Sonography

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Diaphragm Ultrasonography During Respiratory Manoeuvres

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ABSTRACT

This study aimed to describe diaphragm ultrasonography (DU) during mouth occlusion pressure (P0.1) and maximal inspiratory pressure (MIP) in healthy participants. Four participants performed: (i) neurophysiological tests and then (ii) simultaneous DU with P0.1 and MIP. Diaphragm excursion was 2.37 cm (median) during tidal volume of 0.74 L. Additionally, a median diaphragm excursion of 1.25 cm was associated with a median P0.1 of 1.39 cm H_2O, while a median diaphragm excursion of 3.10 cm was associated with a median MIP of 125.88 cm H_2O. DU showed a hold-back movement during P0.1 and a movement plateau during MIP, providing novel insights into the diaphragm movement, with potential clinical practice implications.

1 | Introduction

The diaphragm is the main muscle of respiration acting continuously to sustain the regular task of ventilation. In patients with neuromuscular disorders, diaphragmatic weakness is a major contributor to respiratory failure and protocols for the evaluation of these patients are based on a composite of respiratory and neurophysiological tests [1]. Some respiratory diseases such as chronic obstructive pulmonary disease show themselves functionally during respiratory manoeuvres. Therefore, stress exercises should reveal fragilities of the diaphragm motion.

Diaphragm ultrasonography (DU) has emerged as a promising, non-invasive technique to further evaluate the anatomy and function of the diaphragm. DU can reliably monitor respiratory and muscular disease progression and anticipate successful liberation from invasive mechanical ventilation. Although the number of studies exploring DU has grown considerably, its applicability during respiratory manoeuvres remains insufficiently explored. In particular, the integration of DU with respiratory and strength related tests, such as maximal inspiratory pressures (MIP), should offer new insights in the evaluation of respiratory function. In contrast, diaphragm excursion (DE) during mouth occlusion pressure (P0.1) should also translate participants' neural drive for the breathing task.

This study aims to show the feasibility of DU during P0.1 and MIP in healthy participants while describing physiological reference observations for future pathological applications.

2 | Methods

A preliminary cross-sectional exploratory study was conducted to explore the functional applicability of DU during respiratory manoeuvres in healthy individuals. The study protocol was approved by the local ethics committee (CE-ESTeSL no. 26-2025). All participants were informed about the study protocol and freely signed the informed consent. Four participants (one female) with a median age of 22 years old (interquartile range (IQR) of 0.26 years old), a median height of 1.76 cm (IQR of 0.06 cm) and a median body max index (BMI) of 23 (IQR of 6.25) kg/m^2 were recruited to perform multimodal diaphragm evaluation. Before performing MIP and P0.1, diaphragm motor evoked potential (MEP) and compound muscular action potential (CMAP) were obtained after transcranial magnetic stimulation (TMS) and phrenic nerve conduction (NCS), respectively (see Appendix A). Respiratory manoeuvres were done by a single experienced operator to ensure methodological reliability. All tests were performed with participants seated, using a nasal clip and a disposable mouthpiece with bacterial/viral filter. A MasterScreen PFT system equipped with the maximal respiratory pressure and occlusion pressure module (Jaeger, Germany) was used. This module uses the equipment mouth pressure transducer and the occlusion valve.

P0.1 was measured during tidal volume. The sub-atmospheric pressures (cm H_2O) generated 0.1 s after the start of inspiration, with the airway briefly occluded were automatically recorded. We performed three measurements and calculated a median value. For MIP measures, a small leak between the mouthpiece and the transducer was used in order to prevent glottic closure during the manoeuvres. Participants were instructed to exhale fully to residual volume and then to perform a maximal inspiratory effort with the airway occluded for at least 1 s. On the latter, a maximum variability of 10% and the highest peak pressure value were recorded. The best MIP was saved after ensuring repeatability across manoeuvres. Normality was assessed according to the following widely used criteria: (i) for MIP > 80 cm H_2O in men and > 70 cm H_2O in women, (ii) for P0.1 between 0.5 and 1.5 cm H_2O [2, 3].

DU was performed on the right hemi-diaphragm using a sectorial probe placed subcostal on the midclavicular line, angled cranially and dorsally to observe diaphragm cupula (Figure 1). M-mode imaging was used to record during quiet breathing, P0.1 and MIP, and was expressed in cm. DU system settings were standardised across trials and all images were acquired by a single operator to ensure consistent and reliable acquisition. The DU setup to record ultrasonography frames was configured to record 5 s of frames retrospectively after pushing the store button. The DU settings used were the following: 4 MHz, dynamic range of 80 dB, gain 85%, power 0 dB, compound tissue imaging and time gain compensation turned on, one focus on diaphragm.

P0.1 and MIP were performed simultaneously with DU (LOGIQ P9, GE Healthcare, USA). Two operators were with each subject. While one coached the subject with the respiratory instructions, the other (sonographer) stored the frames after given a vocal indication 'to record' when high-quality manoeuvres were observed.

3 | Results

Table 1 demonstrates the main findings obtained from neurophysiological and simultaneous DU and respiratory manoeuvres in healthy participants. From cortex to diaphragm, TMS stimuli had a median latency of 12.15 ms, whereas delivered neck phrenic nerve stimuli showed a median latency of 2.97 ms. The median amplitude of diaphragm MEP was 0.85 mV and median CMAP was 3.96 mV. The DU showed a median excursion of 2.37 cm during a median tidal volume of 0.74 L.

Figures 2 and 3 demonstrate the P0.1 and MIP trials of subject number 3, whereas simultaneously DE was measured in M mode (Figures 2B and 3B). The DE during P0.1 showed a median of 1.25 cm with a median P0.1 of 1.39 cm H_2O. Figure 2B depicts an interrupted diaphragm movement where the diaphragm held back during P0.1 valve closure. Regarding P0.1, only subject number 1 showed a DE inferior to 1 cm, of 0.62 cm, associated with a pressure of 1.35 cm H_2O.

Healthy participants showed a median pressure of 125.88 cm H_2O at MIP, which was coupled with a median DE of

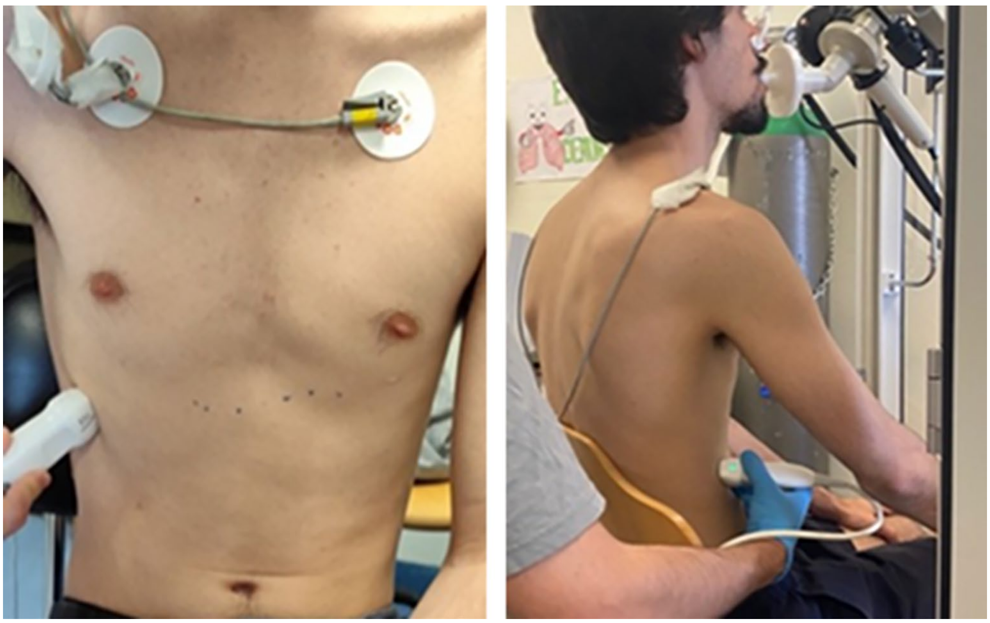

FIGURE 1 | Illustration of ultrasonography sectorial probe position (left) towards right diaphragm cupula during respiratory manoeuvres (right).

TABLE 1 | Findings from healthy subjects' neurophysiological, respiratory and ultrasonography of the diaphragm.

Condition	TMS		NCS		Quiet breathing	DU, P0.1		DU, MIP	
Participant	**L, ms**	**A, mV**	**L, ms**	**A, mV**	**DE, cm/TV, L**	**cm H_2O**	**DE, cm**	**cm H_2O**	**DE, cm**
1	15.20 (0.95)	0.82 (0.10)	3.45 (0.02)	4.83 (0.01)	1.87 (0.12) /0.64 (0.02)	1.35 (0.02)	0.62 (0.12)	125.90 (9.30)	3.14 (0.59)
2	11.80 (1.24)	0.78 (0.07)	3.10 (0.05)	2.60 (0.02)	2.70 (0.11) /0.73 (0.01)	1.80 (0.04)	1.50 (0.40)	125.85 (3.86)	2.96 (0.56)
3	11.10 (0.63)	1.65 (0.12)	2.85 (0.04)	6.10 (0.01)	2.97 (0.16) /1.02 (0.08)	0.88 (0.03)	1.29 (0.10)	143.40 (2.20)	3.07 (0.28)
4	12.50 (0.71)	0.88 (0.04)	2.73 (0.09)	3.10 (0.02)	2.03 (0.08) /0.75 (0.06)	1.43 (0.30)	1.20 (0.08)	96.75 (8.86)	3.17 (0.21)
Median (IQR)	12.15 (4.10)	0.85 (0.87)	2.97 (0.72)	3.96 (2.50)	2.37 (1.10) /0.74 (0.38)	1.39 (0.92)	1.25 (0.88)	125.88 (64.7)	3.10 (0.21)

Note: The values are shown as median (interquartile range) and were recorded in the right hemi-diaphragm.
Abbreviations: A, amplitude; DE, diaphragm excursion; DU, diaphragm ultrasonography; IQA, interquartile amplitude; L, onset latency; TV, tidal volume.

3.10 cm. Figure 3B demonstrates the M-mode DU during MIP, starting from functional residual volume to an inspiration 'plateau' hold. Although subject number 4 showed a MIP inferior to 100 cm H_2O, DE was similar to the median.

4 | Discussion

In this exploratory study, we demonstrated the feasibility of performing DU simultaneously with the P0.1 and MIP respiratory manoeuvres. We performed this study on participants with no respiratory symptoms who showed normal values of diaphragm CMAP and MEP, allowing us to exclude major diaphragm weakness [4, 5]. Key variables were controlled for during the tasks to increase reliability:

- Synchronisation: DU measurements were performed simultaneously with the respiratory task, as asynchronous evaluations may not be as reliable [5].
- Position: Participants were evaluated in a standardised seated position. This is critical, as changes in posture are known to alter diaphragm mechanics [6, 7].
- Lung Volume: MIP manoeuvre was initiated from residual volume, and the M-mode tracing showed a clear 'plateau' in excursion above the functional residual capacity. This is a fundamentally different task than maximal inspiration to total lung capacity, which would naturally produce greater excursion [1].

Our work is the first to our knowledge to describe the sonographic appearance of the diaphragm during the P0.1 test. During this test, we visualised a inspiratory 'hold-back' movement, characterised by the flattening of diaphragmatic excursion curve obtained by the M-mode recordings (Figure 2B, arrow in the bottom right panel). It is hypothesised that such a signature could have implications in the clinical setting. For example, a dissociation between a high measured P0.1 and a blunted sonographic 'hold-back' could indicate neuro-mechanical uncoupling, in turn revealing severe diaphragm dysfunction.

Furthermore, we characterised DE during a maximal inspiratory effort. While the DE values obtained during the MIP manoeuvre did not align with those from major studies (this study: 3.10 cm; Spiesshoefer et al. [5, 8]: 8.1 cm; Gorenc et al. [9]: 6.0 cm), current literature does not support DU as a reliable stand-alone tool to predict diaphragm strength [10, 11].

The 'plateau' observed during the occluded MIP effort (Figure 3) might also be of interest in the intensive care setting, as this sonographic pattern is mechanically analogous to the pressure measurements used to calculate the muscular pressure index (Pmusc) during an inspiratory hold in ventilated patients—a measure used to exclude diaphragm dysfunction [12, 13]. However, the clinical usefulness of both sonographic signatures demonstrated in this work ('hold-back' during P0.1 and 'plateau' during MIP) remains conjecture, requiring validation in large patient cohorts.

The small size of our sample and the collaboration during respiratory manoeuvres pose several challenges which may limit the

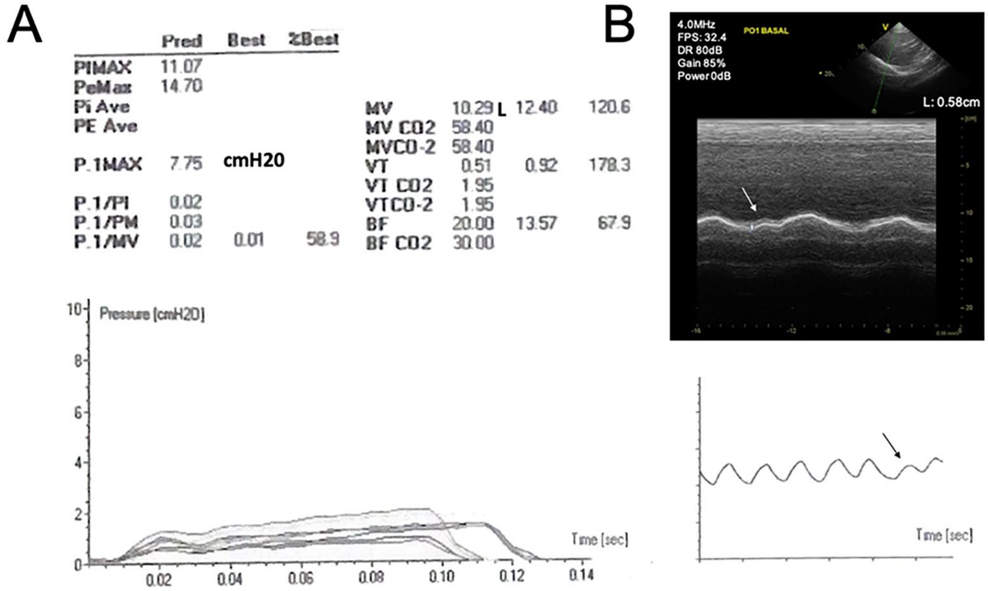

FIGURE 2 | (A) P0.1 trials. Subject was breathing on tidal volume whereby the airway was briefly occluded 0.1 s after the start of inspiration. The starting point was the time-point of zero. (B) Right hemidiaphragm ultrasonography M-mode during a P0.1 trial. Note the diaphragm inspiratory hold-back movement measured as 0.58 cm. The P0.1 starting point was marked with an arrow.

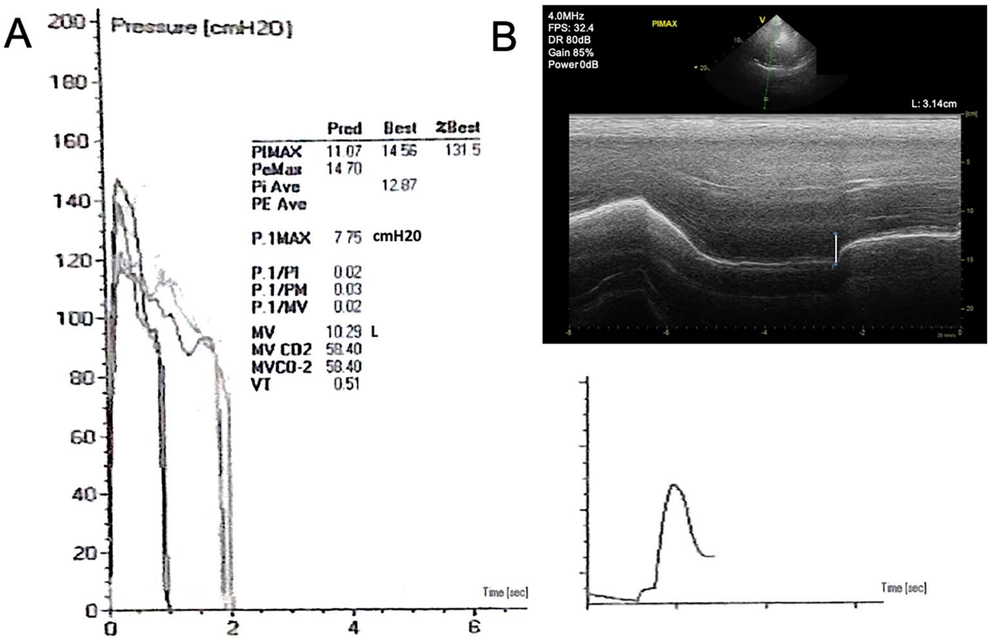

FIGURE 3 | (A) Maximal inspiratory pressure (MIP) trial. Subject was instructed to exhale fully to residual volume and then to perform a maximal inspiratory effort against the occluded airway for at least 1 s. The starting point was the time-point of zero. (B) Right hemidiaphragm M-mode ultrasonography during one MIP trial. Note the diaphragm plateau excursion measured as 3.14 cm. The MIP starting point was marked with the ruler.

generalisation and interpretation of our results. These caveats preclude robust statistical analysis, restraining the ability to detect potential differences and, therefore, these results should be interpreted with caution. On the other hand, the robustness and clinical significance of the results would have been enhanced if a larger number had been assessed. Nevertheless, as a preliminary, exploratory study, we believe the defined objective was achieved and the findings provide a methodological foundation for future research.

5 | Conclusion

This technical note and physiological study in healthy volunteers provides the first sonographic description of the diaphragm's mechanical action during synchronised P0.1 and MIP tests. Sonographic signatures of 'hold-back' and 'plateau' were seen during P0.1 and MIP, respectively, shedding some light on diaphragm excursion during respiratory manoeuvres, although their clinical relevance remains to be determined.

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Ethics Statement

All participants signed an informed consent. The prospective study was approved by an ethics committee (CE-ESTeSL no. 26-2025) from Escola Superior de Saúde, Lisboa, Portugal.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Appendix A

Methodology Used for Neurophysiological Evaluation

Eligible participants performed phrenic nerve conduction study (NCS) and were submitted to transcranial magnetic stimulation (TMS) in order to record both hemidiaphragms' compound muscular action potentials (CMAP) and motor evoked potentials (MEP), respectively. NCS and TMS were done by an experienced operator (JL) to ensure repeatability.

TMS was performed using a magnetic stimulator (Magstim 200, USA) with a 70-mm circular coil. The coil was positioned tangentially to the scalp with anteroposterior current flow. Stimulations were delivered using biphasic current flow: from A → B to evoke responses on one side, and from B → A for the opposite side. Stimulation was applied over the vertex (i.e., Cz). Each side diaphragm motor threshold was defined as the lowest intensity to obtain 50% of responses (i.e., motor hotspot). At this position, MEP were recorded after increasing 20% above the motor threshold.

NCS was conducted with the EMG/Evoked potentials system (Nihon Kohden, Japan). Electrical stimulation was applied at the posterior border of the sternocleidomastoid muscle, laterally to the cricoid cartilage. Cathode was facing the active electrode of diaphragm muscle.

Diaphragm muscle recordings were done bilaterally, using a bipolar surface electrode configuration. The active (G1) and reference (G2) electrodes were positioned 3 cm above the xiphoid process and at subcostal margin above the apposition zone of the diaphragm. The ground electrode was placed over the sternal manubrium. Signal acquisition used a temporal resolution of 5 ms/div and amplitude sensitivity of 500 μV/div and a band-pass filter of 20 Hz–3 kHz to eliminate low frequency artefacts.

The compound muscle action potential (CMAP) was recorded during quiet breathing and stimulus intensity (mA) was gradually increased until a stable and maximal response was achieved. For both TMS and NCS, measured parameters included onset latency (ms), amplitude (mV) and duration (ms). For diaphragm MEPs, reproducible and superimposable MEPs were collected, and the values presented represent the median.