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Elucidating the Fuzziness in Physician Decision Making in ARDS

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Abstract

Purpose—The current standard of care for patients suffering from acute respiratory distress syndrome (ARDS) is ventilation with a tidal volume of 6 ml/kg predicted body weight (PBW), but variability remains in the tidal volumes that are actually used. This study aims to identify patient scenarios for which there is discordance between physicians in choice of tidal volume and positive end-expiratory pressure (PEEP) in ARDS patients.

Methods—We developed an algorithm based on fuzzy logic for encapsulating the expertise of individual physicians regarding their use of tidal volume and PEEP in ARDS patients. The algorithm uses three input measurements: 1) peak airway pressure (PAP), 2) PEEP, and 3) arterial oxygen saturation (SaO₂). It then generates two output parameters: 1) the deviation of tidal volume from 6 ml/kg PBW, and 2) the change in PEEP from its current value. We captured 6 realizations of intensivist expertise in this algorithm and assessed their degree of concordance using a Monte Carlo simulation.

Results—Variability in the tidal volume recommended by the algorithm increased for PAP > 30 cmH₂O and PEEP > 5 cmH₂O. Tidal volume variability decreased for SaO₂ > 90%. Variability in the recommended change in PEEP increased for PEEP > 5 cmH₂O and for SaO₂ near 90%.

Conclusions—Intensivists vary in their management of ARDS patients when peak airway pressures and PEEP are high, suggesting that the current goal of 6 ml/kg PBW may need to be revisited under these conditions.

Keywords

Acute respiratory distress syndrome; mechanical ventilation; fuzzy logic; low tidal volume ventilation; clinical decision making

INTRODUCTION

Improvements in strategies for ventilatory management of patients with acute respiratory distress syndrome (ARDS) have had a major impact on clinical care in recent years [1–3]. Most importantly, a landmark study in 2000 by the ARDS Network showed that use of a low tidal volume (V_T) ventilation of 6 versus 12 ml/kg predicted body weight (PBW)

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ETHICAL STANDARDS

The experiments of this study comply with the laws of the country in which they were performed.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

significantly reduced mortality in these patients [1]. This finding, together with the shift towards evidence-based medicine, has established a V_T of 6 ml/kg PBW as the standard of care in ARDS [4, 5], something that has been estimated to have the potential to prevent 5,500 deaths annually [6]. Nevertheless, there has been some resistance within the medical community to conform to this strategy [7], a reaction that seems to be based on misgivings about a variety of factors. For example, the ARDS Network study only compared 6 ml/kg PBW to a single alternative V_T , which raises the question as to whether some other as yet untested V_T might be even better. Also, physicians continue to debate whether V_T or plateau pressure (P_{plat}) is a better indicator of risk for ventilator-induced lung injury [8]. Adherence to a V_T of 6 ml/kg PBW is further complicated by physician concern about patient comfort, and by the potential failure to identify ARDS early in its course [9, 10].

There currently exists significant discordance between those caregivers who advocate for a V_T of 6 ml/kg PBW in ARDS at all costs, and those who are willing to deviate from it under certain circumstances [7, 9, 10]. This tension is further fueled by current concern about the extent of variation in physician practice [11]. We were thus motivated to determine exactly what is driving variation in the way that physicians choose V_T for ARDS patients. Our approach to this problem was to use the engineering methodology known as fuzzy logic to devise an algorithm encapsulating the decision making process that physicians go through when choosing V_T . By subjecting this algorithm to a spectrum of hypothetical clinical scenarios, we identified those scenarios in which physicians are more inclined to consider the use of a V_T other than 6 ml/kg PBW in ARDS.

METHODS

Fuzzy Logic Algorithm

We have described in previous publications how fuzzy logic control works with respect to pressure support ventilation [12] and fluid administration in the intensive care unit [13]. We used the same approach in the present study to construct a fuzzy logic algorithm for calculating recommended changes to two key ventilator parameters: 1) ΔV_T : the amount by which V_T is to deviate from 6 ml/kg PBW, and 2) $\Delta PEEP$: the amount by which positive end-expiratory pressure (PEEP) is to change from its current setting. The algorithm bases these decisions on the current values of three input variables: 1) peak airway pressure (PAP), 2) PEEP, and 3) arterial oxygen saturation (SaO_2). There are two sets for PAP labeled “Normal” and “High”; three sets for PEEP labeled “Low”, “Normal”, and “High”; and two sets for SaO_2 labeled “Low” and “Normal”. The possible ranges of these three variables are 0 – 45 cmH₂O for PAP, 0 – 25 cmH₂O for PEEP, and 0 – 100 % for SaO_2 . Within these ranges, the vertices of the fuzzy sets demarcate the positions of the fuzzy sets and their degrees of overlap. Membership in a set varies from 0 to 1 to reflect the degree of certainty in classifying a particular variable value. Examples of possible overlapping fuzzy sets for each of these variables are illustrated in Figure 1A.

It should be pointed out that the chosen parameters are not the only factors that might be considered relevant to the management of an ARDS patient. In particular, the inspired oxygen fraction (FiO_2) is also a parameter of major clinical significance which is under physician control. Similarly, one might consider additional input parameters such as end-tidal CO_2 or blood pH. Here, however, we focus our attention on the special case of severe ARDS for which FiO_2 is set to 100%. We do this partly to limit the complexity of the situation, but also because the stakes of decision making are particularly high in the common clinical scenario of refractory hypoxemia, which may call for unsettling and potentially dangerous deviations from standard practice regarding tidal volume and PEEP. The result is a somewhat simpler fuzzy logic algorithm than would be the case for ARDS in general, but it still enables us to use it to explore areas of concordance in physician decision making.

Once the input variables are fuzzified as described above, they must be related using a rule table that describes what action is to be taken for every possible combination of set memberships for PAP, PEEP and SaO₂. These actions state what is to be done, in qualitative terms, to adjust the output variables V_T and PEEP. These qualitative terms are “Decrease”, “Maintain” and “Increase” for both output variables. For example, if PAP is “Normal”, PEEP is “High” and SaO₂ is “Low” the decision of an expert physician might be to “Increase” V_T and “Maintain” PEEP, and so on for all other possible combinations of input variable set memberships. An example of a possible rule table is illustrated in Table 1.

Next, the meanings of “Decrease”, “Maintain” and “Increase” for both V_T and PEEP are specified in terms of the positions and degrees of overlap of three fuzzy sets defined on the allowable range of values for a change in V_T (in units of ml/kg PBW) relative to 6 ml/kg predicted body weight (ΔV_T), and change in PEEP (in units of cmH₂O) relative to its current value ($\Delta PEEP$). Examples of possible fuzzifications for ΔV_T and $\Delta PEEP$ are shown in Figure 1B.

Having completed the above steps, the fuzzy logic algorithm is ready to use. Using conventional rules for fuzzy logic [13, 14], a particular set of values for the input parameters PAP, PEEP and SaO₂ gives rise to memberships lying between 0 and 1 for the three fuzzy sets of ΔV_T and $\Delta PEEP$. The centroid of the polygonal regions defined by these various members for each output parameter are then taken as the “crisp” output values, i.e. those values of ΔV_T and $\Delta PEEP$ that are to be implemented.

Questionnaire

We created a questionnaire (see online supplemental material) designed to gather the fuzzy set vertices (Fig. 1A) and rule table entries (Table 1) that an expert intensivist would need to supply in order to implement the fuzzy logic algorithm described above. We sent this questionnaire to the nine board-certified attending critical care physicians on the Fletcher Allen Health Care MICU Service, and received six anonymous returns. This provided six different information sets that were used to implement six realizations of the fuzzy logic algorithm. In this way, we encapsulated the expertise of the six different intensive care physicians. Approval to gather this information was obtained from the University of Vermont Institutional Review Board.

Monte Carlo Method

The decisions inherent in the 6 different fuzzy logic algorithms were compared to each other using a Monte Carlo approach in which 10,000 hypothetical patient scenarios were generated by choosing 10,000 different sets of values for PAP, PEEP and SaO₂. The values for each parameter were drawn randomly with equal probability from their respective clinically applicable ranges. These ranges are those that define the horizontal axes in the plots in Figure 1A. The 10,000 patient scenarios were then given to each of the six realizations of the fuzzy logic algorithm, generating 10,000 sets of six recommendations for both ΔV_T and $\Delta PEEP$. The degree of discordance between the physicians for each of the patient scenarios was quantified as the standard deviations of the six recommendations for ΔV_T and $\Delta PEEP$. These standard deviations are designated SD- ΔV_T and SD- $\Delta PEEP$, respectively.

RESULTS

Figure 2 shows how the degree of discordance between the six physicians varied as functions of the three input parameters to the fuzzy logic algorithm. Figure 2A, for example, shows where each of the 10,000 values of SD- ΔV_T lies in a plot of SD- ΔV_T versus PAP.

The darkness of the plot is proportional to the number of values of $SD-\Delta V_T$ that fall on a particular location. We thus see that most values of $SD-\Delta V_T$ are zero for $PAP < 30 \text{ cmH}_2\text{O}$, indicating strong agreement between the 6 different physicians. By contrast, as PAP climbs above $30 \text{ cmH}_2\text{O}$ the values of $SD-\Delta V_T$ also climb progressively, indicating increasing discordance. Also notable is a dull peak in $SD-\Delta V_T$ around a PAP of $35 \text{ cmH}_2\text{O}$, indicating some disagreement around this value. Figure 2B shows that agreement regarding $\Delta PEEP$ was strong over the entire range of PAP investigated. Figures 2C and 2D show that agreement regarding ΔV_T and $\Delta PEEP$ was only strong for $PEEP < 5 \text{ cmH}_2\text{O}$, with discordance developing progressively above this value. Finally, Figures 2E and 2F show that agreement regarding ΔV_T and $\Delta PEEP$ was relatively strong for all values of SaO_2 , although some confusion regarding $PEEP$ control arose around values close to 90%. There was also a marked decrease in $SD-\Delta V_T$ associated with “Normal” SaO_2 .

Interactions between input parameters are shown in the three-dimensional color plots of $SD-\Delta V_T$ and $SD-\Delta PEEP$ versus pairs of input parameter values provided in the online supplemental material (Fig. S2 and S3). These plots provide a more comprehensive view of the data by showing how standard deviations depend simultaneously on two parameters, and show that there is little interaction between PAP and SaO_2 . That is, the surfaces in these figures show that $SD-\Delta V_T$ depends almost exclusively on variations in PAP (Fig. S2) while $\Delta SD-PEEP$ depends almost exclusively on variations in SaO_2 (Fig. S3), and this pertains in both cases regardless of the value of $PEEP$.

DISCUSSION

Fuzzy logic is a mathematical engineering discipline that was introduced by Zadeh in the 1960's [15], and has since been used in a variety of control applications [14]. Unlike conventional approaches to servo control that are based on mathematical models of the system being controlled, fuzzy logic allows for the development of control algorithms based on the accumulated experience of experts, and is therefore well suited for applications in medical decision-making [13, 16]. Accordingly, fuzzy logic seemed to us to be an appropriate methodology with which to try to capture the decision processes involved in choosing V_T for ARDS patients, especially as those who make this decision currently appear to be torn between the sole evidence-based recommendation of 6 ml/kg PBW and the doubt they experience arising from a large background of accepted physiological and medical wisdom. Understanding the precise source of this tension is important because ARDS continues to have a substantial impact on public health [17, 18]; a recent cohort study has shown that the incidence of ARDS in the United States could be as high as 190,600 cases per year, with an in-hospital mortality rate of 38.5%, making the impact of ARDS comparable to that of breast cancer or HIV [17].

Our aim was therefore to use a fuzzy logic-based technique to identify those patient scenarios for which physicians are at odds about how to manage patients with ARDS. Several previous studies have investigated barriers to low V_T ventilation protocols, and have identified a number of contributing factors. One obvious factor is deficit of appropriate knowledge on the part of the health care provider [7], as well as simple carelessness. Also, ARDS is sometimes not diagnosed properly [10], in which case the need for a low V_T protocol may not be acknowledged. On the other hand, much of the resistance to use of low V_T in ARDS arises in the context of careful clinical consideration related to ostensibly justifiable factors such as patient comfort [9, 10]. Nevertheless, the reasons for variability in decisions related to mechanical ventilation settings are not always clear, likely representing lost opportunities to provide the best possible care [19].

An important region of discordance among the six different fuzzy logic algorithms occurred at high values of PAP. Figure 2A shows that $SD-\Delta V_T$ increased linearly as PAP increased above 30 cmH₂O. We traced the source of this discordance to variations in the entries the physicians made in the rule tables specifying how V_T should be adjusted when PAP is “High”. The ARDS Network ventilation protocol recommends lowering V_T in steps of 1 ml/kg PBW to a minimum of 4 ml/kg PBW when P_{plat} is above 30 cmH₂O [1]. However, research has shown that physicians are often resistant to employing such low V_T because of concerns about hypercapnia, acidosis, hypoxemia, and increased use of sedatives [9, 10]. We speculate that lack of certainty as to what to do in face of these concerns may have contributed to the variation in strategies employed by the six physicians in the present study as PAP increased above 30 cmH₂O.

Another region of substantial discordance began when PEEP reached 5 cmH₂O, above which $SD-\Delta V_T$ and $SD-\Delta PEEP$ increased linearly (Fig. 2C and 2D). This result is again traceable to differences among the rule table entries, this time related to adjustment of V_T and PEEP when PEEP is “High”. There are several adverse effects associated with high PEEP, notably lung overdistension [20], decreased venous return caused by high intra-thoracic pressure [21], and decreased oxygenation from pulmonary blood flow being redirected to regions of limited ventilation [22]. While these adverse effects are widely appreciated, intensivists may react to them in different ways, which could account for the variability we encountered in the present study. Another potential source of discordance may arise from the apparent disagreement between the results of several studies regarding the use of PEEP in ARDS. The most widely cited study by the ARDS Network demonstrated no benefit of higher PEEP over modest PEEP when the level of PEEP was arbitrarily driven by FiO_2 requirement [23]. However, subsequent studies have suggested a benefit of higher PEEP when guided by airway pressure [24] or esophageal pressure [25].

Discordance did not appear to be strongly related to SaO_2 apart from an elevation in $SD-\Delta PEEP$ when SaO_2 was around 90% (Fig. 2F). This disagreement was due to differences in the way the physicians specified the lowest value at which SaO_2 could possibly be defined as being “Normal”. By contrast, there was strong agreement about what action to take for ΔV_T when SaO_2 was “Normal” (Fig. 2E). This result can be traced to agreement among the rule tables for how to adjust V_T when SaO_2 is “Normal”.

A mild peak in $SD-\Delta V_T$ also occurred around PAP values of 35 cmH₂O (Fig. 2A) due to variations in the way that physicians defined the maximum value of PAP that is unquestionably “Normal”. It is possible that we would have found less variation among the physicians had we used P_{plat} instead of PAP in our algorithm because the ARDS Network protocol specifies the maximum acceptable P_{plat} to be 30 cmH₂O whereas no such value is specified for PAP [1].

The findings of our study reflect the benefits of the fuzzy logic approach to encapsulating physician expertise in an algorithm, as well as the advantages of using a computer to exhaustively explore the vast space of possible clinical scenarios. This approach is not without its limitations, however. For example, we assumed that the decisions made by the fuzzy logic algorithm when it is parameterized by a specific physician for a particular patient would mirror the decisions the physician would make when actually in the presence of the patient. This would not necessarily be the case, particularly if the physician based their decision on information other than that encapsulated in PAP, PEEP and SaO_2 . Our assumption is that this extra information plays a relatively small role in decision-making, as was suggested for control of pressure support mechanical ventilation in our previous study using fuzzy logic in that context [12], but we cannot be sure this applies in the present application. Of course, we can always include additional information in our algorithm by

incorporating additional clinical parameters, but this rapidly increases the complexity of the algorithm.

Our algorithm also purports to apply to ARDS patients in general, but in fact ARDS is a heterogeneous disease that affects different patient groups in different ways (e.g. obese versus lean). Working with a single fuzzy algorithm suits our purposes for the present study because we are simply looking for areas of overall concordance in physician decision making, but in the actual application of fuzzy logic to control V_T in ARDS one might want to construct particular algorithms to suit various clinical situations, and this might include consideration of additional parameters such as FiO_2 and end-tidal CO_2 . Nevertheless, SaO_2 may often be what drives clinicians to manipulate PEEP in an effort to improve regional lung recruitment and ventilation-perfusion matching, so arbitrarily linking PEEP levels to FiO_2 is likely not the most appropriate method for regulating PEEP in a mixed population of patients consisting of those who respond to PEEP and those who do not [26].

Our study is also limited by our small sample size of only six physicians. We felt the advantage of our sample is that these physicians all work together and so likely have knowledge bases and skill sets that overlap about as much as one is likely to find in the profession. Our results therefore probably represent a best-case scenario in terms of levels of contention in the management of ARDS. The power of our study would certainly have been greater had it included additional physicians from other centers. Indeed, physicians with different training backgrounds might make decisions based on quite different considerations than those favored at our own institution, in which case we might expect the degree of discordance to be commensurately higher if multiple institutions were included, similar to the situation found by Allerod et al. [27]. This would significantly increase the complexity of the study, but assessing variations in discordance within and between centers could certainly be an interesting area for future research.

In conclusion, we developed a fuzzy logic algorithm to investigate sources of discordance among physicians who manage ARDS patients. Using a Monte-Carlo method, we determined the ranges of PAP, PEEP and SaO_2 values that led to significant degrees of discordance among physicians in terms of their decisions about setting ΔV_T and $\Delta PEEP$. We related the sources of this discordance to variations in the how physicians define overlapping fuzzy sets of PAP, PEEP and SaO_2 as well as how they specify the actions to be taken in the face of combinations of set membership for PAP, PEEP and SaO_2 . Our findings may have identified patient scenarios for which the current standard of care of V_T less than or equal to 6 ml/kg PBW will need to be reexamined for a possible alternative recommendation, or for deficits in physicians' knowledge bases that need to be more aggressively targeted through training and continual medical education.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1.

Fuzzy set structure. A) The ranges for the input parameters PAP, PEEP and SaO_2 are divided into 2, 3 and 2 overlapping sets, respectively. The sets shown in the figure are illustrative examples; the precise positions of the vertices defining the positions of the sets were provided by each of the physicians we studied and used as part of the setting up process for their specific algorithm. B) The ranges of the output parameters ΔV_t and ΔPEEP are each divided into 3 overlapping sets.

Fig. 2. $SD-\Delta V_T$ and $SD-\Delta PEEP$ plotted against each of the input parameters PAP, PEEP, and SaO₂. The darkness of the plot is proportional to the number of the 10,000 individual patient scenarios that fall on a given value.

Table 1

An example decision table that specifies the actions to be taken in terms of adjusting ΔV_t and $\Delta PEEP$ for each combination of set memberships for the input parameters PAP, PEEP and SaO₂. The entries in this table might vary depending on which particular expert is deciding on the decisions that should be taken.

Input Parameter Set Memberships			Output Parameter Adjustments	
PAP	PEEP	SaO ₂	ΔV_t	$\Delta PEEP$
Normal	Low	Low	Maintain	Increase
High	Low	Low	Decrease	Increase
Normal	Normal	Low	Maintain	Increase
High	Normal	Low	Decrease	Increase
Normal	High	Low	Increase	Maintain
High	High	Low	Maintain	Maintain
Normal	Low	Normal	Maintain	Maintain
High	Low	Normal	Decrease	Increase
Normal	Normal	Normal	Maintain	Maintain
High	Normal	Normal	Decrease	Maintain
Normal	High	Normal	Maintain	Decrease
High	High	Normal	Decrease	Decrease