Research Square

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Effects of tidal volume and respiratory rate on diaphragmatic motion velocities and expiratory muscle recruitment in healthy volunteers: A Tissue Doppler Imaging study

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Abstract

Background

Minute ventilation (MV) can be increased by altering tidal volume (VT) or respiratory rate (RR), potentially imposing different mechanical demands on the respiratory muscles. Diaphragmatic tissue Doppler imaging (TDI) provides non-invasive measurements of diaphragmatic contraction and relaxation velocities. We examined the effects of increasing MV through increased VT or RR on diaphragmatic TDI parameters and transversus abdominis recruitment in healthy volunteers.

Methods

Twenty-one healthy volunteers underwent quiet breathing followed by high-VT and high-RR breathing conditions. In each condition, measurements were obtained over 15 consecutive breaths and summarized at the subject level. Differences among the three conditions were assessed with the Friedman test, followed by paired Wilcoxon signed-rank tests with Holm adjustment. Within-subject associations between ventilatory and TDI variables were assessed using repeated-measures correlations.

Results

All respiratory and diaphragmatic variables differed significantly across the three conditions (all Friedman $p < 0.001$). MV increased from 8.93 ± 1.90 L/min during quiet breathing to 16.56 ± 4.06 L/min during high-VT breathing and 19.23 ± 6.26 L/min during high-RR breathing. PCV increased from 2.59 ± 0.52 to 3.62 ± 0.87 and 4.22 ± 1.45 cm/s, respectively; PRV increased from 2.53 ± 0.55 to 3.57 ± 1.11 and 4.63 ± 1.48 cm/s; and relaxation slope increased from 4.74 ± 1.10 to 7.65 ± 2.17 and 20.29 ± 7.05 cm/s². Within-subject correlations showed strong positive associations of MV with PCV ($r = 0.87$, $p < 0.001$), PRV ($r = 0.85$, $p < 0.001$), and relaxation slope ($r = 0.78$, $p < 0.001$). Relaxation slope was strongly inversely associated with expiratory time ($r=-0.85$, $p < 0.001$).

Conclusions

Increasing MV by either increasing VT or RR was associated with faster diaphragmatic contraction and relaxation velocities. Rapid breathing was accompanied by a larger increase in diaphragmatic relaxation slope and increased transversus abdominis activity, suggesting that increasing breathing frequency imposes greater ventilatory demands on diaphragmatic relaxation than increasing tidal volume at an equivalent MV.

Introduction

Minute ventilation (MV) is regulated through coordinated changes in tidal volume (VT) and respiratory rate (RR) to meet metabolic requirements while limiting the mechanical and energetic demands of breathing. Classical physiological studies demonstrated that breathing pattern reflects a balance between the elastic and resistive components of respiratory work [1, 2]. The relative contribution of these components depends on respiratory system mechanics and consequently influences the breathing pattern adopted at different levels of ventilatory demand.

In healthy individuals, increases in minute ventilation are generally achieved initially through an increase in tidal volume, with respiratory rate becoming progressively more important as ventilatory demand increases [3–6]. In respiratory disease, alterations in airway resistance, respiratory system compliance, and operating lung volume modify this relationship. For example, patients with obstructive lung disease may develop dynamic hyperinflation during rapid breathing, placing the diaphragm at a mechanical disadvantage, whereas patients with restrictive disorders may adopt rapid, shallow breathing because of increased elastic loading [7, 8].

The diaphragm is the principal inspiratory muscle and performs most of the work required to increase ventilation. Expiratory muscles also contribute increasingly as ventilatory demand rises, particularly when expiratory flow must be accelerated or the available expiratory time is shortened. Activation of the abdominal muscles increases abdominal and pleural pressures and can facilitate expiratory displacement of the diaphragm. Restoration of diaphragmatic length before the subsequent inspiration may help preserve its force-generating capacity. Among the abdominal muscles, the transversus abdominis is an important expiratory muscle because of its anatomical orientation and its recruitment during increased ventilatory demand [9].

The ratio of respiratory frequency to tidal volume, commonly known as the rapid shallow breathing index (f/VT), is a well-established predictor of failure to wean patients from mechanical ventilation because it reflects the balance between ventilatory demand and respiratory neuromuscular reserve [10].

Tissue Doppler imaging (TDI) provides a non-invasive method for quantifying tissue motion and has been applied to assessment of diaphragmatic contraction and relaxation. Previous work demonstrated differences in diaphragmatic TDI velocities in critically ill patients undergoing weaning of mechanical ventilation and suggested potential clinical applications of these measurements [11]. However, the physiological determinants of diaphragmatic Doppler-derived velocity profiles remain incompletely characterized. In particular, it is unclear whether diaphragmatic contraction and relaxation velocities are influenced predominantly by tidal volume, respiratory frequency, or the overall level of minute ventilation.

Healthy volunteers provide an appropriate physiological model for addressing these questions because tidal volume and respiratory rate can be manipulated independently without the confounding effects of pulmonary disease. Comparing deeper and faster breathing at similar levels of increased ventilation therefore permits examination of the mechanical consequences of breathing pattern.

The aim of this study was to determine the effects of increasing minute ventilation through either tidal volume or respiratory rate on diaphragmatic contraction and relaxation velocities assessed by TDI. We additionally assessed transversus abdominis electromyographic activity to investigate the relationship between breathing patterns, diaphragmatic relaxation, and expiratory muscle recruitment.

Methods

Participants

Thirty healthy volunteers from the medical and nursing staff of the intensive care unit volunteered to participate. Twenty-one participants (12 men and 9 women; age 28 ± 4 years; body mass index 24 ± 2 $kg \cdot m^{-2}$) completed the study. Nine participants were excluded because they were unable to comply consistently with the breathing protocol or because adequate ultrasound images could not be obtained.

The study was approved by the Ethics Committee of Papageorgiou General Hospital (Study Code 109, 340th Committee Meeting), and all participants provided written informed consent before participation.

Study protocol

The study consisted of three experimental conditions.

During **quiet breathing**, participants were instructed to breathe spontaneously using the depth and frequency that they found comfortable. All participants breathed through a ventilator circuit (Evita XL; Dräger, Lübeck, Germany) while wearing a nose clip to prevent air leaks. The ventilator was set to zero pressure support and zero positive end-expiratory pressure. The resistance of the ventilator tubing system was 3 $cmH_2O \cdot L^{-1} \cdot s^{-1}$.

All participants were aware of their breathing pattern (Vt, RR, MV) looking at the ventilator's screen to comply consistently with the breathing protocol.

During the two experimental conditions, participants were instructed to increase randomly either tidal volume or respiratory rate. During **high-tidal-volume breathing**, participants were instructed to approximately double tidal volume while maintaining the respiratory rate the same as during quiet breathing. During **high-respiratory-rate breathing**, participants were instructed to approximately double respiratory rate while maintaining tidal volume the same as during quiet breathing. A 10-min rest period was provided between experimental conditions.

After stabilization of the breathing pattern, respiratory variables, diaphragmatic TDI, and transversus abdominis electromyographic (EMG) activity were recorded simultaneously for 15 consecutive breaths. Two investigators were present throughout data acquisition to ensure synchronization of the recording systems and adherence to the breathing protocol.

Respiratory measurements

Airflow was measured using a pneumotachograph (TSD127; Biopac Systems Inc., Goleta, CA, USA) connected to the mouthpiece and a signal amplifier (DA100C; Biopac Systems Inc.). The airflow signal was digitally integrated to obtain the tidal volume, with volume reset to zero at the beginning of each inspiration.

The following variables were obtained:

- peak inspiratory flow (L);
- tidal volume (VT, mL);
- inspiratory time (Ti, s);
- expiratory time (Te, s);
- total respiratory cycle duration (Ttot, s);
- respiratory rate (breaths·min^{-1});
- minute ventilation (MV, L·min^{-1}), calculated as (VT\times RR); and
- mean inspiratory flow (VT/Ti, mL·s^{-1}).

The airflow signal was simultaneously transmitted to the ultrasound system through the auxiliary output of the Biopac system, allowing temporal alignment of respiratory flow and diaphragmatic TDI waveforms.

Diaphragmatic Tissue Doppler imaging

Diaphragmatic TDI was performed at the right hemidiaphragm with participants in the semi-recumbent position using a Philips HD15 ultrasound system (Philips Medical Systems, Rochester, NY, USA) equipped with a broadband sector-array transducer (1.7–3.5 MHz).

The right hemidiaphragm was examined using pulsed-wave tissue Doppler imaging, with the ultrasound beam oriented as close to perpendicular as possible to the middle or posterior third of the hemidiaphragm. The sample volume was positioned to encompass the expected range of diaphragmatic motion. The velocity scale was adjusted to the lowest range that permitted visualization of the complete Doppler waveform.

For each analyzed breath, the following TDI-derived variables were measured:

- **Peak contraction velocity (PCV)**: maximum diaphragmatic tissue velocity during inspiration, expressed in cm·s^{-1}.
- **Peak relaxation velocity (PRV)**: maximum diaphragmatic tissue velocity during expiration, expressed in cm·s^{-1}.

- **Diaphragmatic relaxation slope**: the steepest rate of change in diaphragmatic tissue velocity during expiration, expressed in $cm \cdot s^{-2}$.

The TDI acquisition technique has been described previously [11].

Electromyography

Surface EMG activity of the right transversus abdominis was recorded using Ag/AgCl electrodes. Electrodes were positioned 2 cm medial to the proximal end of a vertical line extending from the anterior superior iliac spine toward the costal margin. Correct electrode placement was confirmed by ultrasound visualization of the abdominal muscle layers. The EMG sampling frequency was 1000–2000 Hz and amplifier gain was 1000×.

Because the transversus abdominis is a relatively deep abdominal muscle, surface EMG may be affected by signal contamination from adjacent muscles. Although the recording site was selected to preferentially detect transversus abdominis activity, contributions from adjacent muscles, including the external oblique and rectus abdominis, could not be completely excluded.

Statistical analysis

Statistical analyses were performed using SPSS Statistics version 20 (IBM Corp., Armonk, NY, USA).

Analyses were performed at the participant level, with each participant contributing one mean value for the 15 analyzed breaths in each of the three breathing conditions. Because the same 21 participants were studied under all conditions, comparisons were treated as paired repeated measurements. Continuous variables are summarized as mean ± SD. Overall differences among quiet breathing, high-VT breathing, and high-RR breathing were assessed using the Friedman test. Pairwise comparisons were performed with the Wilcoxon signed-rank test, with Holm adjustment for the three pairwise comparisons. Kendall's W was calculated as an effect-size measure for the Friedman test. Associations between variables measured repeatedly within participants were assessed using repeated-measures correlation, which accounts for the non-independence of observations from the same participant. All tests were two-sided and $p < 0.05$ was considered statistically significant.

Results

Respiratory and diaphragmatic responses

All respiratory and diaphragmatic variables are listed in Table 1.

Table 1

Variable	Quiet	High VT	High RR	Friedman p; Kendall's W
Displacement (cm)	2.81 ± 0.69	4.16 ± 0.81	2.74 ± 0.60	< 0.001; 0.780
Ti (s)	2.02 ± 0.26	2.06 ± 0.39	1.20 ± 0.21	< 0.001; 0.788
Te (s)	3.25 ± 0.64	3.34 ± 0.70	1.50 ± 0.25	< 0.001; 0.800
Ttot (s)	5.24 ± 0.85	5.37 ± 1.03	2.69 ± 0.44	< 0.001; 0.780
RR (breaths/min)	11.49 ± 1.65	11.50 ± 1.99	22.70 ± 4.25	< 0.001; 0.797
MV (L/min)	8.93 ± 1.90	16.56 ± 4.06	19.23 ± 6.26	< 0.001; 0.819
Peak flow (L/s)	0.56 ± 0.11	1.06 ± 0.36	0.99 ± 0.35	< 0.001; 0.778
VT (mL)	779.48 ± 173.79	1453.86 ± 331.88	837.90 ± 211.90	< 0.001; 0.819
PCV (cm/s)	2.59 ± 0.52	3.62 ± 0.87	4.22 ± 1.45	< 0.001; 0.735
PRV (cm/s)	2.53 ± 0.55	3.57 ± 1.11	4.63 ± 1.48	< 0.001; 0.864
Relaxation slope (cm/s²)	4.74 ± 1.10	7.65 ± 2.17	20.29 ± 7.05	< 0.001; 0.955

Statistical analysis of the three breathing conditions. t values are mean ± SD across 21 participants. The Friedman test evaluates the overall three-condition comparison; Kendall's W is its effect size.

All primary respiratory and diaphragmatic variables demonstrated significant overall differences among the three breathing conditions (Friedman $p < 0.001$ for all variables). Kendall's W ranged from 0.735 for PCV to 0.955 for relaxation slope, indicating large within-subject effects.

MV increased from 8.93 ± 1.90 L/min during quiet breathing to 16.56 ± 4.06 L/min during high-VT breathing and 19.23 ± 6.26 L/min during high-RR breathing. Thus, both interventions approximately doubled MV, with the increase greater during high-RR than during high-VT breathing.

Compared with quiet breathing, high-tidal-volume breathing increased tidal volume from 779.48 ± 173.79 to 1453.86 ± 331.88 mL while respiratory rate remained unchanged (11.49 ± 1.65 and 11.50 ± 1.99 breaths·min^{-1}, respectively). High-respiratory-rate breathing increased respiratory rate to 22.70 ± 4.25 breaths·min^{-1}, while tidal volume was 837.90 ± 211.90 ml.

High-tidal-volume breathing increased diaphragmatic displacement from 2.81 ± 0.69 to 4.16 ± 0.81 cm, whereas displacement during high-respiratory-rate breathing remained similar to quiet breathing 2.74 ± 0.60 cm.

High-respiratory-rate breathing markedly shortened both inspiratory and expiratory time. Inspiratory time decreased from 2.02 ± 0.26 to 1.20 ± 0.21 s, while expiratory time decreased from 3.25 ± 0.64 to 1.50 ±

0.25 s (both $p < 0.001$).

Mean inspiratory flow (VT/Ti) increased from 390 ± 86 $mL \cdot s^{-1}$ during quiet breathing to 692 ± 208 and 698 ± 242 $mL \cdot s^{-1}$ during high-tidal-volume and high-respiratory-rate breathing, respectively ($p < 0.001$). Mean inspiratory flow did not differ significantly between the two experimental conditions.

Diaphragmatic tissue Doppler measurements

TDI measurements and patterns during the three breathing conditions are provided in Table 1 and Fig. 1

PCV increased from 2.59 ± 0.52 $cm \cdot s^{-1}$ during quiet breathing to 3.62 ± 0.87 $cm \cdot s^{-1}$ during high-tidal-volume breathing and 4.22 ± 1.45 $cm \cdot s^{-1}$ during high-respiratory-rate breathing ($p < 0.001$).

PRV increased from 2.53 ± 0.55 $cm \cdot s^{-1}$ during quiet breathing to 3.57 ± 1.11 $cm \cdot s^{-1}$ during high-tidal-volume breathing and 4.63 ± 1.48 $cm \cdot s^{-1}$ during high-respiratory-rate breathing ($p < 0.001$).

The diaphragmatic relaxation slope increased from 4.74 ± 1.10 $cm \cdot s^{-2}$ during quiet breathing to 7.65 ± 2.17 $cm \cdot s^{-2}$ during high-tidal-volume breathing and 20.29 ± 7.05 $cm \cdot s^{-2}$ during high-respiratory-rate breathing ($p < 0.001$). The increase was considerably greater during high-respiratory-rate than high-tidal-volume breathing.

After Holm adjustment, PCV, PRV, and relaxation slope differed significantly between all three breathing conditions. Peak inspiratory flow increased from quiet breathing to both experimental conditions but did not differ significantly between high-VT and high-RR breathing. Ti, Te, Ttot, and RR were primarily altered by the high-RR condition, whereas high-VT breathing produced little change in respiratory timing. Table 2.

Table 2

Variable	Quiet vs High VT	Quiet vs High RR	High VT vs High RR
Displacement	< 0.001	0.601	< 0.001
Ti	0.705	< 0.001	< 0.001
Te	0.469	< 0.001	< 0.001
Ttot	0.266	< 0.001	< 0.001
RR	0.793	< 0.001	< 0.001
MV	< 0.001	< 0.001	0.005
Peak flow	< 0.001	< 0.001	0.259
VT	< 0.001	0.020	< 0.001
PCV	< 0.001	< 0.001	0.019
PRV	< 0.001	< 0.001	< 0.001
Relaxation slope	< 0.001	< 0.001	< 0.001

Post-hoc pairwise comparisons of the three breathing conditions. p values are two-sided Wilcoxon signed-rank tests adjusted for three pairwise comparisons using the Holm method.

Associations between respiratory variables and diaphragmatic TDI

Repeated-measures correlations demonstrated strong positive within-subject associations between MV and PCV ($r = 0.87$, $p < 0.001$), PRV ($r = 0.85$, $p < 0.001$), and relaxation slope ($r = 0.78$, $p < 0.001$). Relaxation slope was strongly and inversely associated with Te ($r=-0.85$, $p < 0.001$). These analyses support an association between increased ventilatory demand and faster diaphragmatic velocity profiles. Figure 2

Transversus abdominis activity

Transversus abdominis EMG activity increased progressively across the three breathing conditions, from 0.012 ± 0.001 mV during quiet breathing to 0.022 ± 0.005 mV during high-tidal-volume breathing and 0.032 ± 0.004 mV during high-respiratory-rate breathing ($p < 0.001$). Figure 3.

Although expiratory abdominal muscle activation was clinically detectable by abdominal palpation in all participants, measurable increases in transversus abdominis EMG activity during expiration were identified in only 12 of the 21 participants. Therefore, conclusions regarding expiratory muscle recruitment should be interpreted cautiously.

Discussion

The principal finding of this study is that the breathing pattern used to increase minute ventilation influences diaphragmatic contraction and relaxation dynamics in healthy adults. Both increasing tidal volume and increasing respiratory rate increased PCV, PRV, and diaphragmatic relaxation slope, but the effect on relaxation slope was substantially greater during rapid breathing. The latter condition was also characterized by shorter expiratory time and greater transversus abdominis EMG activity.

The experimental design compared two strategies for increasing ventilation. High-tidal-volume breathing increased ventilation primarily through a larger tidal excursion, whereas high-respiratory-rate breathing increased ventilation through a shorter respiratory cycle. Despite producing a similar physiological objective -an increase in MV- the two strategies therefore imposed different temporal and mechanical demands on the diaphragm.

During high VT breathing, diaphragmatic displacement increased by approximately 50%, consistent with the larger tidal volume achieved in this condition. The accompanying increases in PCV and PRV are compatible with greater diaphragmatic excursion and elastic recoil associated with larger lung inflation.

The increase in diaphragmatic relaxation slope during high VT breathing was accompanied by greater transversus abdominis EMG activity, consistent with increased expiratory muscle recruitment during larger breaths.

The high RR breathing produced a different mechanical pattern. Ti and Te were both substantially shortened with Te decreasing from 3,25 ± 0.64 to 1,5 ± 0.25 s. In parallel, the relaxation slope increased from 4,74 ± 1.1 to 20,29 ± 7.05 cm/s². The strong within-subject inverse association between relaxation slope and Te supports an important relationship between available expiratory time and the diaphragmatic relaxation profile. The marked increase in transversus abdominis activity during high-RR breathing provides additional evidence that expiratory muscle recruitment accompanies rapid breathing.

During quiet breathing, the relatively long expiratory period allows expiration to occur predominantly through passive elastic recoil. When respiratory rate increases, the available expiratory time is markedly reduced. Under these circumstances, greater expiratory muscle recruitment may facilitate more rapid expiration and help restore the respiratory system toward its end-expiratory position before the next inspiratory effort [7, 12]. Active expiratory muscle recruitment may therefore become increasingly important when respiratory cycles are shortened. In addition, diaphragmatic perfusion occurs predominantly during relaxation and can accommodate the increased blood flow requirements associated with greater diaphragmatic work [9, 13, 14].

Although diaphragmatic EMG was not recorded in our study, previous studies have demonstrated a close relationship between diaphragmatic EMG activity and ventilatory output, with diaphragm EMG increasing with increasing minute ventilation and tidal volume, supporting its use as an index of neural respiratory drive [15, 16]. Previous studies have shown that diaphragm EMG decay accelerates as expiratory time shortens and breathing frequency increases, while the relative decay rate of inspiratory muscle pressure similarly increases with respiratory frequency [17]. However, whether equivalent increases in minute

ventilation achieved predominantly by increasing tidal volume or respiratory frequency imposes different demands on diaphragmatic activation has not been clearly established.

Rapid and complete diaphragmatic relaxation is considered particularly important during high-frequency breathing, when the time available for relaxation is reduced [12]. The diaphragmatic relaxation slope may provide information beyond peak relaxation velocity. Whereas PRV reflects the maximum velocity attained during expiration, the relaxation slope describes the rate of change in diaphragmatic velocity during relaxation. Its marked increase during rapid breathing, together with its strong inverse association with Te suggests that this parameter may be sensitive to the temporal constraints imposed by respiratory frequency.

Our findings have implications for interpretation of diaphragmatic TDI. PCV, PRV, and particularly the relaxation slope were substantially influenced by the breathing pattern under which they were measured. Respiratory rate, tidal volume and expiratory time should therefore be considered when interpreting diaphragmatic TDI-derived velocity measurements, particularly when measurements obtained under different physiological conditions are compared.

Several limitations should be considered. First, the study included healthy volunteers. The findings therefore cannot be directly extrapolated to individuals with obstructive or restrictive respiratory disease, in whom respiratory mechanics and diaphragmatic operating conditions may differ substantially. In healthy subjects, increases in tidal volume and respiratory frequency are unlikely to produce significant air trapping despite the physiological changes occurring during exercise [18]. In contrast, similar ventilatory demands in patients with even mild COPD may readily induce dynamic hyperinflation, substantially altering diaphragmatic mechanics and muscle function [19]. Second, respiratory muscle pressures, transdiaphragmatic pressure, lung volumes, and respiratory muscles oxygen consumption were not measured. We therefore assessed diaphragmatic displacement, TDI motion velocities and expiratory muscle electrical activity rather than respiratory muscle work or metabolic cost directly. However, we can assume that greater diaphragmatic displacement, increased contraction and relaxation velocities and expiratory muscle recruitment lead to increased muscle work and metabolic cost. Third, surface EMG was used to assess transversus abdominis activity. Because this is a deep abdominal muscle, crosstalk from adjacent muscles cannot be completely excluded. The relatively small number of participants with clearly detectable expiratory EMG activity further limits the strength of this finding.

Conclusion

Our findings indicate that the physiological context in which diaphragmatic TDI is obtained is important. Increasing respiratory rate imposes greater temporal and mechanical demands on diaphragmatic contraction and relaxation than increasing tidal volume at a similar minute ventilation. Increased transversus abdominis activation suggests that expiratory muscle recruitment may contribute to more rapid diaphragmatic relaxation and restoration toward its optimal operating length. The relaxation slope may represent a potentially useful TDI-derived marker of the temporal demands imposed on the

diaphragm. Further studies are required to establish its physiological determinants and clinical relevance.

Declarations

Conflict of interest.

Authors declare no conflict of interest.

Funding.

None

Author Contribution

Study design: D.M and E.S.Data collection: E.S, Ch.N, P.M, and D.M. Statistical analysis: Ch.N and S.K. Data interpretation: D.M, E.S, Ch.N, S.K, P.M. Manuscript writing: E.S, S.K and D.M. All authors participated in the critical review and revision of the manuscript.

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Data availability statement.

All data presented in the current manuscript are available from the corresponding author upon reasonable request.

References

1. Otis AB, Fenn WO, Rahn H (1950) Mechanics of breathing in man. J Appl Physiol 2:592–607
2. Mead J (1960) Control of respiratory frequency. J Appl Physiol 15:325–336
3. Hey EN, Lloyd BB, Cunningham DJC, Jukes MGM, Bolton DPG (1966) Effects of various respiratory stimuli on the depth and frequency of breathing in man. Respir Physiol 1:193–205
4. Fitting JW, Easton PA, Grassino AE (1986) Velocity of shortening of inspiratory muscles and inspiratory flow. J Appl Physiol 60:670–677

5. Younes M, Kivinen G (1984) Respiratory mechanics and breathing pattern during and following maximal exercise. J Appl Physiol 57:1773–1782
6. Georgopoulos D, Mitrouska I, Bshouty Z, Webster K, Patakas D, Younes M (1997) Respiratory response to CO_2 during pressure-support ventilation in conscious normal humans. Am J Respir Crit Care Med 156:146–154
7. Tobin MJ, Laghi F, Jubran A (2012) Ventilatory failure, ventilatory support, and ventilator weaning. Compr Physiol 2:2871–2921
8. Spinelli E, Mauri T, Beitler JR, Pesenti A, Brodie D (2020) Respiratory drive in the acute respiratory distress syndrome: pathophysiology, monitoring and therapeutic interventions. Intensive Care Med 46:606–618
9. De Troyer A, Boriek AM (2011) Mechanics of the respiratory muscles. Compr Physiol 1:1273–1300
10. Yang KL, Tobin MJ (1991) A prospective study of indexes predicting the outcome of trials of weaning from mechanical ventilation. N Engl J Med 324:1445–1450
11. Soilemezi E, Savvidou S, Sotiriou P, Smyrniotis D, Tsagourias M, Matamis D (2020) Tissue Doppler imaging of the diaphragm in healthy subjects and critically ill patients. Am J Respir Crit Care Med 202:1005–1012
12. Coirault C, Chemla D, Lecarpentier Y et al (1999) Relaxation of diaphragm muscle. J Appl Physiol 87:1243–1252
13. Hu F, Comtois A, Grassino AE (1992) Optimal diaphragmatic blood perfusion. J Appl Physiol 72:149–157
14. Hussain SNA, Magder S (1991) Diaphragmatic intramuscular pressure in relation to tension, shortening and blood flow. J Appl Physiol 71:159–167
15. Katz RL, Fink BR, Ngai SH (1962) Relationship between Electrical Activity of the Diaphragm and Ventilation. Proceedings of the Society for Experimental Biology and Medicine. ;110(4):792–794
16. Luo YM, Hart N, Mustfa N, Lyall RA, Polkey MI, Moxham J Effect of diaphragm fatigue on neural respiratory drive. J Appl Physiol. (2001) ;90(5):1691–1699
17. Citterio G, Agostoni E (1981) Decay of inspiratory muscle activity and breath timing in man. Respir Physiol 43(2):117–132
18. Stubbing DG, Pengelly LD, Morse JL, Jones NL (1980) Pulmonary mechanics during exercise in normal males. J Appl Physiol Respir Environ Exerc Physiol 49:506–510
19. Thomas M, Decramer M, O'Donnell DE (2013) No room to breathe: the importance of lung hyperinflation in COPD. Prim Care Respir J 22:101–111

Figures

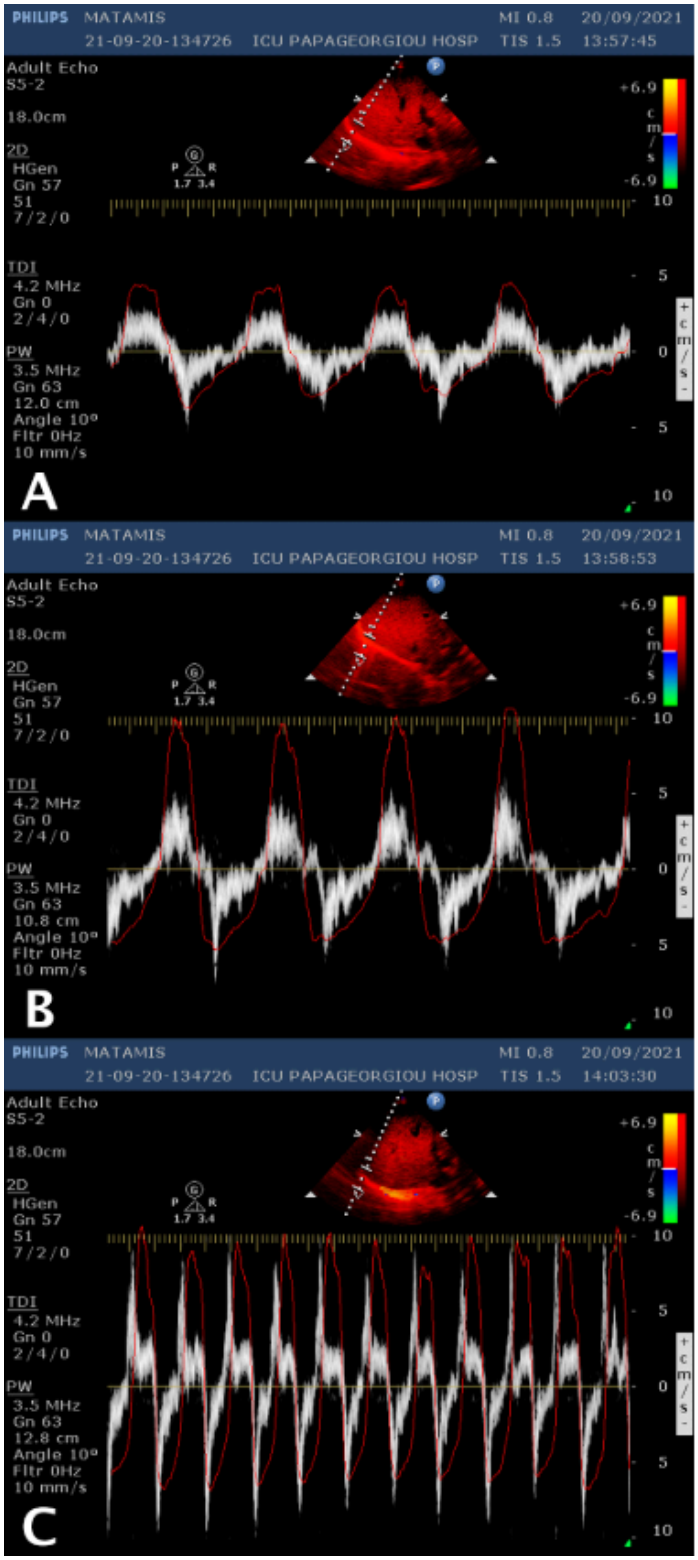


Figure 1

Representative diaphragmatic tissue Doppler imaging (TDI) recordings superimposed on the respiratory flow signal from a healthy subject. The yellow arrow indicates peak contraction velocity (PCV), the blue arrow indicates peak relaxation velocity (PRV), and the yellow line indicates the slope of diaphragmatic relaxation. The red continuous trace represents the respiratory flow signal obtained from the pneumotachograph and transmitted to the ultrasound system through the auxiliary input. Quiet

breathing. B) High tidal volume breathing, demonstrating higher PCV, PRV and diaphragmatic relaxation slope than during quiet breathing. C) High respiratory rate breathing, demonstrating further increases in PCV, PRV and diaphragmatic relaxation slope compared with both quiet breathing and high tidal volume breathing.

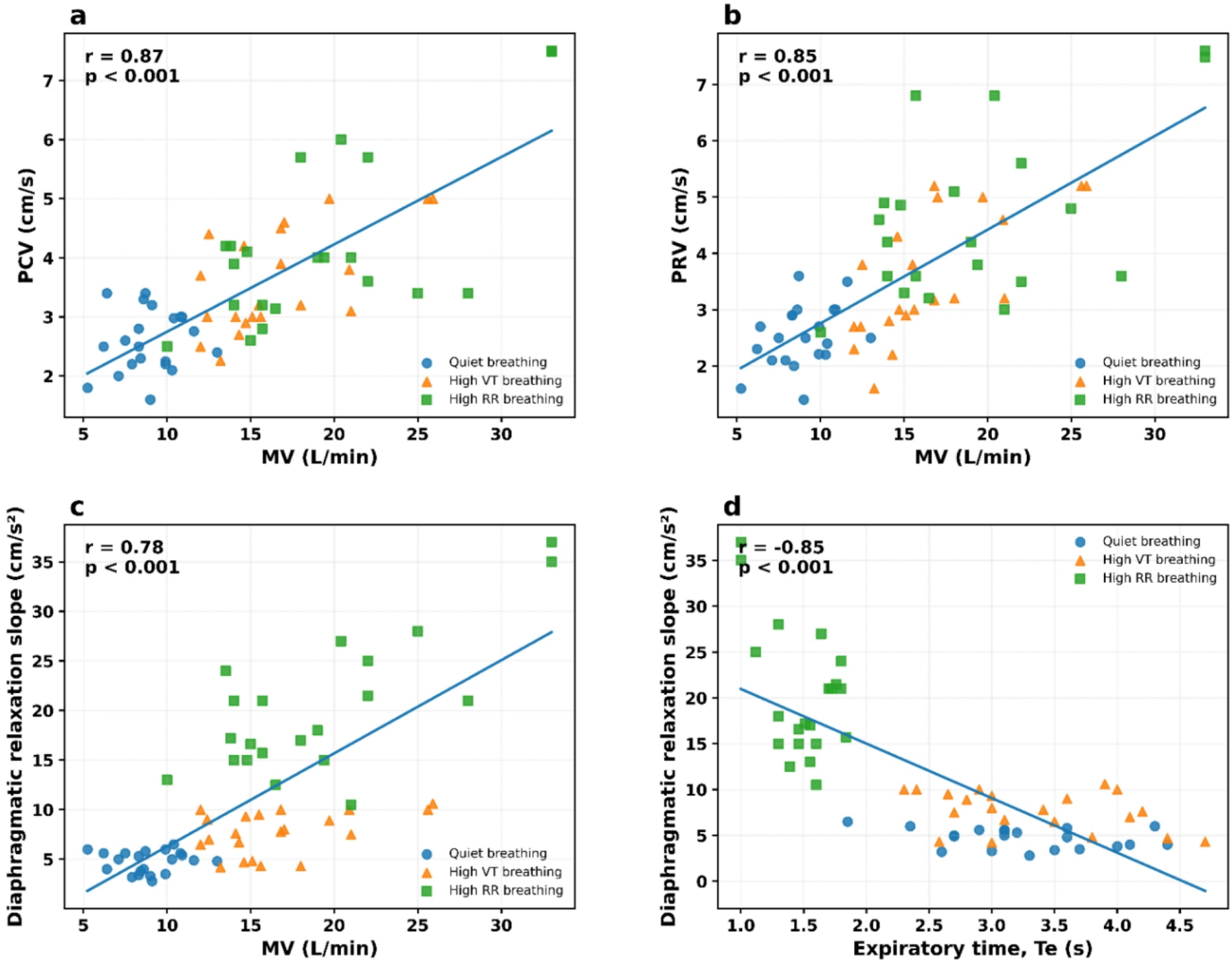


Figure 2

Repeated-measures correlations based on within-participant centered values across the three conditions. a) PCV versus minute ventilation. b) PRV versus minute ventilation. c) Slope of diaphragmatic relaxation versus expiratory time (Te). d) Slope of diaphragmatic relaxation versus minute ventilation. PCV: peak contraction velocity; PRV: peak relaxation velocity; TDI: tissue Doppler imaging.

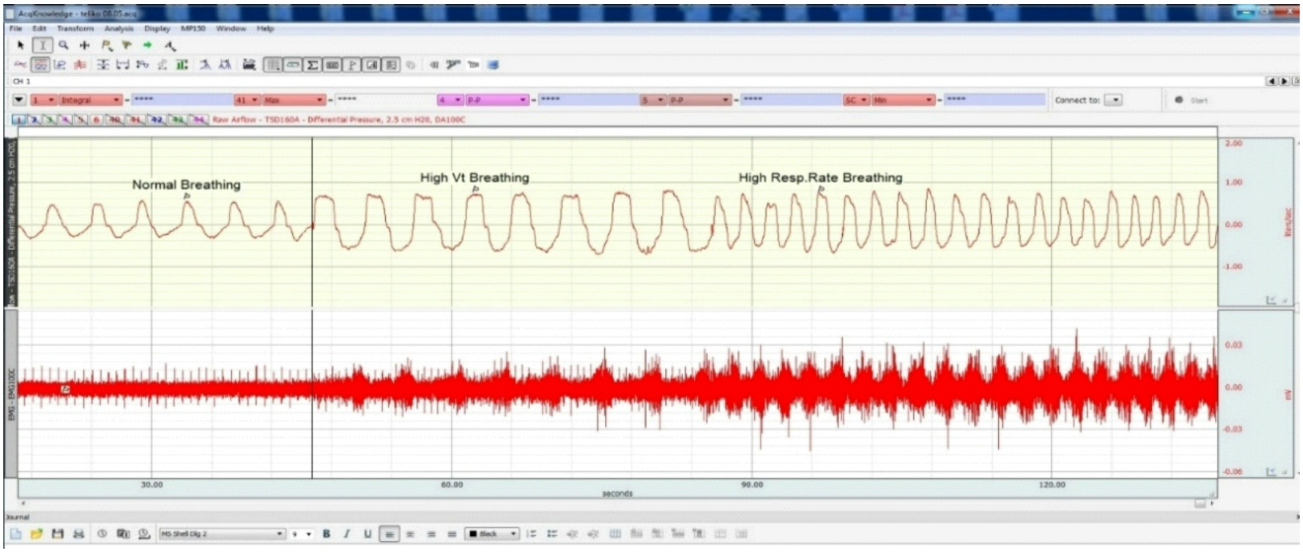


Figure 3

Simultaneous recordings of respiratory flow and transversus abdominis electromyographic (EMG) activity during the three study phases. The vertical line indicates from the flow pattern the activation of the transversus abdominis during expiration. Expiratory EMG activity was the highest during high respiratory rate breathing compared with the other breathing conditions.

Image not available with this version

Figure 4

Legend not included with this version