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CONTROLLING MECHANICAL VENTILATION IN ARDS WITH FUZZY LOGIC

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Abstract

Purpose—The current ventilatory care goal for acute respiratory distress syndrome (ARDS), and the only evidence-based approach for managing ARDS, is to ventilate with a tidal volume (V_T) of 6 ml/kg predicted body weight (PBW). However, it is not uncommon for some caregivers to feel inclined to deviate from this strategy for one reason or another. To accommodate this inclination in a rationalized manner, we previously developed an algorithm that allows for V_T to depart from 6 ml/kg PBW based on physiological criteria. The goal of the present study was to test the feasibility of this algorithm in a small retrospective study.

Materials and Methods—Current values of peak airway pressure (PAP), positive end-expiratory pressure (PEEP) and arterial oxygen saturation (SaO_2) are used in a fuzzy logic algorithm to decide how much V_T should differ from 6 ml/kg PBW and how much PEEP should change from its current setting. We retrospectively tested the predictions of the algorithm against 26 cases of decision making in 17 patients with ARDS.

Results—Differences between algorithm and physician V_T decisions were within 2.5 ml/kg PBW except in 1 of 26 cases, and differences between PEEP decisions were within 2.5 cm H_2O except in 3 of 26 cases. The algorithm was consistently more conservative than physicians in changing V_T , but was slightly less conservative when changing PEEP.

Conclusions—Within the limits imposed by a small retrospective study, we conclude that our fuzzy logic algorithm makes sensible decisions while at the same time keeping practice close to the current ventilatory care goal.

Keywords

6 ml/kg predicted body weight; retrospective study; positive end-expiratory pressure; peak airway pressure; arterial oxygen saturation; protocol

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Introduction

The management of acute respiratory distress syndrome (ARDS) centers around the delivery of supportive mechanical ventilation^{1–3}, the goal being to avoid further ventilator-induced injury (VILI) while the lungs are allowed to recover. The central principle behind avoiding VILI is the minimization of stresses and strains applied to the lung tissue, as exemplified by the demonstrated advantages of ventilating ARDS patients with a tidal volume (V_T) of 6 ml/kg predicted body weight (PBW) as part of an overall strategy that includes appropriate choice of other ventilator parameters such as plateau pressure, positive end-expiratory pressure (PEEP) and inspired oxygen fraction (F_{iO_2})¹. Indeed, striving for a V_T of 6 ml/kg PBW coupled with the maintenance of plateau pressure below 30 cm H₂O, is considered the current ventilatory care goal in ARDS^{4, 5}. Nevertheless, while ventilating with a low V_T in ARDS has saved many lives⁶, a significant number of caregivers are not content to adhere dogmatically to this goal of 6 ml/kg⁷ for a variety of reasons^{8, 9}. Also, the landmark ARDS Network that produced the evidence for V_T of 6 ml/kg PBW only compared this to a single alternative¹, which leaves open the possibility that a somewhat different V_T might be even better. Furthermore, even if 6 ml/kg PBW is optimal for the average ARDS patient, it cannot possibly be optimal for each individual patient.

A V_T of 6 ml/kg is thus the current ventilator care goal for ARDS patients. Some feel, however, that this goal is not always pursued as carefully as it should be^{7–10}. Certainly, evidence-based protocols have the singular advantage of reducing capricious and unwanted variation in practice patterns^{3, 11}. On the other hand, resistance to the adoption of a protocol may signal the existence of situations in which its advisability is open to question. In order to provide a formal structure within which to accommodate such possibilities with regard to the ventilatory management of ARDS patients, we recently devised an algorithm for specifying the amount by which V_T may depart from 6 ml/kg in those ARDS patients for whom such departure could be warranted¹². The algorithm bases its decisions on ongoing measurements of arterial oxygen saturation (SaO_2), positive end-expiratory pressure (PEEP) and peak airway pressure (PAP), and uses fuzzy logic to represent clinical judgment. Its parameters can therefore be adjusted to reflect the expertise of a particular expert physician, or the collective expertise of a group of physicians. In our previous study¹², we used this algorithm to compare how a number of different experts decided to set V_T and PEEP over a spectrum of hypothetical clinical scenarios.

The conclusions of our previous study¹², however, are contingent upon the extent to which the fuzzy logic algorithm captures what physicians actually do when confronted with ARDS patients in the intensive care unit (ICU). In other words, the information required for the setting of V_T and PEEP must be contained in the input parameters SaO_2 , PEEP and PAP. Accordingly, the goal of the present study was to test if this is so by assessing the capacity of our fuzzy logic algorithm to make sensible clinical decisions. We performed this comparison retrospectively by comparing the decisions made by the algorithm to decisions that were actually made by physicians in the intensive care unit (ICU).

Methods

Fuzzy logic algorithm

We have previously described in detail our fuzzy logic algorithm for setting V_T and PEEP in ARDS¹². Briefly, the algorithm bases its decisions exclusively on the current values of SaO_2 , PEEP and PAP. These input variables were chosen because of their obvious physiological relevance, and because all are measured routinely and so can potentially be used to automatically control mechanical ventilation. The ranges of possible values for these 3 input variables are each divided into a small number of overlapping sets that are assigned descriptive names. Each set is given a level of membership that varies from 0 to 1 over the range of values that it encompasses. Thus, for example, there are two fuzzy sets for PAP labeled *Normal* and *High*. These sets overlap where there is some equivocation as to whether one might actually call PAP normal or high, which in this study was determined to be between 35 and 45 cmH₂O (Fig. 1a). The *Normal* set begins at the low end of the range of possible PAP values, namely 0, where it has a full membership level of 1, and proceeds at membership level 1 until it reaches the equivocation range starting at 35 cmH₂O. At this point, membership in the *Normal* set decreases linearly to reach zero at 45 cmH₂O. Conversely, the *High* set begins at a level of zero at 35 cmH₂O and increases linearly to reach 1 at 45 cmH₂O. The other two input variables are treated in corresponding fashion, there being three overlapping fuzzy sets for PEEP labeled *Low*, *Normal* and *High* (Fig. 1a) and two sets for SaO_2 labeled *Low* and *Normal* (Fig. 1a).

Next, the fuzzy sets are linked via a rule table that describes what action is to be taken for every possible combination of set memberships for PAP, PEEP and SaO_2 . These actions state, in qualitative terms, how both V_T and PEEP are to be adjusted. These adjustments give rise to changes in V_T and PEEP that constitute the output variables of the algorithm defined, respectively, as 1) the departure of V_T from 6 ml/kg, labeled ΔV_T , and 2) the change in PEEP from whatever its current value is, labeled $\Delta PEEP$. The ranges of possible values for these two output variables are each divided into 3 overlapping fuzzy sets labeled *Decrease*, *Maintain* and *Increase* (note that *Maintain* corresponds to the decision to keep either output variable at its current level, so that its change is zero). As with the input variables, the levels of membership in the output fuzzy sets are specified by an expert, and the regions of overlap between adjacent sets define the ranges of ΔV_T and $\Delta PEEP$ for which there is some uncertainty as to the most appropriate set membership. The fuzzy sets for the two output variables are shown in Fig. 1b, while the complete list of decisions are given in Table 1.

After the structure of a fuzzy logic algorithm (i.e. the specific input and output variables involved, and the number of fuzzy sets for each) has been specified, encapsulating the expertise of a particular physician is merely a question of having them define the positions of the vertices of each of the fuzzy sets and the entries in the rule table. This information was obtained for the present study by taking the mean values for the set vertices and the modes of the rule table entries from our previous study in which we separately encapsulated the expertise of 6 intensivists in 6 different realizations of the algorithm [1]. Figures 1a and 1b and Table 1 define the specific algorithm that resulted.

Retrospective clinical data

We obtained approval from University of Vermont Institutional Review Board to retrospectively review the electronic records of all patients admitted to the medical ICU of Fletcher Allen Health Care from October 2010 to October 2011 who received mechanical ventilation. The medical ICU at Fletcher Allen Health Care is a closed unit attended on only by board-certified intensive care physicians. We screened approximately 200 patients and identified 17 patients with the following inclusion criteria: 1) had a diagnosis of ARDS, 2) received mechanical ventilation with an initial inspired oxygen fraction (FiO_2) of 100% (a criterion chosen simply to make the patient group more uniform), and 3) had clinician-initiated adjustments to their mechanical ventilation recorded appropriately within 2 hours in the electronic health record (a criterion chosen to reduce the likelihood of memory errors and the occurrence of additional confounding events prior to data recording).

For all instances in which adjustments were made to the ventilator settings of these 17 patients by the attending physician, we obtained the pre-decision settings of SaO_2 , PAP, PEEP, and V_T , and the corresponding post-decision values of PEEP and V_T within 2 hours of the decision. The differences between the pre- and post-decision values of PEEP and V_T gave values for physician-determined V_T and PEEP, designated $V_{T,\text{Phys}}$ and

$\text{PEEP}_{\text{Phys}}$, respectively. The pre-decision values of SaO_2 , PAP and PEEP were then used as the inputs to the fuzzy logic algorithm to obtain algorithm-determined values for V_T and PEEP, designated $V_{T,\text{Fuzz}}$ and $\text{PEEP}_{\text{Fuzz}}$, respectively. Some patients had more than one decision made by their attending physician, giving a total of 26 decisions in all 17 patients. The 26 corresponding values of the input variables SaO_2 , PAP and PEEP had memberships in the various fuzzy sets illustrated in Fig. 1. The numbers of times each of the fuzzy sets was represented in all 26 decisions was: PAP Normal = 25, PAP High = 4, SaO_2 Low = 24, SaO_2 Normal = 19, PEEP Low = 0, PEEP Normal = 26, PEEP High = 17. When a variable value was located within a region of overlap between two adjacent sets (Fig. 1), it gave rise to two fuzzy set memberships simultaneously. This occurred in 3 of the PAP values, 17 of the SaO_2 values, and 17 of the PEEP values.

We compared the algorithm and physician decisions in two ways. First, we compared $V_{T,\text{Fuzz}}$ to $V_{T,\text{Phys}}$, and $\text{PEEP}_{\text{Fuzz}}$ to $\text{PEEP}_{\text{Phys}}$, at each of the 26 decision points observed in the 17 patients. Second, we compared the aggregate, or net, decisions made by algorithm and physician in each patient (that is, the differences between the first and last values of both V_T and PEEP). For those patients in whom only one decision to adjust ventilation was made, the two types of comparison were identical. In those patients who experienced more than one adjustment decision, however, the aggregate decisions for V_T and PEEP were blind to any intermediate decisions made by the physician that might have been reversed by a subsequent decision.

The difference between algorithm and physician decisions was similar when considering either the individual or aggregate decisions. For this reason, we chose to center our results, detailing this difference, around the individual decisions. Even so, the aggregate decision analysis provides an additional viewpoint on the performance of the algorithm, particularly in terms of its ability to change V_T and PEEP simultaneously. We have addressed this in our

discussion of the algorithm's performance, and show the aggregate data analysis in the Online Supplement.

Results

Figure 2 shows comparisons made with respect to $V_{T,Fuzz}$ vs $V_{T,Phys}$. The algorithm recommended maintaining the current V_T at 6 ml/kg PBW in 22 of 26 cases, and decreasing V_T below this level in the remaining 4 cases (Fig. 2a). The physicians kept V_T at 6 ml/kg PBW in 17 cases, but departed either side of this in the remaining 9 cases (Fig. 2a). Thus, for most of the 26 individual decisions, the algorithm and the physician agreed to keep V_T at the ARDSNet recommended level of 6 ml/kg PBW. When they disagreed the differences were within 2.5 ml/kg PBW of each other for all but 1 case, and the algorithm was clearly more conservative than the physician. Figure 2b shows a histogram of $V_{T,Fuzz} - V_{T,Phys}$ which again demonstrates the preponderance of agreement among the two decisions.

Figure 3 shows corresponding plots for the comparisons of $PEEP_{Fuzz}$ vs $PEEP_{Phys}$. In 22 of 26 cases the algorithm recommended increasing the current PEEP. The physician was more apt to maintain the current PEEP, and recommended no change in 20 of 26 cases (Fig. 3a). Although there were 4 cases where the physician recommended a significant increase in PEEP, the algorithm tended to increase PEEP more than the physician (Fig. 3b). Despite this difference, the algorithm and physician decision were within 2.5 cm H₂O of each other for all but 3 cases (Fig. 3b).

The differences between algorithm and physician decisions were not random, but rather depended on the values of the other physiologic parameters. In particular, $PEEP_{Fuzz} - PEEP_{Phys}$ exhibited a negative dependence on SaO₂ (Fig. 4a), while $V_{T,Fuzz} - V_{T,Phys}$ exhibited a decreasing trend as PAP increased above 35 cmH₂O (Fig. 4b). Additionally, the relationship between $PEEP_{Fuzz} - PEEP_{Phys}$ and input PEEP exhibited a slightly positive trend (Fig. 4c).

Discussion

Fuzzy logic is well suited for applications in medical decision-making because it can capture the subjective nature of human judgment^{13, 14}. For this reason, we decided to use fuzzy logic as the basis for an algorithm to decide how much V_T might be able to depart from 6 ml/kg PBW in ARDS patients. The 6 ml/kg V_T strategy is the only evidence-based approach for managing ARDS^{1, 8, 9}, so there is considerable conviction within the medical community that it should be strictly adhered to. Nevertheless, there is also widespread hesitation to do so at all costs, with many physicians feeling that particular situations call for a deviation from 6 ml/kg PBW⁷⁻⁹. In our previous study, we used our fuzzy logic algorithm to identify situations in which such discord might arise by capturing the expertise of 6 intensive care physicians in individual parameterizations of the algorithm¹². We then subjected each of the 6 algorithms to a wide range of values for the input parameters PAP, PEEP and SaO₂. Most of the time the 6 physicians agreed about how to set V_T , but there were ranges of some of the input parameters over which they disagreed quite markedly¹². This suggests that while the standard of 6 ml/kg PBW makes sense much of the time, it cannot be considered optimal

under all clinical circumstances encountered in ARDS, which is hardly surprising considering the numerous factors that can contribute to ARDS and the heterogeneity of the disease in the patient population. Our fuzzy logic algorithm is thus an attempt to provide a rationalized approach to departing from 6 ml/kg PBW under those circumstances that seem to call for it. Of course, whether such departures really are beneficial, regardless of their physiological appeal, can only be established via future randomized clinical trials. Fuzzy logic in the present application might thus be viewed as a technique for codifying departures from 6 ml/kg in a way that can serve as the basis for designing such trials. Related to this is the question of why physicians would disagree in their decisions as to what to do in a given situation. The fuzzy logic algorithm used in the present study represents the average decision making of 6 physicians who were in general agreement most of the time, but who did also disagree in some situations¹². The reasons for these disagreements are difficult to delineate precisely because they represent differences of opinion based on the experiential backgrounds of the particular physicians concerned, but it seems likely that they would be related to the concerns that have been expressed by others in the medical community^{8, 9}.

The goal of the present study was to retrospectively compare the decisions of our fuzzy logic algorithm to those made by experienced intensive care physicians. We found, overall, that the algorithm gave similar decisions to the physicians who actually attended on the cases. Interestingly, the algorithm was generally more conservative than the physicians, which might seem to suggest that the algorithm could have difficulty making bold decisions when they are called for. However, if the algorithm were implemented in an automated control loop it would have the opportunity to render many more decisions within a given period of time than is typical of a physician who rounds perhaps once or twice per day, making the aggregate consequences of the algorithm capable of matching even the most aggressive physician. This perhaps raises the concern that the algorithm might get into a runaway mode and produce an excessive aggregate change in either V_T or PEEP, but the limited extent to which we were able to test aggregate decisions in the present study (Figs. S4, and S5) suggests that this will not be the case. Our analysis of aggregate decisions was admittedly limited, but it does suggest that the algorithm may be able to perform well over the course of a patient's care, and that the algorithm can arrive at end point decisions that are comparable to those suggested by a physician even when simultaneously changing both V_T and PEEP. This is a fundamentally different approach from that of the physician who changes one parameter at a time.

Nevertheless, there were some systematic differences between the algorithm and physician decisions. For example, as PAP increased past 35 cm H₂O the algorithm decision on V_T became systematically less than that of the physician (Fig. 4b). This is interesting because the 6 physicians in our previous study, whose combined wisdom gave rise to the algorithm of the present study, were among those who would have been attending on the patients we examined here, and we had previously shown this to be an area of discordance amongst these physicians¹¹. A difference between the decisions these physicians made in the presence of the patient and their virtual decisions made via the algorithm could be indicative of their use of information other than PAP, PEEP and SaO₂ in setting V_T and PEEP. Such information could include knowledge of parameter values from the recent past, as well as other non-specific indicators of patient well-being such as perceived level of discomfort or

increased use of sedatives^{8,9}. On the other hand, these inconsistencies could also reflect the vagaries and imperfections of human decision-making. Such vagaries and imperfections are, of course, what protocols are designed to eliminate. In this regard, our fuzzy logic approach may eventually prove useful for codifying departures from the current 6 ml/kg V_T target, and thus providing a means of reducing variation in these departures.

The algorithm was less conservative about changing PEEP, sometimes matching the physicians and sometimes even recommending rather larger values for PEEP (Fig. 3). In general, the algorithm was more willing to increase PEEP than the physician. Additionally, when we assessed decisions based on the current value of PEEP, we saw that this difference was further exacerbated as the current PEEP increased (Fig 4c). This trend possibly reflects the fact that physicians are well aware of the adverse effects associated with high PEEP. The dangers include over-distension of the lung¹⁵, and compromised venous return¹⁶ that can lead to decreased oxygenation due to ventilation-perfusion mismatch¹⁷.

We also found that the algorithm decision on PEEP progressively increased above that of the physician as SaO₂ decreased below 100% (Fig 4a). This is consistent with the findings of our previous study¹² that physicians become more discordant as SaO₂ decreased from 100% toward 90%. It also indicates that physicians do not necessarily do in practice exactly what they plan to do via the fuzzy logic algorithm. A key assumption in any algorithm that uses measured parameters to make clinical decisions, regardless of whether or not fuzzy logic is involved, is that the information required to make a sensible decision is actually embodied in the parameters. If this is true, then the algorithm may be used to make decisions automatically, even without a human caregiver being involved, which has obvious benefits for future automation in the ICU. We could, of course, incorporate the use of additional information into our algorithm by fuzzifying other clinical parameters. We could also include the rates of change of PAP, PEEP and SaO₂ as additional parameters, which could improve the predictive behavior of the algorithm by taking trends into account. This might make the algorithm more responsive to the spectrum of clinical possibilities, but at the same time the complexity of a fuzzy logic algorithm increases rapidly with its number of parameters^{13,18}. There is thus a tradeoff to be considered between the number of parameters and algorithm complexity. In general, it is best to keep the number of parameters to a minimum, adding additional parameters only if it becomes apparent that the algorithm is seriously compromised without them. The limited scale of the present study does not allow us to determine if this would be the case, but if the algorithm were tested on a significantly larger scale it might become clear that additional detail, and thus complexity, would be required to properly deal with the spectrum of clinical situations.

Our algorithm, as used in the present study, is also limited by the fact that it reflects the average opinion of only 6 intensive care physicians, all of whom had worked together for several years at the same institution and who therefore presumably took a similar approach to managing ARDS. Deriving an average algorithm from these 6 physicians seemed to us to be the most sensible way to achieve robustness, especially as these physicians were in general agreement as to how to manage ARDS over substantial portions of the ranges of PAP, PEEP and SaO₂. Nevertheless, they did not agree in every case, as we have previously shown¹², and the level of disagreement might well have been more pronounced had we

included physicians from other institutions. In other words, the algorithm might have behaved somewhat differently if it had been calibrated to a different group of physicians. Accordingly, we cannot claim on the basis of the present study to have devised an algorithm that is robust enough to be adopted as a clinical tool; this would require input from a larger physician group followed by testing in a clinical trial. Our purpose here is merely to demonstrate that an algorithm of this nature, based on fuzzy logic, has the potential to work in a useful and safe manner. We performed this demonstration for the specific situation of ARDS patients ventilated with 100% FiO₂, not because this is advisable in any way but rather simply as an attempt to control the potential variability in this patient population. It is worth noting that, however, that our fuzzy logic algorithm can, in principle, be tailored to a particular patient population. This could prove useful for example, if the ARDS population were to eventually become stratified into sub-populations on the basis of differing pathophysiological characteristics.

Finally, our study is limited by being a retrospective comparison of decisions made on a small number of patients arising from a limited source of expert knowledge contained within a single close-knit group of ICU physicians. As such, the results of our study can only be taken to provide a preliminary indication of the feasibility of using a fuzzy logic based algorithm for deciding how to ventilate ARDS patients. Furthermore, in the decisions that we examined retrospectively, a change was made to either V_T or PEEP at any point in time, but not both, and we need to bear in mind that our algorithm made simultaneous decisions on V_T and PEEP. Our brief analysis of aggregate decisions (Online Supplement) addresses this issue to a limited extent, but addressing it definitively will require a prospective trial.

In summary, we have shown retrospectively that a fuzzy logic algorithm for adjusting V_T and PEEP in ARDS patients makes decisions that are clinically close to those of a group of experienced intensive care physicians, and that the algorithm is generally more conservative than the physicians. We have also shown that the algorithm is strongly inclined to keep V_T at 6 ml/kg PBW, but does allow for modest departures from this standard when the physiological indicators seem to call for it. We do not claim that the particular algorithm used in the present study is the best that could be devised, as that is a matter that will first require general debate among the intensive care community and can only be settled properly with an appropriate prospective randomized clinical trial. We believe, however, that our study shows valuable proof of concept for the potential role of fuzzy logic in the management of mechanical ventilation in ARDS.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 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 b) The ranges of the output parameters ΔV_T and ΔPEEP are each divided into 3 overlapping sets. The sets shown here are those that were used in the present study. The general set structure was presented in our previous study¹².

Figure 2.

Decisions on V_T made by fuzzy logic algorithm and physician: a) Scatter plot of physician vs algorithm decisions. The concentric circles indicate multiple points falling on the same location, and indicate that the large majority of the decisions by both physician and algorithm were for no change to be made in V_T . b) Histogram of differences in decisions.

Figure 3.

Decisions on PEEP made by fuzzy logic algorithm and physician: a) Scatter plot of physician vs algorithm decisions. The concentric circles indicate multiple points falling on the same location. b) Histogram of differences in decisions.

Figure 4.

Differences between algorithm and physician decisions: a) Differences in PEEP as a function of SaO_2 , b) differences in V_T as a function of PAP, and c) difference in PEEP as a function of PEEP. The concentric circles indicate multiple points falling on the same location.

Table 1

The rule table specifying the actions to be taken, in terms of adjusting V_T and PEEP, for each combination of set memberships for the input parameters PAP, PEEP and SaO_2 . The adjustments to V_T and PEEP produce V_T and PEEP, respectively as shown in Fig. 1. The structure of this rule table was presented in our previous study¹². The specific table entries shown here are those that were used in the present study.

Input Parameter Set Memberships for:			Actions in terms of adjustments in:	
PAP	SaO_2	PEEP	V_T	PEEP
Normal	Low	Low	Maintain	Increase
High	Low	Low	Decrease	Increase
Normal	Normal	Low	Maintain	Maintain
High	Normal	Low	Decrease	Maintain
Normal	Low	Normal	Maintain	Increase
High	Low	Normal	Maintain	Increase
Normal	Normal	Normal	Maintain	Maintain
High	Normal	Normal	Decrease	Maintain
Normal	Low	High	Maintain	Increase
High	Low	High	Decrease	Increase
Normal	Normal	High	Maintain	Decrease
High	Normal	High	Decrease	Decrease