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Research article

The influence of gravity on electrical impedance tomography measurements during upper body position change

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ABSTRACT

Objective: The aim of the study was to examine the influence of gravity on regional ventilation measured by electrical impedance tomography (EIT) with the standard electrode belt position at the 5th intercostal space during tilting from supine to sitting positions.
Methods: A total of 30 healthy volunteers were examined prospectively in supine position during quiet tidal breathing. Subsequently, the bed was tilted so that the upper body of the subjects achieved 30, 60 and 90° every 3 min. Regional ventilation distribution and end-expiratory lung impedance (EELI) were monitored with EIT throughout the whole experiment. Absolute tidal volumes were measured with spirometry and the volume-impedance ratio was calculated for each position.
Results: The volume-impedance ratio did not differ statistically between the studied body positions but 11 subjects exhibited a large change in ratio at one of the positions (outside 99.3% coverage). In general, ventilation distribution became more heterogeneous and moved towards dorsal regions as the upper body was tilted to 90-degree position. EELI increased and tidal volume decreased. The lung regions identified at various positions differed significantly.
Conclusion: Gravity has non-negligible influence on EIT data, as the upper body tilted from supine to sitting positions. The standard electrode belt position might be reconsidered if ventilation distribution is to be compared between supine and sitting positions.

1. Introduction

Electrical impedance tomography (EIT) is an imaging modality that tracks the regional ventilation and perfusion distribution within the lungs [1,2]. Imperceptible alternating currents are injected to the thorax and the corresponding electrical potentials at the chest wall surface are measurement. Since changes in air content and blood flow modify the electrical impedance of the lung tissue, the ventilation and perfusion are captured. The EIT technique has already been validated by conventional methods, such as CT [3], single

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photon emission computer tomography [4], positron emission tomography [5] and pneumotachography [6]. The correlation between relative impedance changes and volume changes is significant (e.g. $R^2 = 0.95$ observed in Ref. [7]). Typical EIT devices require an array of 16–32 electrodes in one elastic belt. The recommended belt position is the 5th to 6th intercostal space in the parasternal line [8]. When the belt position is not optimal, the tidal volume to tidal impedance ratio differs at various lung volume levels [9–11]. If the electrodes are placed below the 6th intercostal space, the diaphragm moves into or out of the measurement plane during tidal breathing and the relative impedance changes also capture the volume changes in the abdomen.

The position of diaphragm differs at various upper body positions, which influences the lung volume [12]. The postural effects may improve lung function of ICU patients, as suggested in previous studies with EIT [13,14]. In these studies, EIT-derived parameters between supine and sitting positions were compared. The prerequisite of such comparison was that the lung regions included in the EIT measurement plane remained unchanged when the subjects were moved from supine to sitting positions. The influence of gravity on EIT images was studied intensively for the anterior-posterior and lateral directions [15–17]. Some studies also looked into the ventilation alteration in tilted positions [18,19]. However, up to now, no study has ever investigated the influence of gravity (superior-inferior direction) on EIT measurements during upper body position change. Whether the EIT measures obtained in the supine and sitting positions could be compared was not systematically studied. The aim of the study was to examine the influence of gravity on regional ventilation via altering the diaphragm position induced by upper body tilting.

2. Methods

The ethics committee of the Fourth Military Medical University has approved the prospective observational study (KY20224101-1). All subjects provided their informed consent prior to the study. Thirty lung-healthy volunteers were examined prospectively (male: female, 23:7; age, 26.1 ± 4.0 years; height, 174.2 ± 7.9 cm; weight, 70.2 ± 13.3 kg).

The subjects were lying in supine position, breathing spontaneously. A dedicated belt with 16 electrodes was placed around the chest at the level of the 5th intercostal spaces. For female subjects, if 5th intercostal space was not accessible, the electrode belt was placed above the breast (~4th intercostal spaces). Raw EIT data were acquired with VenTom-100 (MidasMED Biomedical technology, Suzhou, China) with a frame rate of 20 images/s. The device applied excitation currents (1 mArms) through opposite electrodes and the data were reconstructed using the GREIT algorithm [20]. During quiet tidal breathing, the reference frame for image reconstruction was captured individually. Subsequently, the bed was tilted so that the upper body of the subjects achieved the following angles: 0, 30, 60 and 90° head up (Fig. 1). The subjects were refined from any body movements to avoid any shift of the electrodes. At each angle, the subjects breathed in a relaxed quiet manner for 3 min with EIT measurement conducted simultaneously. Exact tidal volume changes at each body angle were measured with a commercial spirometer (HI-101; CHEST M.I., INC., Tokyo, Japan).

2.1. EIT data analysis

Functional EIT (fEIT) images were constructed as the differences between the end-expiration and the end-inspiration images, which denotes the tidal breathing (TV) variation.

$$TV_j = \Delta Z_{j,Ins,n} - \Delta Z_{j,Exp,n} \tag{1}$$

where TV_j is the pixel j in the fEIT image; $\Delta Z_{j,Ins}$ and $\Delta Z_{j,Exp}$ are the pixel values in the raw EIT image at the end-inspiration and end-expiration, respectively.

In order to assess the influence of diaphragm position on regional ventilation, several EIT-based measures were calculated to characterize spatial and temporal ventilation distributions:

The measured tidal volume (global) and relative tidal impedance change (global difference between end inspiration and end

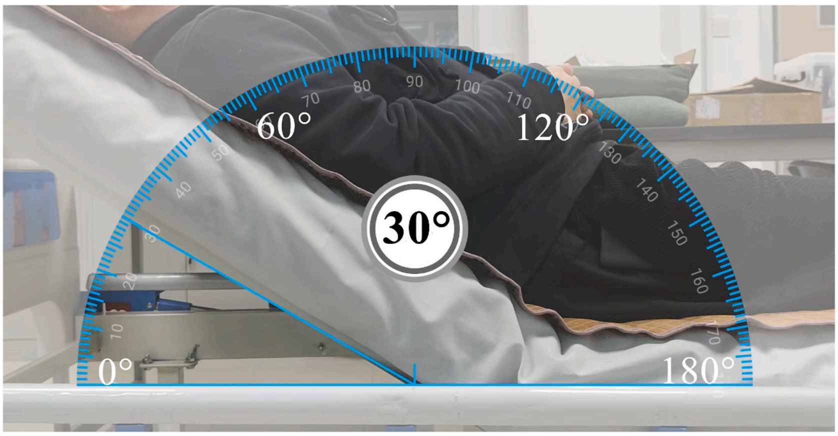

Fig. 1. Illustration of upper body position changes on the tilted bed. The photo shows an angle of 180°–150° = 30°.

expiration) was calculated for each position (denoted as *V/Imp*), which was the primary endpoint of the study. Besides, in order to remove the arbitrary units the measured global *TV* was normalized to ml according to the measured tidal volume in the corresponding body positions respectively. The change of end-expiratory lung impedance (*EELI*) in respect to the EELI in supine position was also calculated to assess the change of end-expiratory lung volume. Since no absolute value can be obtained, the ΔEELI was normalized to the global *TV* during the supine position. Data from the last minute of each measuring position were averaged to minimize the natural variation during spontaneous breathing.

The global inhomogeneity index (*GI*) was used to evaluate the spatial ventilation distribution from the *TV*s [21]. The calculation is described in Eq. (2):

$$GI = \sum_{l \in lung} \left| TV_l - Median\left(TV_{lung}\right) \right| \Big/ \sum_{l \in lung} TV_l \tag{2}$$

where TV_l is the pixel in the lung regions (all positions shared the same lung area for each individual for this GI calculation); Pixel l belongs to lung regions if $TV_l > \max(TV) \times 20\%$. TV_{lung} represent the group of all pixels from the lung area. Low *GI* index suggests homogeneous ventilation distribution.

The ventilation distribution affected by gravity can be calculated using center of ventilation (*CoV*) [22]. The calculation is described in Eq. (3):

$$CoV = \sum \left(y_j \times TV_j\right) \Big/ \sum TV_j \times 100\% \tag{3}$$

where y_j is the pixel index and of pixel j scaled from 0 (the top) to 100% (the bottom of the image).

Regional ventilation delay (*RVD*) can be used to assess the ventilation delay at the beginning of inspiration [23], as described in Eq. (4).

$$RVD_l = t_{l,40\%} \Big/ T_{ins,global} \times 100\% \tag{4}$$

where $t_{l,40\%}$ is the actual time for pixel l to reach 40% of its maximum *TV*. $T_{ins,\ global}$ represents the inspiration time calculated from the global impedance curve. In a previous study, standard deviation of *RVD* was proposed [23] to quantify the heterogeneity of regional ventilation delay:

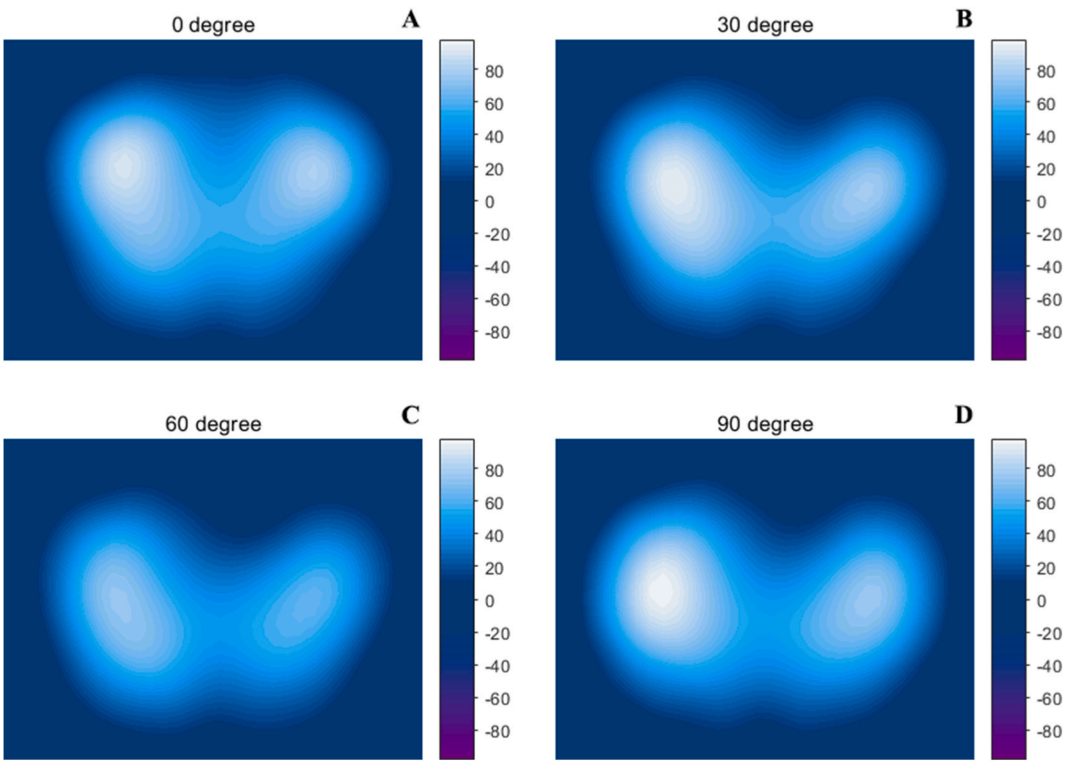

Fig. 2. Functional EIT images showing the tidal ventilation distribution at each body position. A: 0°; B: 30°; C: 60°; D: 90°.

$$RVD_{SD} = \sqrt{\frac{1}{L}\sum_{l \in lung}\left(RVD_l - mean\left(RVD_{lung}\right)\right)^2} \quad (5)$$

where L is the total number of pixels in the lung regions.

The parameter values (V/Imp, TV, GI, CoV, RVD_{SD}) calculated for 30, 60 and 90° were compared to that obtained at 0°. For *EELI*, the differences were normalized to *TV* at 0°.

The lung region for each position was denoted as $TV_{lung,x}$. $\Delta Area$ represented the number of pixels that were in either $TV_{lung,x}$ or $TV_{lung,0}$ but not in both (Eq. (6)):

$$\Delta Area = \left(TV_{lung,x} - TV_{lung,0}\right) \cup \left(TV_{lung,0} - TV_{lung,x}\right) \quad (6)$$

Besides, the $\Delta Area$ values for ventral and dorsal regions of the image were also calculated. The values were presented as percentage of size to the corresponding regions.

2.2. Statistical analysis

Data analysis was performed using MATLAB 2015b (The MathWorks Inc., Natick, USA). For normality testing we used the Lilliefors test. Results were expressed as mean ± standard deviation if the data were normally distributed. One-way ANOVA was used to compare the changes at different upper body positions. A p value < 0.05 was considered statistically significant. Since the *V/Imp* was decisive in regarding whether the impedance data could be compared at different positions, Bland-Altman analysis was applied to show the deviation of *V/Imp* between 0-degree and other angles.

3. Results

The results were normally distributed. Typical changes of ventilation distribution are illustrated in Fig. 2. Ventilation distribution was more homogeneous in 0-degree position and moved towards dorsal regions in 90-degree position. The EIT measures are summarized in Table 1 and the changes compared to 0-degree are presented with boxplots in Fig. 3. $\Delta V/Imp$ was small for some subjects. However, 11 subjects were identified as outliers (at least one red pluses in Fig. 3 top left). Only one female (14.3%) but 10 males (43.5%) were identified as outlier. Bland-Altman analysis in Fig. 4 showed that most of $\Delta V/Imp$ were small but outliers deviated from 0 with high absolute *V/Imp*. The statistics of Bland-Altman were summarized in Table 2.

For other EIT-derived parameters, EELI increased and tidal volume decreased significantly from supine to sitting positions ($P < 0.0001$). The lung regions identified at various positions also differed significantly in both ventral and dorsal regions ($P < 0.0001$).

4. Discussions

In the present study, we systematically investigated the influence of gravity on regional ventilation from supine to sitting positions when the electrode belt was placed at the recommended level (5th intercostal space). The change of diaphragm position may alter the *V/Imp* in some subjects, which might render the regional ventilation in the corresponding positions incomparable. Besides, it also influences the regional ventilation distribution and EELI.

Although multi-plane EIT is proposed in experimental settings, in clinical practice, measurements are conducted with single plane of electrodes. Since the EIT measurement plane only covers part of the lungs, it is essential to obtain constant *V/Imp* throughout the measurement period for data analysis and ventilation monitoring. The position of diaphragm is influenced by many factors e.g. the absolute lung volume, gravity, muscle paralysis, wounds. The *V/Imp* was suggested to be a useful index to assess whether the electrode plane is optimal [11]. As showed in a previous study [10], the influence of lung volume on the *V/Imp* should be minimized with the standard electrode placement (i.e. the 5th intercostal space). It is found in the present study that the standard electrode placement worked well in most of the subjects. Nevertheless, diaphragm position introduced large changes in *V/Imp* in 11 subjects in at least one

Table 1
Results of EIT measures of the studied subjects.

Parameter \ Angle	0-degree	30-degree	60-degree	90-degree
V/Imp (ml/AU)	16.04 ± 8.75	13.04 ± 4.68	14.97 ± 10.34	18.18 ± 15.99
ΔEELI/TV %	~	−0.49 ± 48.34	1.44 ± 68.32	51.64 ± 60.57
TV (ml)	819 ± 335	697 ± 276	605 ± 264	572 ± 236
GI	0.42 ± 0.11	0.42 ± 0.11	0.45 ± 0.12	0.44 ± 0.11
CoV (%)	48.4 ± 1.55	49.5 ± 1.76	51.2 ± 2.30	51.2 ± 2.58
RVD_{SD}	3.82 ± 1.34	3.93 ± 1.25	4.12 ± 1.94	3.57 ± 1.06
$\Delta Area_{ventral}$ (%ventral)	~	3.2 ± 2.2%	5.8 ± 3.4%	6.7 ± 2.7%
$\Delta Area_{dorsal}$ (%dorsal)	~	3.3 ± 3.1%	4.4 ± 3.3%	5.4 ± 3.6%

V/Imp, volume to impedance ratio; AU, arbitrary unit; EELI, end-expiratory lung impedance; TV, tidal variation; GI, the global inhomogeneity index; CoV, the center of ventilation; RVD_{SD}, standard deviation of regional ventilation delay. ΔArea was normalized to the size of corresponding regions (ventral or dorsal).

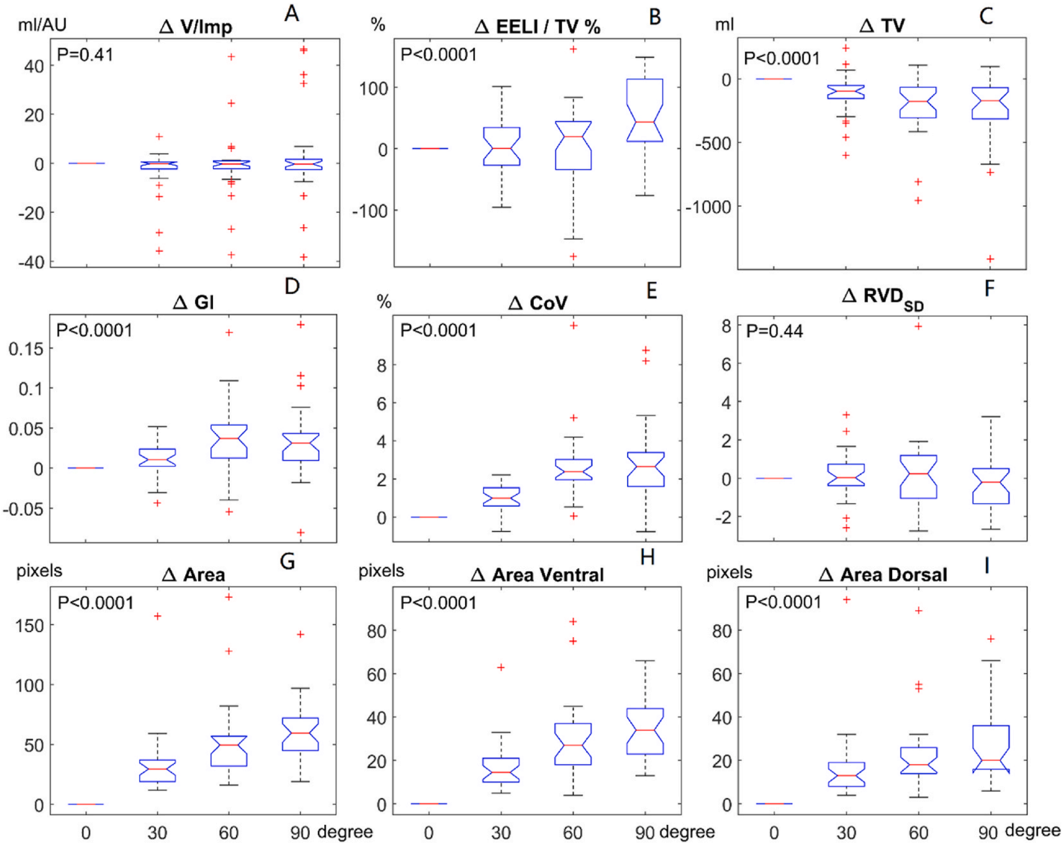

Fig. 3. Boxplots of EIT-derived parameters. The central mark is the median (red line), the edges of the box are the 25th and 75th percentiles, the whiskers extend to 1.5 interquartile range outside the box edges, and the outliers are marked with red pluses. A: ΔV/Imp; B: ΔEELI/TV%; C: ΔTV; D: ΔGI; E: ΔCoV; F: ΔRVD_{SD}; G: ΔArea; H: ΔArea Ventral; I: ΔArea Dorsal. V/Imp, volume to impedance ratio; AU, arbitrary unit; B: EELI, end-expiratory lung impedance; TV, tidal variation; GI, the global inhomogeneity index; CoV, the center of ventilation; RVD_{SD}, standard deviation of regional ventilation delay.

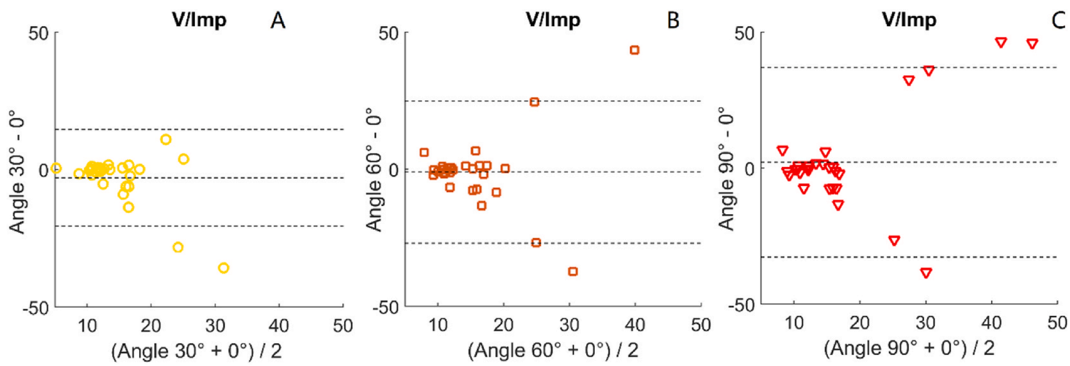

Fig. 4. Bland-Altman plots showing the differences of volume to impedance ratio (V/Imp) between 30-degree to supine (A), 60-degree to supine (B) and 90-degree (sitting) to supine (C). The dashed lines indicated the mean and ±1.96 standard deviations.

of the consecutively studied upper body positions. More male than female subjects (43.5 vs. 14.3%) had been influenced by gravity-induced diaphragm displacement. Due to the size of breasts, the position of electrode belt was in general placed above the breasts (~4th intercostal spaces) in the present settings for female subjects, which may explain why the influence on female subjects was lower. It implied that in some subjects, diaphragm might still intercept the measurement plane even if the electrodes were placed at the recommended level (5th intercostal space). If ventilation at different tilted positions should be compared, 3–4th intercostal spaces might be a more suitable level for electrode placement.

Table 2
The statistics of Bland-Altman in Fig. 4.

V/Imp	Differences 30°–0°	Differences 60°–0°	Differences 90°–0°
Bias	−3.00	−1.07	2.14
LoA (95%)	[-20.59, 14.60]	[-27.03, 24.89]	[-32.72, 37.01]
CI (95%)	[-6.35, 0.36]	[-6.02, 3.88]	[-4.50, 8.79]

V/Imp, volume to impedance ratio; LoA, limits of agreement; CI, confidence intervals.

Gravity influences not only the diaphragm but also the chest wall. From supine to sitting positions, the chest wall compliance increases so thus the respiratory system compliance. Therefore, the EELI increases and less pressure is posed onto the lungs. The shape of the diaphragm becomes flatter in tilted positions so the tidal volumes in a relaxing manner are smaller compared to that in the supine position. Since the lung regions became smaller and ventilation distributed towards dorsal part, the GI slightly increased in tilted positions. In general, gravity-dependent diaphragm displacement influenced the regional ventilation distribution and therefore, could be used on ICU patients for early rehabilitations [13,14]. In addition, the heart descended towards abdomen during the position change from supine to sitting. It is observed that the ventilation area tends to decrease in the heart area in the sitting posture (Fig. 2). Further confirmation of heart position with cardiac function imaging is needed.

The study has a few limitations: (1) only healthy volunteers of younger age were included in the study. Patients with e.g. spinal cord injury or flail chest have different kind of diaphragm displacements, which might behave differently. Nevertheless, the findings in healthy subjects could be used as reference for other future studies with patients. (2) The variety of age and body-mass index of the subjects was limited. The influences on adolescent and elderly, as well as large body-mass index are unknown. An early study suggested that age might pose a significant effect on posture-dependent changes in ventilation distribution [24], which was not explored in the current study (3) Only the upper body of the subjects was tilted, instead of the whole body. The lower body remained horizontal, which may have restricted the diaphragm displacement. (4) The calculation of GI is affected by lung region assessment. In the present study, the lung regions identified in different body positions were combined. Due to the change of lung volume covered in the EIT measurement plane, we might overestimate the real lung regions for each individual position. Therefore, we introduced a parameter ΔArea to assess the change of lung regions. Assuming that the GI should be similar if the lung volume assessed by EIT in different positions were the same for healthy volunteers, The ΔGI might reflect whether regional ventilation in the corresponding positions were comparable.

5. Conclusion

Gravity alters the diaphragm position, which has non-negligible influence on EIT measurements. The standard electrode belt position at 5th intercostal space might be reconsidered if ventilation distribution is to be compared between supine and sitting positions.

Author's contribution

MD and ZZ conceived and designed the experiments; LY and ZG performed the experiments. XC, FF, KM and IF analyzed and interpreted the data. ZZ and LY wrote the paper. The others critically revised the manuscript. All authors approved the final version submitted.

Declaration of competing interest

ZZ receives a consulting fee from Dräger Medical. He is also a member of the advisory board of the journal Heliyon. Inéz Frerichs reports funding from the European Union's Framework Programme for Research and Innovation Horizon2020 (WELMO, Grant No. 825572). Other authors declare no conflict of interest.

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