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# A Pilot Bench Study of Decision Support for Proportional Assist Ventilation

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*Abstract*— **The purpose was to develop a bench setup for testing a decision support system (DSS) for proportional assist ventilation (PAV). The test setup was based on a patient simulator connected to a mechanical ventilator with the DSS measurement sensors connected to the respiratory circuit. A test case was developed with parameters of lung mechanics reflecting a patient with mild acute respiratory distress syndrome. Five experiments were performed starting at different levels of percentage support (%Supp) and continuing until the DSS advised to remain at current settings. Final advice ranged from %Supp of 50-70%, indicating some dependence of baseline level, but with resulting patient effort estimates indicating that this may not be clinically important. Further studies are required of test cases reflecting different patient types and in patients.**

## I. Introduction

Setting mechanical ventilation can be considered as an optimization problem of balancing competing goals. In supported ventilation modes where patients' spontaneous efforts trigger ventilator support, one important tradeoff is to the correct levels of support to avoid both under-support, which may cause inappropriately high work of breathing (WOB) [1], and over-support, which can depress respiratory drive and cause atrophy of the respiratory muscles [2].

The Beacon Caresystem (Mermaid Care A/S, Nørresundby, Denmark) is a model-based decision support system (DSS) for mechanical ventilation which applies models of physiology and clinical preferences regarding goals of mechanical ventilation [3,4]. The system has been shown to provide appropriate advice in patients on controlled mechanical ventilation and pressure support ventilation [5,6].

Proportional Assist Ventilation (PAV) is a mechanical ventilation mode for patients with spontaneous breathing efforts [7]. In contrast to pressure support where a set pressure is delivered when inspiratory effort is detected, PAV supports breathing proportionally to inspiratory effort as a percentage support (%Supp) of inspiratory resistive and elastic work [7]. Potential advantages include better comfort, less peak airway pressure ($P_{aw,peak}$) and less risk of overventilation [7]. PAV has resulted in similar WOB as pressure support [8] but improved patient-ventilator synchrony [9].

The purpose of this study was to develop a bench test setup to evaluate decision support for PAV %Supp, including whether advice depend on the baseline %Supp. As a pilot study, the bench test was performed on the Beacon Caresystem (the DSS) on a single test case.

## II. Methods

### A. DSS models of physiology and clinical preferences

The DSS includes mechanistic steady state models of pulmonary gas exchange, mechanics, drive and blood acid-base status. These models can be identified from a single arterial blood gas measurement entered into the DSS and measurements of pressures and settings from the ventilator collected via RS-232 communication, in combination with DSS built in continuous oxygenation measurements by pulse oximetry and side-stream breath-by-breath calorimetry giving flows, volumes, respiratory rate (RR), $O_2$ and $CO_2$ levels as well as metabolism ($VO_2$ and $VCO_2$) [4]. When identified, models can describe how the patient responds to changes in ventilator settings. In case of considerable gas exchange problem, the identification also requires measurement of ventilation and oxygenation at three inspiratory oxygen levels.

The physiological models are combined with models of clinical preferences associating simulated patient response with penalties reflecting risks primarily considered in mechanical ventilation. In controlled ventilation modes with no or limited spontaneous efforts, these functions quantify over-ventilation by risk of mechanical lung trauma and oxygen toxic effects and under-ventilation by risk of acidosis and low oxygenation. During supported ventilation modes ventilation, including PAV, over-ventilation is also quantified by risk of muscle atrophy with penalty increasing with low RR unless significant effort is identified as above normal dynamic compliance [10]. Under-ventilation is also quantified by risk of patient stress, this penalty increasing with RR to tidal volume ratio (rapid shallow breathing index) [10]. In addition, patient stress is identified by as increase in $O_2$ consumption and $CO_2$ production following changes in support [10]. By simulating combinations of settings and associating outcomes with a total penalty, the sum of all penalties, the advice constitutes settings associated with least total penalty.

The system adapts to patient response by applying simple linear regression models to learn changes in metabolism, dead space ($V_d$) and tidal volume ($V_t$) following a change in support, as described in detail previously [10]. E.g. if a reduction in support causes the patient to reduce inspiratory effort then this is reflected in a lower Vt than initially simulated, which is then

*Mermaid Care A/S provided a Beacon Caresystem device as well as necessary Beacon Caresystem one-use items for the study.

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learned and included in following simulations and calculations of advice. A similar learning model was applied to learn the response to %Supp with one additional learning model required to calculate pressures and volumes for a given %Supp, this constituting necessary changes for use in PAV.

### *B. Bench test setup and protocol*

A patient simulator (TestChest, neosim AG, Chur, Switzerland) was connected to the respiratory circuit of a ventilator (Puritan-Bennett PB840, Medtronic, Minneapolis, MN, USA) via an intubation tube, see Fig. 1. The DSS sampling tube for flow and sidestream gas analysis was inserted between the intubation tube and the ventilator respiratory circuit. TestChest simulates human cardio-respiratory physiology, allowing changes in gas exchange, haemodynamics, lung mechanics and spontaneous breathing effort. The respiratory muscle pressure ($P_{mus}$) can be directly controlled via csv file import to the control software.

For this study, a test case reflecting mild acute respiratory distress syndrome (ARDS) was selected as such patients have reduced lung compliance requiring tradeoffs between under- and overventilation to consider lung mechanics. TestChest parameters were set to reflect previously observed values in mechanically ventilated patients with mild ARDS [8, 11]. The primary lung mechanics parameters are listed in table I.

Five experiments were performed each experiment starting at a different baseline %Supp (20, 30, 50, 70 and 80%). DSS %Supp advice were followed and an experiment ended when advice was to remain at current settings. All other ventilator settings were kept constant throughout experiments to focus breathing effort support *per se*, see table I. To produce reproducible test case ventilation despite varied baseline levels, a linear relationship between %Supp and Pmus and RR was identified to maintain similar alveolar ventilation at all %Supp and reflect previously observed effort in patients on PAV [8] (Fig. 2A). Within breath Pmus CSV files were generated using a model of human respiratory muscle pressure [12], modified for test case parameters assuming equal inspiratory and expiratory time constants.

$$P_{mus}(t) = P_{mus,peak}\left(1 - e^{-\frac{1}{\tau_c}t}\right), for\ 0 < t \leq t_i$$
$$P_{mus}(t) = P_{mus,peak}\left(e^{-\frac{1}{\tau_r}(t-t_i)}\right), for\ t_i < t \leq t_{tot} \quad (1)$$

Where $P_{mus,peak}$ is maximum muscle pressure available from Fig. 2A, $t_i$ and $t_{tot}$ are inspiratory and total time, and $\tau_c$ and $\tau_r$ are time constants assumed equal and calculated as the product of respiratory system resistance and compliance ($R_{rs}$ and $C_{rs}$), from Table I. Fig. 2B shows Pmus calculated using (1) for %Supp of 20, 50 and 80%. Breaths were generated to maintain constant I:E ratio despite varying RR.

The DSS requires entering results of an arterial blood gas analysis to identify models and provide advice. To focus on WOB per se, values were entered reflecting healthy levels.

### *D. Data analysis and statistics*

The first 10 breaths at steady state following ventilator changes were selected for analysis excluding breaths affected by airway occlusions performed intermittently and automatically by the ventilator when in PAV mode.

Campbell diagrams were drawn for each breath and WOB was calculated as the integrated product of tidal volume change (Vt) and the difference between of pressure due to chest wall compliance and the pleural pressure (Ppl) [13]. WOB was then normalized to tidal volume. Ppl swing (ΔPpl) was calculated as the maximum negative change in Ppl from the end-expiratory plateau [11].

Figure 1. Bench test experimental setup. *(Communication between laptop and simulator as well as the DSS (BEACON) and ventilator. Pulse oximetry reading of the DSS on simulator, and respiratory circuit between simulator and ventilator with DSS sidestream gas sampling.)*

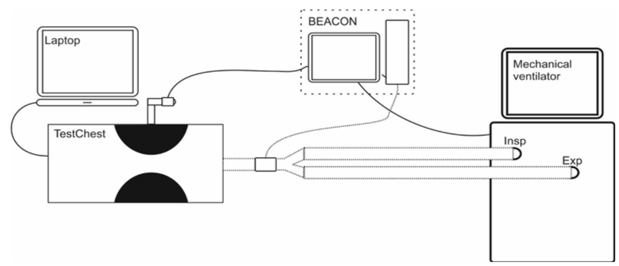
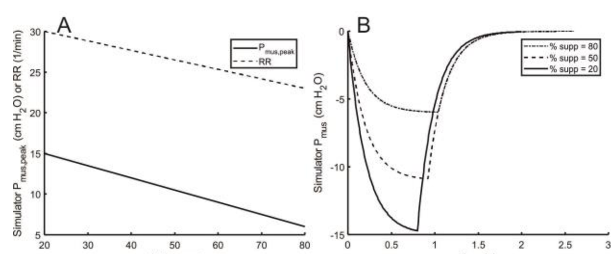



TABLE I. CONSTANT TEST CASE AND VENTILATOR VALUES

| **Test case parameters** | | | | |
|---|---|---|---|---|
| ***$C_{cw}$ (mL/cm $H_2O$)*** | ***$C_{rs}$ (mL/cm $H_2O$)*** | ***$R_{aw}$ (cm $H_2O$/(L/s))*** | ***$V_d$ (mL)*** | ***$FRC_{ZEEP}$ (mL)*** |
| 143 | 39 | 5.1 | 190 | 2250 |
| **Ventilator settings** | | | | |
| ***PEEP (cm $H_2O$)*** | ***PAV rise (%)*** | ***$\dot{V}$ sensitivity (L/min)*** | ***E sensitivity (L/min)*** | ***$FiO_2$ (%)*** |
| 7 | 50 | 3.0 | 3.0 | 21 |

Ccw: Chest wall compliance. Crs: Respiratory system compliance. Raw: Airway resistance. Vd: Anatomical dead space. $FRC_{ZEEP}$: Functional residual capacity at zero end-expiratory pressure. PEEP: Positive end-expiratory pressure. $\dot{V}$ sensitivity: Inspiratory flow sensitivity. E sensitivity: Expiratory flow sensitivity. $FiO_2$: Inspiratory oxygen fraction.

Figure 2. Simulation changes with % support. *(A: Changes in simulator settings for peak muscle pressure and respiratory rate with changes in %Supp on the ventilator. B: Example simulator inspiratory muscle pressures used for %Supp of 20, 50 and 80%.)*




Intrinsic positive end-expiratory pressure (PEEPi) was estimated as the fall in Ppl at end of expiration due to inspiratory effort until inspiratory flow starts [13]. $P_{pl}$ or its surrogate esophageal pressure is not routinely available in an ICU so estimates of peak muscle pressure ($P_{mus,peak}$) and muscle pressure time product (*PTPmus*) proposed for ventilation with PAV were also calculated [14], see (2) and (3):

$$P_{mus,peak} = (P_{aw,peak} - PEEP)\frac{100 - supp\%}{supp\%} \quad (2)$$

Where $P_{aw,peak}$ is the peak airway pressure.

$$PTP_{mus} = \frac{P_{mus,peak} \times t_i}{2} RR \quad (3)$$

Statistical analysis was performed using MatLab (R2017b, MathWorks, Natick, MA, USA). Descriptive statistics are reported as mean ± SD over the analyzed breaths.

## III. Results

### A. Baseline values

Table II shows average measured ventilation and estimates of work of breathing for baseline support level of 20, 30, 50, 70 and 80%. As support was increased, RR decreased, $\dot{V}_E$ remained relatively unchanged and $V_t$ increased, this resulting in increased $P_{aw,peak}$. $t_i/t_{tot}$ and $PEEP_i$ remained relatively unchanged. All other WOB estimates decreased with increasing support level, except the $P_{mus,peak}$ estimate which primarily showed a change when increasing support from 50 to 70 and 80% which resulted in decreased $P_{mus,peak}$.

### B. Advice

Table III shows that the final support level ranged from 50-70% for baseline levels of 20-80%. Number of advice varied from 0-4 with fewest advice at 70 and 80% support level and most advice at 50%. The range of final support level resulted in more narrow ranges of final ventilation and WOB measurements as compared to the baseline values in table II.

TABLE II. Baseline

| Measurement | Baseline PAV (%) | | | | |
|---|---|---|---|---|---|
| | ***20*** | ***30*** | ***50*** | ***70*** | ***80*** |
| RR ($min^{-1}$) | 30±0.1 | 29.1±0.1 | 26.1±0.2 | 24.0±0.1 | 23.1±0.1 |
| $V_t$ (mL) | 480±1 | 497±1 | 543±2 | 564±3 | 612±5 |
| $\dot{V}_E$ (L/min) | 14.4±0.1 | 14.5±0.1 | 14.2±0.1 | 13.6±0.1 | 14.1±0.1 |
| $P_{aw,peak}$ (cm $H_2O$) | 13.8±0.2 | 15.0±0.1 | 18.1±0.2 | 21.1±0.1 | 23.9±0.2 |
| $t_i/t_{tot}$ | 0.42±0.00 | 0.41±0.00 | 0.41±0.00 | 0.42±0.00 | 0.44±0.00 |
| $\Delta P_{pl}$ (cm $H_2O$) | 12.0±0.0 | 11.1±0.0 | 8.4±0.0 | 5.5±0.0 | 4.4±0.0 |
| $PEEP_i$ (cm $H_2O$) | 2.1±0.0 | 2.1±0.0 | 2.0±0.0 | 2.0±0.0 | 2.0±0.0 |
| WOB (J/L) | 1.24±0.00 | 1.17±0.00 | 0.94±0.00 | 0.66±0.00 | 0.53±0.00 |
| $P_{mus,peak}$ *(cm $H_2O$)* | 5.0±0.2 | 5.3±0.1 | 5.0±0.1 | 4.0±0.0 | 3.1±0.0 |
| $PTP_{mus}$ ($\frac{cm\,H_2O\,s}{min}$) | 63.3±2.7 | 65.5±1.4 | 61.6±1.0 | 49.8±0.6 | 41.5±0.8 |

TABLE III. Advice

| Measurement | Baseline PAV % support | | | | |
|---|---|---|---|---|---|
| | ***20*** | ***30*** | ***50*** | ***70*** | ***80*** |
| Final % Supp | 50 | 60 | 50 | 70 | 70 |
| No. advice | 2 | 2 | 4 | 0 | 1 |
| % Supp range | 20-50 | 30-60 | 30-65 | 70 | 70-80 |
| RR ($min^{-1}$) | 26.1±0.1 | 25.0±0.1 | 26.1±0.2 | 24.0±0.1 | 24.0±0.1 |
| $V_t$ (mL) | 534±2 | 528±2 | 528±2 | 564±3 | 573±2 |
| $\dot{V}_E$ (L/min) | 13.9±0.1 | 13.2±0.1 | 13.8±0.1 | 13.6±0.1 | 13.8±0.1 |
| $P_{aw,peak}$ (cm $H_2O$) | 17.9±0.2 | 18.9±0.2 | 17.7±0.2 | 21.1±0.1 | 21.3±0.1 |
| $t_i/t_{tot}$ | 0.41±0.00 | 0.41±0.00 | 0.41±0.00 | 0.42±0.00 | 0.42±0.00 |
| $\Delta P_{pl}$ (cm $H_2O$) | 8.4±0.0 | 6.8±0.0 | 8.4±0.0 | 5.5±0.0 | 5.5±0.0 |
| $PEEP_i$ (cm $H_2O$) | 2.0±0.0 | 2.0±0.0 | 2.0±0.0 | 2.0±0.0 | 2.0±0.0 |
| WOB (J/L) | 0.94±0.00 | 0.78±0.00 | 0.94±0.00 | 0.66±0.00 | 0.66±0.00 |
| $P_{mus,peak}$ *(cm $H_2O$)* | 4.9±0.1 | 4.3±0.1 | 4.8±0.1 | 4.0±0.0 | 3.9±0.0 |
| $PTP_{mus}$ ($\frac{cm\,H_2O\,s}{min}$) | 60.6±1.2 | 52.3±1.2 | 60.1±1.6 | 49.8±0.6 | 49.6±0.6 |

Fig. 2B, D and F depict elements of the DSS advice for three cases of current (blue), simulated (white) and advised (grey) support levels. Support level settings are illustrated above a hexagonal display of the six clinical preferences modeled by the system illustrating the penalty for each preference type as distance from the center of each axis. The grey boxes at the hexagon corners illustrate variable values at current, simulated and response to advised support level. For the Fig. 2 simulated support was set equal to advised. Fig. 2A, C and D are Campbell diagrams for a representative breath at the current support level of Fig. 2B, D and F, respectively.

Fig. 2A shows that for the baseline of 20% support, a significant resistive WOB component can be observed, this constituting the area to the left of the zero-flow line (dash-dotted line). The first advice from 20% was to increase support to 40% (Fig. 2B) expecting a reduction in RR (Rf in figure) associated with lower risks of mechanical trauma and patient stress. Fig. 2C shows the Campbell diagram for advice to remain at 50%. Resistive work and $P_{pl}$ swing was less than at 20% with also elevated $V_t$. 50% support (Fig. 2D) was associated with lower risk of mechanical trauma and stress than 20%. Resistive work and Ppl swing were further reduced at 80% support (Fig. 2E) compared to 20 and 50% but with a larger $V_t$. From 80% the DSS advised to reduce to 70% (Fig. 2F), this being associated with an expected reduction in risks of mechanical trauma and atrophy but increased risk of patient stress compared to 80%, although with greater risk of mechanical trauma and atrophy than 20 and 50% and lower risk of patient stress.

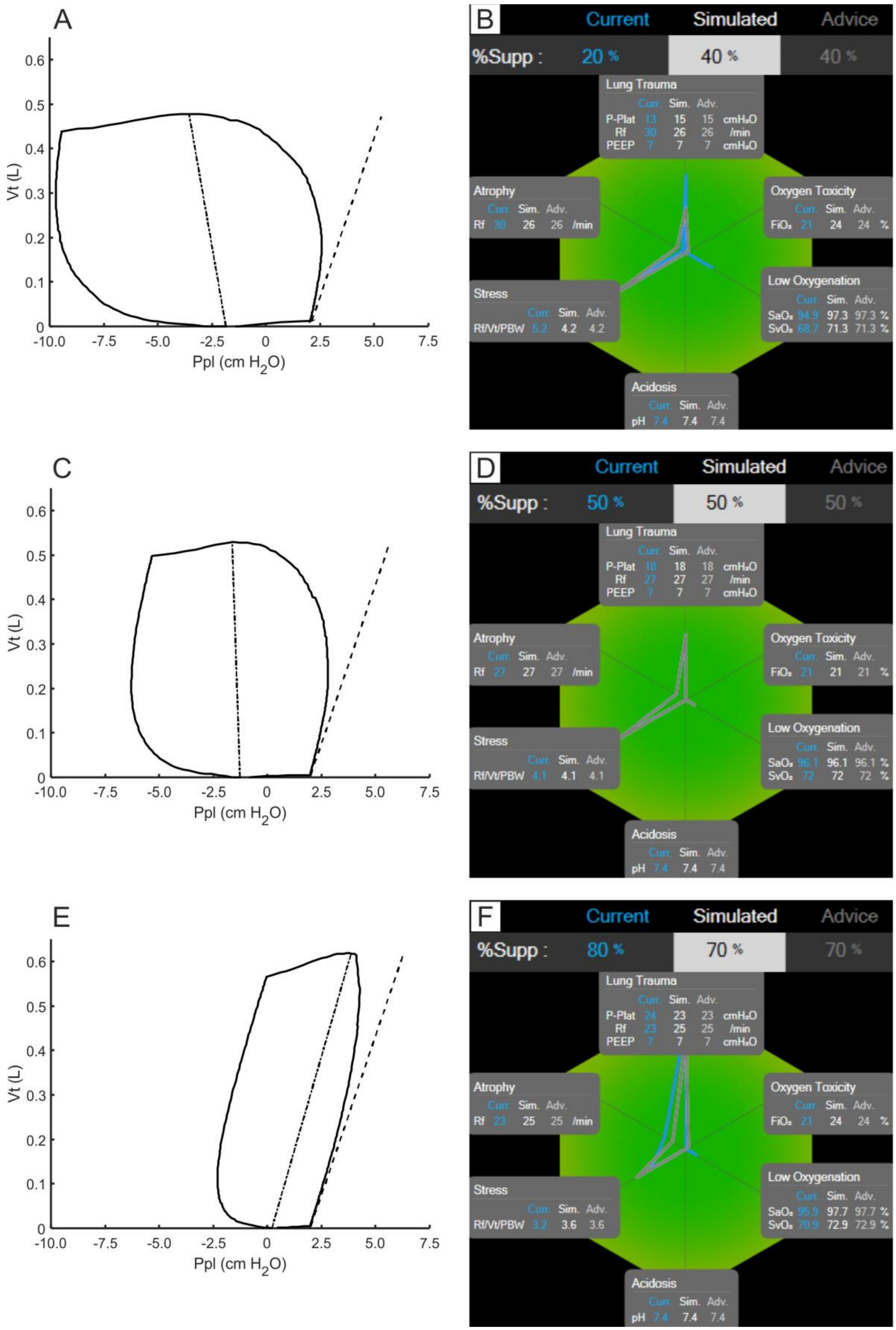
## IV. Discussion

Using a bench test setup consisting of a simulator and a ventilator with test case parameters and ventilation set according to previously observed values in clinical studies, it was possible to simulate a patient breathing in a ventilator at levels of ventilation and WOB reflecting those previously observed in mild ARDS patients during support ventilation modes [8,11]. The test case was specifically designed to reflect average observations of these studies (Table I and Fig. 1) indicating that those control settings selected on the simulator were also obtained using the test setup. Values of $\dot{V}_E$, RR and $t_i/t_{tot}$ at 50 and 80 %Supp were within 10% of those observed in patients on PAV by Delaere et al. [8], but WOB was higher in the present study although with lower ΔPpl and Vt. Ccw and Raw used in the test case were based on values observed by Kallet et al. in ARDS patients [11]. Delaere et al. did not report $R_{aw}$ and assumed a $C_{cw}$ of 200 ml/cm $H_20$, i.e. 25% higher than in the present study likely explaining their lower WOB [8].

The most frequently observed %Supp during the study was 50% occurring five times across experiments. The largest observed relative variations in average values (not shown) were for Pawpeak, Vt and $t_i/t_{tot}$ with [17.4 - 18.3 cm $H_2O$], [523 - 543 mL] and [0.41 - 0.42], respectively, indicating that the bench test setup yielded reproducible results, although more systematic study of reproducibility is necessary.

DSS advice increased %Supp in cases of low support and reduce when support was excessive as most clearly shown for baseline %Supp of 20, 30 and 80%. %Supp of 20 and 30% resulted in excessive patient effort reflected in WOB > 1 J/L and identified by the DSS as increased risk of patient stress due to rapid shallow breathing index and lung trauma risk due to high RR (Fig. 2B). The increased WOB at low support was primarily due to increased resistive work (Fig. 2A).

Figure 3. Individual advice. *(A, C and E: Campbell diagram of tidal volume (Vt) vs pleural pressure (Ppl) (solid line) for a breath at current support level depicted to the right, zero-flow line from start to end of inspiration (dash-dot line) and relative chest wall pressure (dashed line). B, D and F: Advice on support level (%) and associated hexagon depicting preference function values for mechanical ventialtion goals. Figure caption.)*



Final %Supp advice ranged between 50-70%, with most advice observed from a baseline of 50%. This indicates that when the initial %Supp is not obviously under- or over-support, the system tests the response of the patient by reducing and increasing support learning the response and adapting advice accordingly. The spread in advice is due to the limited difference in patient response across these levels of support. The observed patient effort can appear as ranging from slightly aggressive to conservative depending on which parameter used to judge the response. WOB in a healthy subject is around 0.5 J/L [15] indicating that regardless of support level, a patient as the test case would experience increased breathing effort. Carteaux et al. proposed to use a bedside estimate of muscle work to set %Supp targeting a PTPmus between 50-150 $\frac{cm\,H_2O\,s}{min}$ [14]. In the present study maximum observed PTPmus was 65.5 $\frac{cm\,H_2O\,s}{min}$ at 30% whilst 70-80% yielded PTPmus below the target range proposed by Carteaux et al. Further studies are required to clarify how optimal patient effort differs between patient types. It would be interesting to include test cases with healthy levels to verify that it is possible to obtain healthy levels of WOB as well as test cases with more severe airway resistance as this may be several factors higher in some patient types.

This pilot study has some limitations. More test cases would allow inferential statistical analysis in addition to the above considerations. It was assumed that alveolar ventilation, metabolism and I:E ratio remained constant when varying %Supp. However, this may not always be the case, in particular when the patient is under-supported as insufficient ability to sustain the breathing effort may cause alveolar ventilation to drop [16]. Alveolar ventilation may also change following changes in metabolism in response to different breathing efforts. The focus of this study was WOB, ventilation and lung mechanics. However, the different clinical goals of mechanical ventilation are not independent with, for example, increased metabolism potentially requiring increased inspiratory oxygen to maintain appropriate oxygenation as also considered in the studied DSS. Similarly, PEEP can be increased both to support the breathing effort and to improve gas exchange but may affect risk of mechanical trauma to the lung both positively and negatively (17). Future bench studies could therefore benefit from including all ventilator settings as well as gas exchange and acid base problems in test cases to elucidate the role of these aspects in %Supp advice.

## V. Conclusion

Results indicate that the developed bench setup produced realistic and reproducible simulations of a spontaneously breathing patient on PAV as intended. Result also indicated that DSS advice acted to prevent under- and over-support with some dependence on baseline support level, likely due to limited difference between these levels for the studied test case. Further studies are required to understand bench setup and advice in different simulated patient types as well as in real patients.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