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Evaluation of a pulmonary graphical display in the medical intensive care unit: an observational study

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Abstract

We developed a pulmonary graphic display that depicts pulmonary physiological variables for intubated, mechanically ventilated patients in a graphical format. The pulmonary graphical display presents multiple respiratory variables and changes are depicted by alterations in shape and color. Learning how this new technology will be integrated and accepted by users is an important step before it is introduced into the clinical arena. This study observed use and acceptance of the pulmonary graphical display by health care providers in an intensive care unit. Investigators noted that physicians, respiratory therapists, and nurses observed the pulmonary graphical display on average six, three, and one times, respectively, per patient room entry. Based on questionnaires, the pulmonary graphical display was perceived as useful, a desirable addition to current ICU monitors, and an accurate representation of respiratory variables.

Keywords: Graphic data displays; Computer graphics; Human factors; Patient monitoring; Usability testing

1. Introduction

Monitoring and assessing patients in an intensive care unit (ICU) presents a challenge to caregivers. One of the goals of monitoring devices is to detect critical events early so they can be corrected before patient injury occurs [1]. Monitoring systems that increase situation awareness shorten the time between the occurrence of unexpected events and the correction of these events [2,3]. Graphical displays integrate, organize, and present data in a manner that aids caregivers in assimilating information more rapidly and facilitates efficient and timely medical interventions [4].

Current ICU medical monitors provide discrete data and discrete alarms that alert clinicians to parameters outside a set range. They do not, however, integrate multiple data points to provide a comprehensive representation of patient physiology. Most medical monitoring systems use a "single-sensor-single-indicator" display paradigm [3]. As a result, clinicians must observe and integrate multiple data points generated by independent sensors. This process of sequential, piecemeal data gathering may be an impediment to quickly understanding changes in patient's physiological states [5]. To add even more complexity, researchers have reported that 67–90% of alarms generated by monitoring devices are falsely positive and thus clinicians must also decide when not to react [6,7].

An integrated graphical display would be an enhancement to current physiological monitors and may provide better support for diagnosis and treatment of problems involving alterations of multiple physiological variables. We developed a pulmonary display that graphically

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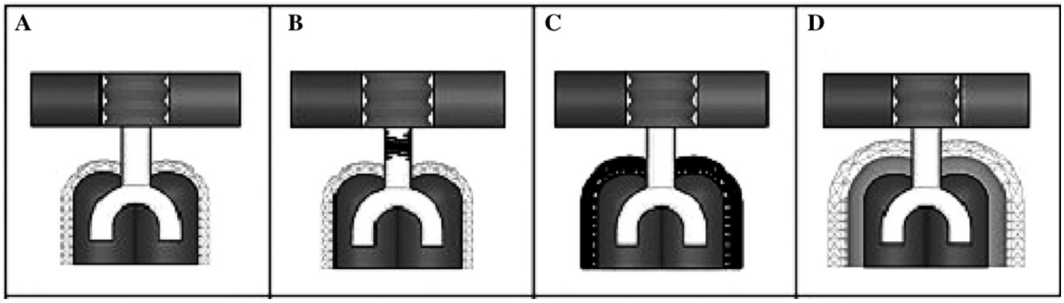

Fig. 1. The pulmonary graphical display. The pulmonary graphical display anatomically represents the bellows, airway, lung parenchyma, inspired gas, and expired gas. The upper left box (green) represents the fraction of inspired oxygen. The middle box (light blue) represents tidal volume. The upper right box (gray) represents end tidal carbon dioxide. The airway is shown as a simplistic anatomical picture of the trachea and the branched bronchi. (A) The pulmonary display when all measured pulmonary variables are within normal range. (B) The pulmonary display showing increased airway resistance. (C) The pulmonary display showing decreased lung compliance. (D) The pulmonary display representing intrinsic positive end expiratory pressure.

portrays respiratory information for intubated, mechanically ventilated patients (Fig. 1). The pulmonary display pictorially presents the bellows, airways, lung parenchyma, and inspired and expired gas; it uses color, shape, and highlights portions of the display that become more salient to emphasize abnormal pulmonary physiology.

We used an iterative development cycle to create a pulmonary display that presents critical information about the respiratory system using unique combinations of simple shapes and colors as shown in Fig. 1 [8]. The pulmonary display graphically and numerically presents fraction of inspired oxygen (F_IO_2), end tidal carbon dioxide ($ETCO_2$), and tidal volume (V_T) (Fig. 1A). Black fingers restricting the anatomical representation of the trachea depicts an increase in airway resistance (Fig. 1B). A decrease in lung compliance is shown by a thick black cage surrounding the lung image (Fig. 1C). Finally, an image of over-inflated lungs appears when breath stacking (i.e., intrinsic positive end expiratory pressure (iPEEP)) is detected (Fig. 1D). The display is intuitive as evidenced by clinicians ability to guess, without prior training, the anatomical representation with 98% accuracy, the pulmonary measurements with 91% accuracy, and the underlying pulmonary events with 79% accuracy [8].

The pulmonary graphical display has also been tested in an anesthesia simulator [9]. In this study, clinicians were challenged to treat simulated patients suffering from critical pulmonary events. The clinicians who used the pulmonary display in addition to the standard physiological monitors were able to diagnose iPEEP ($p < 0.05$), treat iPEEP ($p < 0.05$), and treat obstructed endotracheal tubes ($p < 0.05$) faster compared to those who did not use the display.

How this new graphical monitor will be integrated and accepted by users in a patient setting has yet to be determined. We sought to determine how users would perceive the pulmonary graphical display in an ICU. We hypothesized that: (1) users would observe the pulmonary display as they cared for patients and (2) the pulmonary display would be perceived as favorable, as having utility, and being accurate.

2. Methods

The study protocol was reviewed and approved by the University of Utah Institutional Review Board. The 11-day evaluation of the pulmonary display took place in the Medical Intensive Care Unit (MICU) at the University of Utah Hospital. Study investigators observed caregivers (study subjects) attend eight patients over the course of the study. Thirty-two caregivers (critical care physicians, residents, nurses, and respiratory therapists) consented and participated in the study. The participating MICU caregivers were trained on interpretation of pulmonary display graphics each morning as needed. Training lasted approximately 10 min and participants were encouraged to ask questions.

At the beginning of each day, two ventilator dependent patients in the MICU were selected by the critical care physician in charge to participate in the study. Investigators observed each room for 5 h. The pulmonary display was shown on a 15 in. flat screen monitor situated by the patient's bedside next to the mechanical ventilator. CO2SMO (NOVAMETRIX, Hartford, CT), a respiratory monitor inserted in line with the patient's ventilator tubing, measured the respiratory variables and was used to drive the pulmonary display. The pulmonary graphic used shape, color, and highlighted features to represent changes in underlying pulmonary measurements and displayed the numeric values next to the graphic. The pulmonary parameters measured and displayed included: peak airway pressure, airway resistance (R_{AW}), total lung compliance (C_L), respiratory rate (RR), iPEEP, $ETCO_2$, and V_T.

Two study investigators observed subjects' actions in both of the selected patient rooms during the day (8am–6pm). Investigators noted how often subjects entered the rooms and how often a subject looked at the pulmonary display. The investigators used handheld pocket personal computers and clipboards to capture their observations. To facilitate the investigators data capture with the pocket PC, an application was developed using abcDB database 3.0 software. Using the pocket PC application, investigators were able to quickly capture the room number and subject type entering the room; investigators also noted general comments on a clipboard with a paper form.

At the conclusion of the day, the health care team members who cared for the selected patients and were study subjects, were given a questionnaire to determine perceived usefulness and accuracy of the pulmonary display. Participants were encouraged to write general comments regarding the pulmonary display on the questionnaire sheet. The questionnaire consisted of four questions regarding usefulness, acceptance, desirability, and accuracy. The questionnaires used a 0–9 scale with 9 representing the most useful or desirable. Each of the four questions of the questionnaire was reviewed, analyzed using analysis of variance, and tabulated based on person type. General comments on each questionnaire were also reviewed and tabulated.

Data were analyzed by reviewing the data captured by the investigators on the pocket PC. We counted how many participants entered the patients' room and calculated the daily average of number of glances per visit towards the pulmonary display stratified by subject type (critical care physician, resident, nurse, and respiratory therapist). We compared the number of glances per room visit by subject type using the Kruskal–Wallis non-parametric test.

3. Results

Caregivers observed the display 775 times during the 375 times they entered the room. Nurses entered the room the most often ($N = 269$) and observed the display an average of 1.31 times per visit (Fig. 2). Respiratory therapists entered the room 74 times and looked at the display an average of three times per visit. Critical care physicians entered the room 34 times and glanced at the pulmonary display an average of six times per visit. Resident's entered the room during the study only on three of the 11 days and were therefore not analyzed. Physicians and respiratory therapists glanced at the display significantly more often per visit than the nursing group ($p \leqslant 0.001$). Trending lines of average glances of the display during the 11 days of the study are shown in Fig. 2. Number of glances per room visit increased over the study period for physicians and respiratory therapists while nurses' number of glances slightly decreased.

A total of 51 questionnaires were completed. Five questionnaires were completed by critical care physicians, 22 by nurses, 16 by respiratory therapists, and eight by resident physicians (Table 1). Subjects were asked to rank how desirable and accurate they perceived the pulmonary display to be. The average response to usefulness, desirability, acceptance, and accuracy ranged

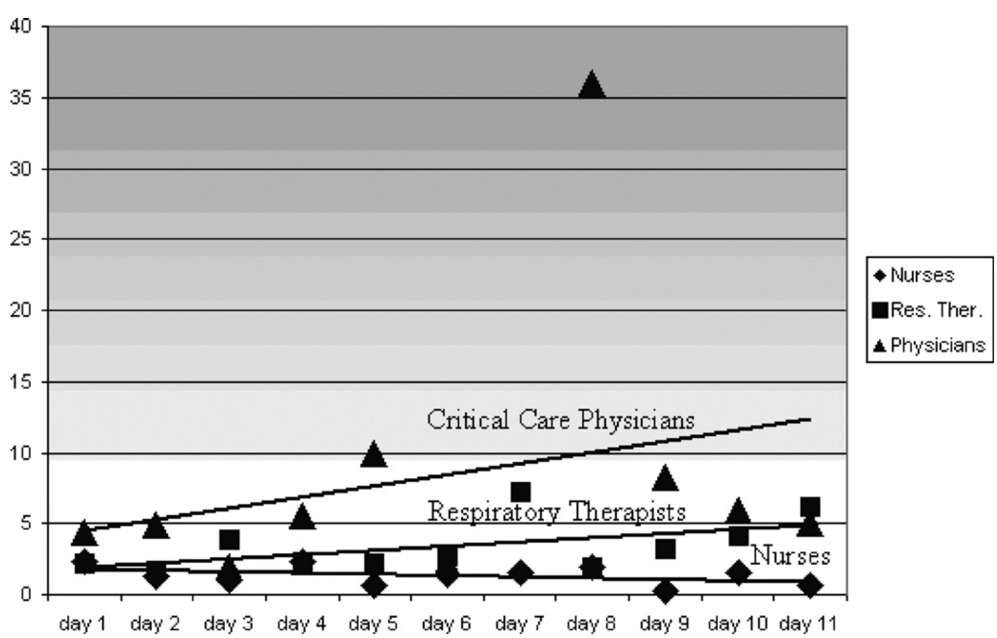

Fig. 2. Average number of glances per visit per day. Critical care physicians and respiratory therapists looked at the display more often over the course of the study.

Table 1
Questionnaire scores by person type

	Nurses ($n = 22$)	Respiratory therapists ($n = 16$)	Critical care physicians ($n = 5$)	Residents ($n = 8$)	Average
How useful was information provided by the display	5.7 (±1.7)	5.1 (±2.0)	5.0 (±0.7)	5.4 (±2.8)	5.4 (±1.9)
How desirable is the pulmonary display	6.0 (±1.5)	5.7 (±1.9)	5.6 (±0.9)	6.1 (±2.4)	5.9 (±1.7)
Pulmonary display should be added to equipment in ICU	5.9 (±1.4)	5.7 (±1.7)	5.4 (±1.1)	6.5 (±2.1)	5.9 (±1.6)
Pulmonary display showed adequate representation of patient information	6.1 (±1.9)	5.9 (±1.8)	5.0 (±1.9)	6.3 (±2.1)	5.9 (±1.9)

The questionnaires were distributed at the end of the day to the ICU caregivers who attended the patients. Scores were tallied and tabulated by subject type (mean ± SD).

from 5.00 to 6.50 on a 0–9 scale. There were no significant differences between groups (Table 1).

Many subjects commented favorably about the display indicating that they liked it and would not change the design. Some particularly liked the $ETCO_2$ measurement, as this was new information in their ICU. One commented that the iPEEP feature was particularly helpful to her. When asked about suggestions to improve the display, some noted the size of the display (wanted it smaller), the lack of ventilator settings on the pulmonary display, and some wanted to emphasize the highlighted features when values measured in the extreme ranges by turning the portion red. Many commented that they would like more exposure and training with the display reflecting the short duration of the study and lack of continued exposure among the caregivers.

4. Discussion

Physicians showed the most interest in the pulmonary display as indicated by the higher number of glances per room visit compared with respiratory therapists and nurses, and an increase in average number of glances over time. The display was designed using the iterative process using physicians as the test subjects during the intuitive testing of the display and may reflect that the pulmonary display fit better with the physicians' mental model compared to the nurses.

The information presented by the pulmonary graphical display was subjectively perceived as useful, a desirable addition to current ICU monitors, and an accurate representation of patient status as indicated by the average questionnaire scores greater than 4 on a 0–9 scale. The pulmonary display became distorted when pulmonary measurements became abnormal, creating patterns representing the underlying abnormal pulmonary physiology. A graphical display such as ours could provide ICU nurses, physicians, and respiratory therapists with an assessment tool that leads to a more rapid detection of a change in respiratory physiology.

Current research has focused on the development of graphical displays to help clinicians assess patient status accurately and quickly [10–16]. Gurushanthaiah developed and evaluated a graphic display where variables are displayed as histograms. When all variables were normal, the display showed a normal "horizon." Test subjects detected changes in 15% less time with the normal horizon display than with numerical displays [12]. Michels developed the comprehensive graphic anesthesia display that organized 32 variables by organ system and showed that changes were seen an average of 3 min sooner [13]. Blike developed a graphical display that mapped physiologic variables into display objects with meaningful shapes. The objects were designed to aid in the reduction of errors by improving the way data was mapped to the anesthesiologist's mental model of cardiovascular physiology. The analysis showed that the recognition and the diagnosis of the etiology of shock was 27% faster using the object display [14].

Potentially, the pulmonary display could aid clinicians in more rapidly diagnosing the cause of ventilator alarms as was suggested by the simulator study [9]. Additionally, the pulmonary display may be helpful in the determining if and when pulmonary interventions are necessary. For example, the pulmonary display, with its integration of discrete pulmonary measurements, may aid clinicians in deciding if endotracheal suctioning is necessary as would be suggested by an increase in airway resistance depicted by black fingers obstructing the upper airway. As studies have shown, suctioning can cause alveolar derecruitment [17], painful recollection from patients after discharge [18], and induce an initial bronchospastic response [19] thus, optimal use of this intervention is desirable.

We recognize the limitations that an observational study presents. The presence of an investigator in the room may have triggered the caregiver to look more often at the display. The study was limited to day shift hours and we recognize that caregivers working at night may view the pulmonary display differently. We acknowledge $ETCO_2$ was new information and caregivers may have observed the pulmonary display only for this new information it provided. Similarly, numeric numbers were shown next to the pulmonary graphic making it difficult to determine if caregivers were looking at the pulmonary display for all the information presented or just specific portions of it. Eye tracking studies would be necessary to distinguish which part of the pulmonary display caregivers were focused on and their observational patterns. We also recognize caregivers observing the display does not correlate with the utilization of the information. Further studies combining display observation, eye tracking studies, and workload assessment may provide more complete assessments regarding usability of the pulmonary display.

Healthcare professionals' acceptance and positive attitude of the pulmonary display are important to the success of introducing this technology into the medical care setting. Their positive feedback, thoughtful criticism, and interest were encouraging. Caregivers perceived the pulmonary display as useful and desirable and they continually looked at the display throughout the 11-day study.

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References

[1] Eichhorn JH. Prevention of intraoperative anesthesia accidents and related severe injury through safety monitoring. Anesthesiology 1989;70(4):572–7.
[2] Kerr JH. Symposium on anaesthetic equipment. Warning devices. Br J Anaesth 1985;57(7):696–708.
[3] Allnutt MF. Human factors in accidents. 1987. Qual Saf Health Care 2002;11(4):369–74 (Discussion 374–5).
[4] Staggers N. Human factors: imperative concepts for information systems in critical care. AACN Clin Issues 2003;14(3):310–9 (Quiz 397–8).
[5] Cook R, Woods D. Operating at the sharp end. In: Human error in medicine, vol. 13; 1994. p. 255–310.
[6] Cropp AJ, et al. Name that tone. The proliferation of alarms in the intensive care unit. Chest 1994;105(4):1217–20.
[7] Meredith C, Edworthy J. Are there too many alarms in the intensive care unit? An overview of the problems. J Adv Nurs 1995;21(1):15–20.
[8] Wachter SB, et al. The employment of an iterative design process to develop a pulmonary graphical display. J Am Med Inform Assoc 2003;10(4):363–72.
[9] Wachter SB, et al. The development of a pulmonary metaphor. Anesthesiology 2002:A-523.
[10] Cole WG, Stewart JG. Metaphor graphics to support integrated decision making with respiratory data. Int J Clin Monit Comput 1993;10(2):91–100.
[11] Cole WG, Stewart JG. Human performance evaluation of a metaphor graphic display for respiratory data. Methods Inf Med 1994;33(4):390–6.
[12] Gurushanthaiah K, Weinger MB, Englund CE. Visual display format affects the ability of anesthesiologists to detect acute physiologic changes. A laboratory study employing a clinical display simulator. Anesthesiology 1995;83(6):1184–93.
[13] Michels P, Gravenstein D, Westenskow DR. An integrated graphic data display improves detection and identification of critical events during anesthesia. J Clin Monit 1997;13(4):249–59.
[14] Blike GT, Surgenor SD, Whalen K. A graphical object display improves anesthesiologists' performance on a simulated diagnostic task. J Clin Monit Comput 1999;15(1):37–44.
[15] Jungk A, et al. Ergonomic evaluation of an ecological interface and a profilogram display for hemodynamic monitoring. J Clin Monit Comput 1999;15(7–8):469–79.
[16] Jungk A, et al. Evaluation of two new ecological interface approaches for the anesthesia workplace. J Clin Monit Comput 2000;16(4):243–58.
[17] Maggiore SM, et al. Prevention of endotracheal suctioning-induced alveolar derecruitment in acute lung injury. Am J Respir Crit Care Med 2003;167(9):1215–24.
[18] Van de Leur JP, et al. Patient recollection of airway suctioning in the ICU: routine versus a minimally invasive procedure. Intensive Care Med 2003;29(3):433–6.
[19] Guglielminotti J, Desmonts JM, Dureuil B. Effects of tracheal suctioning on respiratory resistances in mechanically ventilated patients. Chest 1998;113(5):1335–8.