation alongside other quality-improvement interventions, and a reliable design strategy will make it easy to do the right thing and difficult to do the wrong thing when it comes to lung-protective ventilation.

Declaration of interest

K.D.R. is critical care faculty for the Institute for Healthcare Improvement, Cambridge, MA, USA.

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CRITICAL CARE

Evaluation of an intervention to reduce tidal volumes in ventilated ICU patients[†,‡]

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Abstract

Background: There is considerable evidence that the use of tidal volumes <6 ml kg^{-1} predicted body weight (PBW) reduces mortality in mechanically ventilated patients. We evaluated the effectiveness of using a large screen displaying delivered tidal volume in ml kg^{-1} (PBW) for reducing tidal volumes.

Methods: We assessed the intervention in two 6-month periods. A qualitative study was undertaken after the intervention period to examine staff interaction with the intervention. The study was conducted in a mixed medical and surgical intensive care unit at University Hospitals Bristol, UK. Consecutive patients requiring controlled mechanical ventilation for more than 1 h were included. Alerts were triggered when tidal volume breached predetermined targets and these alerts were visible to ICU clinicians in real time.

Results: A total of 199 patients with 7640 h of data were observed during the control time period and 249 patients with 10 656 h of data were observed in the intervention period. Time spent with tidal volumes <6 ml kg^{-1} PBW increased from 17.5 to 28.6% of the period of controlled mechanical ventilation. Time spent with a tidal volume <8 ml kg^{-1} PBW increased from 60.6 to 73.9%. The screens were acceptable to staff and stimulated an increase in attendance of clinicians at the bedside to adjust ventilators.

Conclusions: Changing the format of data and displaying it with real-time alerts reduced delivered tidal volumes. Configuring information in a format more likely to result in desired outcomes has the potential to improve the translation of evidence into practice.

Key words: acute respiratory distress syndrome; behavioural economics; computerised decision support systems; lung protective ventilation; quality improvement

The translation of evidence-based interventions into clinical practice in patients receiving mechanical ventilation remains a challenge. Randomized controlled trials and meta-analyses have shown that the use of lung protective ventilation (LPV) reduces mortality in patients with acute respiratory distress syndrome (ARDS).[1–4] A large randomized controlled trial demonstrated reduced mortality (31% *vs* 40%) in patients ventilated with low tidal volumes [<6 ml kg^{-1} predicted body weight

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Editor's key points

- The implementation of proven interventions into clinical practice is often delayed.
- This study evaluated the effect on clinicians' behaviour of using a large visual screen to display real-time delivered tidal volumes in ICU patients.
- Use of the real-time displays led to an increase in clinicians' adjustments to ventilator settings at the bedside. Consequently, compliance with recommended standards improved.
- These data suggest that simple changes in the way in which information is displayed to clinicians can change their practice.

(PBW)] compared with patients ventilated with higher tidal volumes (>12 ml kg^{-1} PBW).[2] More recently, several trials have demonstrated that the use of lower tidal volumes benefits patients both with and without ARDS at the onset of mechanical ventilation.[5–11]

Although reducing tidal volumes remains one of the few proven interventions to reduce mortality in mechanically ventilated patients, this intervention is inconsistently applied to patients who may benefit.[12–15] A recent observational study on patients with ARDS undertaken in four academic teaching hospitals found that only 41% of eligible ventilator settings were adherent to LPV criteria and 37% of patients never received LPV.[16] In the control group of the High Frequency OSCillation in ARDS (OSCAR) trial undertaken in patients with ARDS in UK intensive care units (ICUs), patients were ventilated with an average tidal volume of 8.3 ml kg^{-1} PBW for the first 3 days after enrolment despite clinicians being encouraged to use LPV.[17]

Difficulty diagnosing ARDS; lack of education; lack of a protocol; concerns over hypercarbia, acidosis, and hypoxemia; and physician perceptions of the contraindications to LPV have all been suggested as reasons for the underuse of LPV.[14 18–21] Interestingly, although physicians may document an intention to use LPV and state that they deliver it frequently or always, they still often fail to deliver it to their patients.[19 22] Failure to implement LPV is clearly not just a failure of intent.

To test whether the way clinical information is presented to staff can improve the compliance with low tidal volume ventilation, we deployed two large screens that display delivered tidal volume in the format of ml kg^{-1} PBW at either end of our ICU. Information was displayed for all patients in the ICU with values derived from the clinical information system (CIS), using real-time alerts when volumes breached 6 and 8 ml kg^{-1} PBW. A qualitative study of the acceptability and impact of the displays among staff was undertaken after the intervention period in this study was complete.

Methods

We performed a prospective before and after evaluation of the effect of the displays on delivered tidal volume to all patients receiving controlled mechanical ventilation in two distinct 6-month periods in the ICU at University Hospitals Bristol. The first 6-month period (November 1, 2010–April 30, 2011) acted as the control period and during this time there was no access to the alerting displays. In the second 6-month period (November 1, 2011–April 30, 2012), the displays were in use. The intervention period commenced after the displays had been installed and checked over a period of 6 months. No other interventions were introduced between the two time periods. No protocols or quality improvement processes were changed and ventilation equipment was the same in both the control and intervention period.

The ICU at University Hospitals Bristol is a closed-format tertiary medical and surgical ICU with 13 consultants, 10 senior fellows, and 5 junior fellows. Consultants are permanent and fellows rotate through the unit every 3 months. There were two rotations of fellows during each study period. Ventilator settings are predominantly adjusted by the consultants and senior fellows. A small number of experienced nurses also make adjustments to ventilator settings, but they tend to check these with a doctor shortly afterwards. The unit does not employ respiratory therapists. Pressure-controlled ventilation is the preferred method for delivery of controlled mechanical ventilation. The institutional research board classified the study as a service evaluation and waived the requirement for individual patient consent and formal ethical review.

The unit has used the Innovian Solution Suite clinical information system (Dräger, Lübeck, Germany) since 2008. This is an electronic charting system that automatically collects all information relating to patient care, including physiological data, laboratory results, and data from ventilators. This information is displayed on a computerised chart and is also stored on a database (SQL Server 2008; Microsoft, Redmond, WA, USA). The data in the database are available for immediate analysis. An algorithm was constructed to take real-time data from the database and automatically calculate delivered tidal volumes in the format ml kg^{-1} PBW using the formulas PBW=[height in cm−154]×0.9+50 for males and PBW=[height in cm−154]×0.9+45.5 for females.[23] Staff can access the CIS at the bedside, on central desktop computers, and remotely on computers housed away from the ICU. The display screens described in this study are not visible from within the CIS; they operate completely separately and are mounted on the wall.

Intervention

Two large 48-inch display screens were configured to display a number of metrics derived from the CIS database using freely available reporting software (Visual Studio 2008, Microsoft) (Fig. 1). They were mounted on the wall at either end of the ICU and were visible to most staff working in the unit.

Tidal volume alerts

The screens alerted to increased tidal volume by turning yellow when the tidal volume was ≥6 and <8 ml kg^{-1} PBW. When the tidal volume was ≥8 ml kg^{-1} PBW the display turned red. The alerts did not cancel until the measured tidal volume returned to <6 ml kg^{-1} PBW. The alerts were only applied to patients receiving controlled mechanical ventilation. Tidal volumes for patients on spontaneous breathing modes were displayed in ml kg^{-1} PBW, but without coloured alerts. The information on the screens was refreshed every 5 min. The latest P_{O_2} from an arterial blood gas was also displayed on screens among other metrics. If the P_{O_2} was >100 mmHg the box turned red. This was the only other metric displayed that had a coloured alert. For the purposes of this study we only analysed the effect of the screens on tidal volume.

All ICU physicians were notified by email that the screens would be introduced at the start of the second study period. Rotating fellows received one standard email when they joined the

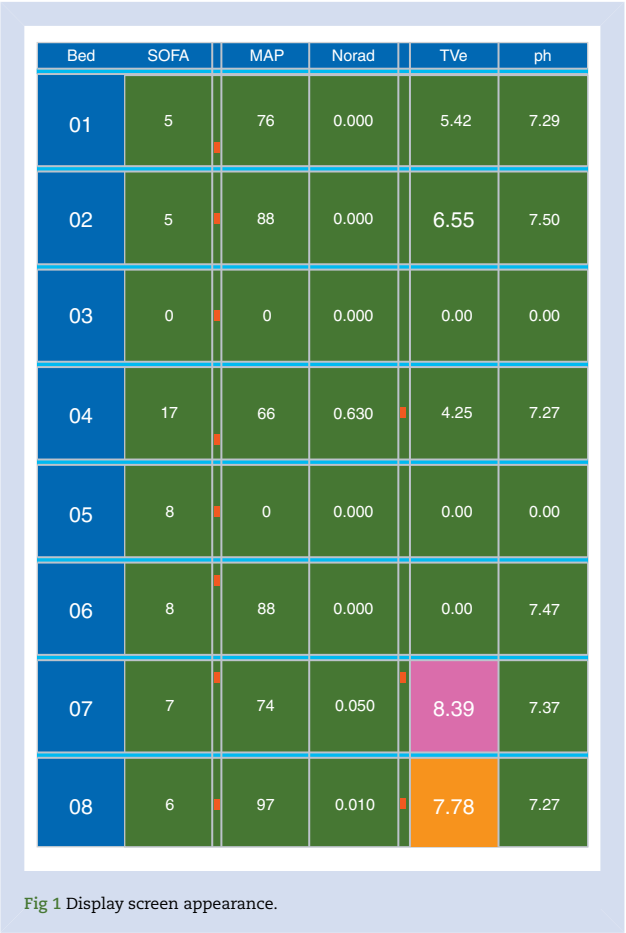

Fig 1 Display screen appearance.

unit informing them of the function of the screens. Nurses received a similar notification via the staff communication book. No other education or information campaign relating to low tidal volume ventilation occurred during the two study periods.

Patients

All patients receiving conventional controlled mechanical ventilation for more than 1 h during the two study periods were eligible for inclusion in the study. Patients receiving high-frequency oscillatory ventilation or airway pressure release ventilation were excluded since tidal volume is not directly manipulated in these modes.

Data collection

Data were collected on the CIS database. The configuration of the displays did not alter the format of the database and data were collected in the same way for both the control and intervention period. The tidal volumes for every hour of controlled mechanical ventilation were available for analysis; tidal volumes when patients were on spontaneous modes were excluded. Data were extracted for tidal volume (ml kg^{-1} PBW), patients' age (categorized as <50, 50–<60, 60–<70 and ≥70 years), sex, Acute Physiology and Chronic Health Evaluation (APACHE) II score, Sequential Organ Failure Assessment (SOFA) score, peak inspired pressure (PIP) set (in mbar), positive end expiratory pressure (PEEP) (in mbar), pH (multiplied by 100), day of the week (classified into hours falling on weekdays and hours falling on weekends), time of day (8 AM–6:59 PM and 7 PM–7:59 AM), and patient status (improved or died at ICU discharge).

Statistical methods

Mixed effects logistic regression models that take repeated measures within individual patients into account were used to quantify associations of exposures with the binary outcome of a tidal volume <6 ml kg^{-1} PBW (i.e. consistent with LPV and coded 1 for the analysis). The first model included all variables that either stayed constant for each patient or were measured for every hour of data collection. Unadjusted and fully adjusted odds ratios (ORs) and 95% CIs are presented. Models were run on the sample with complete data for all variables of interest. A second model, on a reduced sample size, included the same variables as the first model, as well as variables that were only measured sporadically (pH and Pa_{O_2}/FI_{O_2}). The 3-month moving averages were calculated for mean tidal volume for a time period of 1 year prior to implementation and 1 year after full implementation to account for linear trends in tidal volume with time. The association between the time period (control or dashboard intervention) and patient status was examined using a chi-squared test. All analyses were carried out using Stata version 12 (StataCorp, College Station, TX, USA).

Qualitative analysis of staff interaction with the screens

An interview-based qualitative study was undertaken after the screens had been deployed for 9 months (i.e. 3 months after the intervention period in this study) to assess staff reactions to the intervention. An independent qualitative researcher interviewed a representative sample of staff (consultants, fellows, senior and junior nurses). Interviews were audio recorded and transcribed. A thematic analysis of the interview data was performed by an experienced qualitative researcher using an iterative approach.[24]

Results

Effect of screens on tidal volume

A total of 199 patients with 7640 h of data were observed during the control time period and 249 patients with 10 656 h of data were observed in the dashboard intervention period. Baseline characteristics were similar between the control and intervention groups (Table 1). Overall, the majority (69%) of patients were male and 24.1 and 31.7% of patients were ≥70 years of age in the control and intervention periods, respectively. The mean APACHE II score was 16.7 (SD 5.5) in the control period and 17.6 (SD 6.0) in the intervention period. The proportion of time spent with a tidal volume <6 ml kg^{-1} PBW was lower in the control period (17.5%) compared with the dashboard intervention period (28.6%). The proportion of time spent with a tidal volume <8 ml kg^{-1} PBW was 60.6% in the control period and 73.9% during the intervention period. The mean tidal volume decreased from 7.7 (SD 2.1) to 7.0 (SD 2.0) ml kg^{-1} PBW from the control to the intervention period.

In the fully adjusted model, the dashboard intervention period was associated with an approximate two-fold increased odds of achieving a tidal volume <6 ml kg^{-1} PBW (OR 1.91; 95% CI 1.29, 2.82; P=0.001; Table 2). The estimate for the dashboard intervention was not substantially changed in the model that also controlled for the sporadically measured variables (OR 2.00; 95% CI 1.18, 3.39; P=0.010; Table 3). Other variables that were associated with achieving a tidal volume <6 ml kg^{-1} PBW in fully adjusted

Table 1 Study characteristics. APACHE:Acute Physiology and Chronic Health Evaluation; IQR: interquartile range; PEEP: positive end expiratory pressure; PIP: peak inspired pressure; SOFA: Sequential Organ Failure Assessment.

Characteristics by patient	Control period	Dashboard period
Patients, *n*	199	249
Age group (years), *n* (%)		
<50	47 (23.6)	58 (23.3)
50–<60	55 (27.6%)	50 (20.1)
60–<70	49 (24.6)	62 (24.9)
≥70	48 (24.1)	79 (31.7)
Sex, *n* (%)		
Female	62 (31.2)	78 (31.3)
Male	137 (68.8)	171 (68.7)
APACHE II score, mean (SD)	16.7 (5.5)	17.6 (6.0)
Median length of stay, h (IQR)	120 (61–242)	116 (69–233)
Median length of ventilation, h (IQR)	34 (10–93)	34 (10–84)
Characteristics by hour of ventilation		
Total hours of ventilation	7640	10 656
Days of week, h (%)		
Falling on weekdays	5382 (70.4)	7721 (72.5)
Falling on weekends	2258 (29.6)	2935 (27.5)
Time of day, h (%)		
8 AM–6:59 PM	3333 (43.6)	4553 (42.7)
7 PM–7:59 AM	4307 (56.4)	6103 (57.3)
SOFA score, *n* [mean (SD)]	6201 [8.9 (3.3)]	9043 [8.9 (3.9)]
PIP set, *n* [mean (SD)]	7640 [23.6 (5.8)]	10 655 [21.0 (5.0)]
PEEP, *n* [mean (SD)]	7638 [8.0 (3.0)]	10 655 [8.3 (3.0)]
pH, *n* [mean (SD)]	3071 [7.35 (10.8)]	4099 [7.35 (10.8)]
Pa_{O_2}/FI_{O_2}, *n* [mean (SD)]	3050 [212 (108)]	4090 [228 (116)]
Tidal volume, ml kg^{-1}, *n* [mean (SD)]	7628 [7.7 (2.1)]	10 652 [7.0 (2.0)]
Tidal volume group, *n* (%)		
<6	1333 (17.5)	3045 (28.6)
6 to <7	1510 (19.8)	2677 (25.1)
7 to <8	1778 (23.3)	2147 (20.2)
≥8	3007 (39.4)	2783 (26.1)

models were the PIP set, PEEP and pH. An increase in the proportion of hours with a tidal volume <6 ml kg^{-1} PBW was seen for the dashboard intervention compared with the control period and was observed across all levels of Pa_{O_2}/FI_{O_2} at the start (Table 4). For example, for patients with a Pa_{O_2}/FI_{O_2} at the start of <100, 230/1490 (15.4%) of their hours of data achieved a tidal volume of <6 ml kg^{-1} PBW in the control period compared with 326/1252 (26.0%) hours in the intervention period. For patients who had the highest Pa_{O_2}/FI_{O_2} (≥300), the percentage of hours with a tidal volume <6 ml kg^{-1} PBW increased from 23.5% in the control period to 31.0% in the intervention period.

The mean tidal volume dropped after the introduction of the display screens, but appeared to have risen slightly 6 months after full implementation (Fig. 2). There was no evidence that the control/intervention period was associated with patient outcome (chi-square P=0.538).

Factors affecting staff interaction with the screens—qualitative analysis

Four consultants, three fellows, eight nurses, and one physiotherapist were interviewed and their data extracted and analysed. LPV was accepted as a fundamental concept by all staff. The tidal volume alerts were considered helpful. Two clear staff groups with contrasting views emerged; doctors and senior nurses who have responsibility for the entire ICU, and bedside nurses who are primarily responsible for one patient at a time. The screens were used differently by each group. The doctors and senior nurses with responsibility for the whole unit found the screens more useful than did the bedside nurses. They indicated that the most useful aspect of the screens was that they stimulated attendance of either a doctor or senior nurse to the bedside to assess the patient, often leading to a subsequent recalculation of the target tidal volume. Bedside nurses found the display less useful and commented that they would prefer a bedside display of target tidal volume in order to incorporate this into their patient checks. A greater explanation of the rationale for the screens would have been beneficial for the bedside nurses.

Discussion

This study demonstrated an improvement in the delivery of low tidal volumes to patients receiving controlled mechanical ventilation. Time spent at <6 ml kg^{-1} PBW and 8 ml kg^{-1} PBW as a percentage of time on controlled ventilation was increased. The average tidal volume was reduced during the intervention period and the findings were sustained throughout the intervention period. The reduction in tidal volumes was still apparent more than 1 yr after the screens were deployed. Increased deployment of low tidal volumes was achieved independently of any attempt to change the intentions of clinicians to deploy lower tidal volumes. No educational interventions or quality improvement

Table 2 Odds ratios for achieving tidal volume <6 ml kg^{-1}, from mixed effects logistic regression models. Binary outcome of Tve <6 coded as 1. APACHE: Acute Physiology and Chronic Health Evaluation; OR: odds ratio; PEEP: positive end expiratory pressure; PIP: peak inspired pressure; SOFA: Sequential Organ Failure Assessment.

	Unadjusted (*n*=305 people, 12 991 h)			Fully adjusted (*n*=305 people, 12 991 h)		
	OR	95% CI	*P*	OR	95% CI	*P*
Time period						
Control (reference group)	1.00		<0.001	1.00		0.001
Dashboards	2.19	(1.50, 3.20)		1.91	(1.29, 2.82)	
Age, years						
<50 (reference group)	1.00		0.408	1.00		0.306
50–<60	0.93	(0.54, 1.59)		1.03	(0.60, 1.78)	
60–<70	0.81	(0.47, 1.40)		0.82	(0.47, 1.41)	
≥70	0.65	(0.38, 1.11)		0.65	(0.37, 1.12)	
Sex						
Female (reference group)	1.00			1.00		0.087
Male	0.81	(0.54, 1.22)	0.319	0.70	(0.46, 1.05)	
APACHE II (per score unit)	1.01	(0.98, 1.05)	0.412	1.01	(0.97, 1.05)	0.613
SOFA (per score unit)	1.03	(1.01, 1.06)	0.018	1.05	(1.02, 1.08)	0.001
Days of week						
Weekday (reference group)	1.00		0.876	1.00		0.612
Weekend	0.99	(0.88, 1.12)		0.99	(0.86, 1.09)	
Time of day						
8 AM–6:59 PM (reference group)	1.00		0.561	1.00		0.509
7 PM–7:59 AM	0.97	(0.88, 1.07)		0.97	(0.88, 1.07)	
PIP set (per mbar)	0.95	(0.94, 0.96)	<0.001	0.95	(0.92, 0.95)	<0.001
PEEP (per mbar)	1.02	(1.00, 1.05)	0.092	1.02	(1.05, 1.11)	<0.001

Table 3 Odds ratios for achieving tidal volume <6 ml kg^{-1}, from mixed effects logistic regression models including the variables pH and Pa_{O_2}/FI_{O_2} which were only measured sporadically. *pH×100. APACHE: Acute Physiology and Chronic Health Evaluation; OR: odds ratio; PEEP: positive end expiratory pressure; PIP: peak inspired pressure; SOFA: Sequential Organ Failure Assessment.

	Unadjusted (*N*=297 people, 5093 h)			Fully adjusted (*N*=297 people, 5093 h)		
	OR	95% CI	*P*	OR	95% CI	*P*
Time period						
Control (reference group)	1.00		<0.001	1.00		0.010
Dashboards	2.17	(1.44, 3.27)		2.00	(1.18, 3.39)	
Age, years						
<50 (reference group)	1.00		0.251	1.00		0.307
50–<60	0.95	(0.54, 1.68)		0.85	(0.41, 1.74)	
60–<70	0.74	(0.42, 1.33)		0.64	(0.31, 1.33)	
≥70	0.59	(0.33, 1.05)		0.52	(0.25, 1.09)	
Sex						
Female (reference group)	1.00		0.651	1.00		0.224
Male	0.90	(0.58, 1.41)		0.71	(0.41, 1.24)	
APACHE II (per score unit)	1.03	(1.00, 1.07)	0.079	1.03	(0.98, 1.08)	0.220
SOFA (per score unit)	1.03	(1.00, 1.07)	0.087	0.99	(0.95, 1.03)	0.645
Days of week						
Weekday (reference group)	1.00		0.495	1.00		0.222
Weekend	1.07	(0.88, 1.29)		0.88	(0.71, 1.08)	
Time of day						
8 AM–6:59 PM (reference group)	1.00		0.385	1.00		0.985
7 PM–7:59 AM	0.94	(0.8, 1.09)		1.00	(0.85, 1.18)	
PIP set (per mbar)	0.95	(0.93, 0.97)	<0.001	0.91	(0.89, 0.94)	<0.001
PEEP (per mbar)	1.04	(1.00, 1.08)	0.040	1.08	(1.03, 1.13)	0.002
pH*	0.913	(0.905, 0.921)	<0.001	0.899	(0.888, 0.909)	<0.001
Pa_{O_2}/FI_{O_2} (per mmHg)	0.999	(0.998, 1.00)	0.098	1.000	(0.999, 1.000)	0.411

initiatives relating to the use of lower tidal volumes were conducted during the study period. The screens were accepted by a cross section of staff and they appear to have stimulated a greater discussion of target tidal volume between doctors and senior nurses and nurses at the bedside.

This study analysed tidal volumes for every consecutive hour of controlled mechanical ventilation applied to all our patients over a total of 12 months and, as such, gives excellent insight into the ventilation practice within our ICU. Most studies examining compliance with low tidal volumes only quote discrete ventilator settings measured at a few predetermined time points during the day. Compliance with low tidal volume ventilation measured in this way is subject to error if clinicians pay more attention to ventilator settings at these time points. An important limitation is that the intervention in this study was not randomized and the before and after effects reported originate from one ICU. As with any before-and-after design, our results may be influenced by other unmeasured factors. Every attempt was made to standardise the care delivered in the two time periods analysed and no co-interventions relating to ventilation practice changed during the study. The reduction of tidal volume in the intervention group in this study suggests the need for a larger randomised, multicentre trial, which will now be undertaken.

Compliance with low tidal volume ventilation was low in this study, but it compares reasonably with previous studies.[12 13] The average tidal volume in both groups is substantially lower than that reported in the conventional ventilation group of the OSCAR trial[17] and, as such, the practice observed in this trial is likely to represent that of a well-performing UK ICU. During the period of data collection our ICU used predominantly pressure-controlled ventilation in which tidal volumes can vary according to changes in lung compliance. It may be easier to control tidal volumes using a volume-controlled mode, but we are aware of no evidence that suggests that volume-controlled ventilation results in better adoption of LPV. The choice of the mode of ventilation deserves further study, and we plan to do this.

Computerized decision support systems have been shown in several studies to improve adherence to LPV protocols when used in conjunction with a CIS. In one study, a ventilator-induced lung injury 'sniffer' was employed to screen the medical record for patients at risk and alert staff via a page when ventilator settings were potentially injurious.[25] This led to a significant reduction in the time spent with excessive tidal volumes. A non-rule-based alert within the medical record that reminded staff of the target tidal volume in ml kg^{-1} PBW was effective at reducing excessive tidal volumes in all patients ventilated for >24 h.[26] Retrospective feedback on compliance with LPV in conjunction with an education programme successfully improved compliance with LPV in one study.[27]

We displayed information regarding tidal volume in ml kg^{-1} PBW in all patients receiving controlled mechanical ventilation

Table 4 Whether Tve <6 ml kg^{-1} PBW was achieved by Pa_{O_2}/FI_{O_2} at the start of ventilation. Tve, tidal volume (of expired breath)

Pa_{O_2}/FI_{O_2} at start	Control period		Dashboards period	
	Total hours of data	*n* (%) with Tve <6	Total hours of data	*n* (%) with Tve <6
<100	1490	230 (15.4)	1252	326 (26.0)
100 to <200	2476	334 (13.5)	3595	950 (26.4)
200 to <300	1634	311 (19.0)	1909	577 (30.2)
≥300	1712	403 (23.5)	3050	946 (31.0)

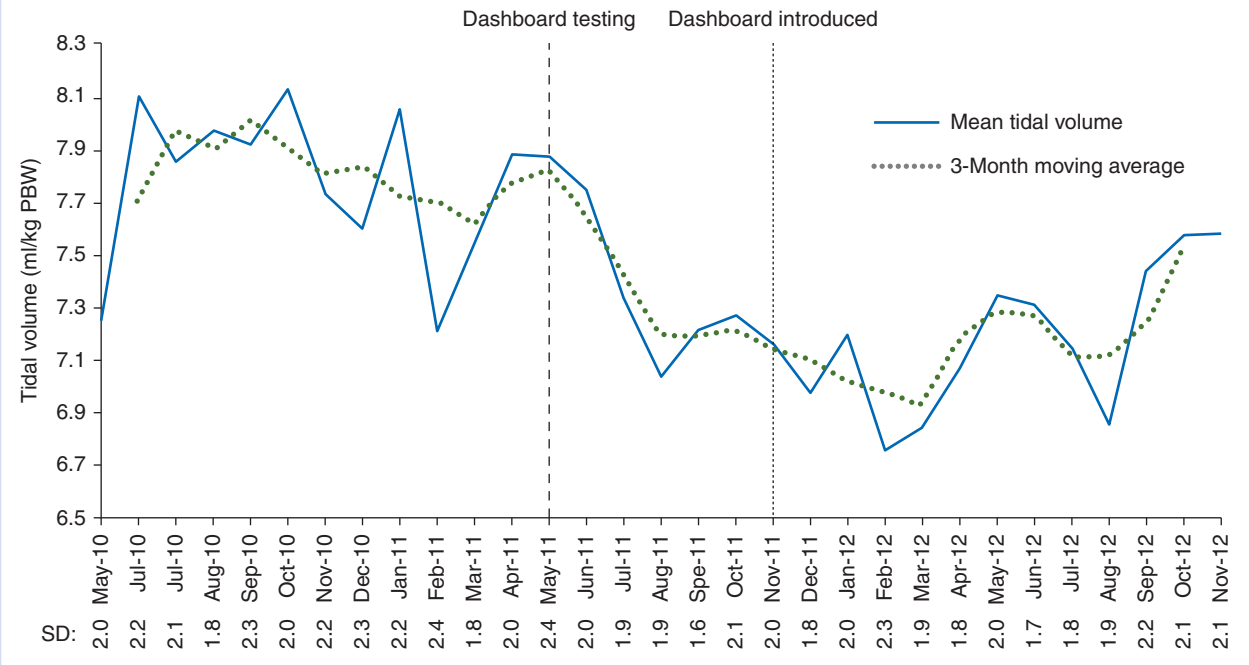

Fig 2 Mean tidal volume in each month and 3-month rolling averages during the periods before dashboards, during testing (May–November 2011), and after the full introduction of the display screens in November 2011.

in real time. This is simpler to configure than systems that attempt to filter for patients with criteria for ARDS, which require free text searches of radiology reports.[25 28 29] The dashboard display is constantly visible, with the advantage that staff don't need to enter individual patient records to ascertain compliance. No education programme was associated with our intervention and our analysis demonstrates the effectiveness of real-time feedback alone in changing practice.

It could be argued that a formal quality improvement process with repeated education, use of champions, repeated meetings, and strategies to share and feed back data would have enhanced compliance with LPV in this study. We deliberately avoided this approach in order to demonstrate the effect of simple changes to the display of information on clinical practice. As such, our study highlights a useful additional strategy to be deployed alongside established quality improvement methodologies. Our qualitative work demonstrated that bedside nurses may have found an education programme useful alongside introduction of the screens, and we will include this in future work.

Several studies have suggested that difficulties with the identification of the subgroup of patients with ARDS is a barrier to implementation of LPV.[14 18 19] We alerted for high tidal volumes in all patients, not just those with ARDS, and this is likely to have contributed to the effect in the intervention group. Interestingly, the severity of lung injury as evidenced by Pa_{O_2}/FI_{O_2} at the start of controlled ventilation was not associated with the increased use of low tidal volumes in our study, although all patients with a Pa_{O_2}/FI_{O_2}<300 mm Hg benefited from an increased use of low tidal volume ventilation in the intervention group.

Improving the implementation of evidence-based interventions involves changing behaviour and influencing the decisions that clinicians make. Research in the fields of cognitive psychology, neuroscience, and behavioural economics has converged on a dual process model of decision-making.[30] Many decisions are rapid, often subconscious, and are heavily influenced by environmental and emotional factors. A minority of decisions are made more deliberately but require a high degree of cognitive effort. Influencing the environment in which decisions are made has the potential to deliver significant behaviour change independent of changing people's intentions.[31 32]

Simple changes to the choices presented to clinicians can have profound effects on their subsequent decisions. One study found a highly significant difference in the dose of sedation delivered to endoscopy patients, which depended on the volume of pre-filled syringes available to the endoscopist.[33] The screens in our study improved the availability of salient information regarding tidal volume. Calculation of the 'correct' tidal volume for any particular patient requires knowledge of their height, the use of a formula to calculate predicted body weight, and the division of the actual tidal volume by the predicted body weight. This kind of complex cognitive activity is difficult to incorporate into busy clinical practice.

The screens in this study changed the clinical environment by presenting information from multiple sources in a format that is more likely to result in the reliable delivery of ventilation with lower tidal volumes. The configuration of the clinical environment is often *ad hoc* and based on historic preferences that may not reflect changes in desired care processes as new evidence emerges. This is one of the first studies to demonstrate the impact of environmental influences on clinician behaviour in the ICU and, as such, provides insight into how this approach might be developed in the ICU and beyond.

The control of tidal volume must occur at all times of the day in order to be effective. In our unit, ventilator settings are often only adjusted when clinicians pay attention to individual patients during rounds or when prompted by nursing staff on the basis of clinical concern. Adherence to low tidal volume ventilation is one consideration among many that clinicians must bear in mind when adjusting the ventilator. The intervention in this study appears to have stimulated greater interaction between clinicians with oversight of the entire unit and staff at the bedside with particular reference to the desired tidal volume. This resulted in a highly significant reduction in delivered tidal volumes. Reducing tidal volume is important because the consistent implementation of low tidal volumes is likely to improve outcomes and be cost effective in patients with acute lung injury/ARDS.[34] The principle of changing the format of displayed information from a CIS is highly applicable to all ICUs with a CIS and may improve the delivery of many evidence-based interventions unrelated to ventilation.

Conclusions

The implementation of a large screen configured to display information routinely collected from a CIS in a format more likely to promote the implementation of low tidal volume ventilation resulted in a significant and sustained improvement in the use of evidence-based ventilation practice and was acceptable to the staff. The principle of configuring the clinical environment in which decisions are made in order to make it easier to comply with desired goals is widely applicable to health care. It has the potential to reduce unwanted variation in clinical practice and improve the implementation of evidence-based interventions.

Authors' contributions

C.B., M.T. and T.G. designed the study. C.B. and K.B. wrote the manuscript. K.B., J.S., A.T. and J.D. undertook the statistical analysis. J.B. and J.B. designed and undertook the qualitative evaluation.

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Declaration of interest

None declared.

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