Normative values for ultrasonographic assessment of thoracic diaphragm function

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Abstract

Due to variety of benefits, ultrasonography (US) has recently been utilized to determine thoracic diaphragm (TD) function. Normative values are crucial for adequate evaluation. Therefore, the aim of present study was to gathered standard data for specific US parameters necessary for the evaluation of TD function. 80 participants were subjected to study (51.7 age ± 17.0). US was used to measure the right side of TD thickness at functional residual capacity (FRC) and total lung capacity (TLC). It was also used to calculate TD thickening fraction (Δd), the amplitude (AMP) of TD movement during quiet (QB) and deep (DB) breathing, as well as TD velocity during sniff maneuver. The lower limit of normal for the FRLC was 1.1 mm, TLC 1.7 mm, Δd 0.3 mm, AMP during QB 8.0 mm and DB 28.0 mm and velocity during sniff maneuver 40.0 mm/s. Normative values will be used in a clinical setting for the diagnosis of patients with neuromuscular and pulmonary diseases. Key words: Thoracic diaphragm, ultrasonography, normative values.

Normativne vrednosti ultrazvočnih spremenljivk za oceno funkcije trebušne prepone

Povzetek

Ultrasonografija (US) se zaradi številnih prednosti uporablja tudi za oceno funkcije trebušne prepone (TP). Normativne vrednosti so ključnega pomena pri diagnosticiranju, zato je bil namen raziskave pridobitev normativnih vrednosti izbranih US-spremenljivk za oceno funkcije. V raziskavo je bilo vključenih 80 preiskovancev (51.7 let ± 17.0). Z US smo merili debelino desne polovice TP pri funkcionalni rezidualni (FRK) in totalni pljučni kapaciteti (TPK), izračunali koeficient zadebelitve TP (Δd), amplitudo gibanja TP pri sproščenem (SP_{dih}) in globokem dihanju (GL_{dih}) ter hitrost premika TP pri njuhu (kratek in sunkovit inspirij skozi nos). Normativne vrednosti, ki smo jih dobili znašajo za FRPK 1.1 mm, TPK 1.7 mm, Δd 0.3 mm, SP_{dih} 8.0 mm, GL_{dih} 28.0 mm in njuh 40.0 mm/s. Dobljene normativne vrednosti so uporabne v kliničnem okolju pri diagnostiki bolnikov z živčno-mišičnimi, pljučnimi in internističnimi boleznimi. Ključne besede: trebušna prepona, ultrasonografija, normativne vrednosti.

1. INTRODUCTION

Thoracic diaphragm (TD) is not only the most important respiratory muscle (Vivier et al., 2012), but is also important for efficient coughing, vomiting, swallowing, urination, defecation and maintaining body posture (Bordoni et al., 2016). The main symptom of TD dysfunction or phrenic nerve is dyspnea. It is present during physical activity and if more pronounced also at rest or sleep (Ricoy et al., 2019). Dysfunction of TD is unilateral or bilateral. The most important causes of unilateral dysfunction are traumatic or iatrogenic injuries, compression of the TD or phrenic nerve due to tissue masses (cancer), inflammation, neurological diseases and regional anesthesia (Vetrugno et al., 2019). Unilateral dysfunction is frequently asymptomatic or it is shows as a shortness of breath during physical activity. It is usually diagnosed coincidently (Caleffi-Pereira et al., 2018). However, the most important causes of bilateral dysfunction are neurologic diseases (myopathy or dystrophy), connective tissue disorders, electrolyte deficiency, endocrine diseases, compression of the TD or phrenic nerve due to tissue masses (cancer), virus infections, amyloidosis, porphyria, malnutrition, corticosteroid intake, sepsis and mechanical ventilation (Vetrugno et al., 2019). The cause of dysfunction is often unknown (i.e. idiopathic). Diagnostic procedure include anamnesis, clinical examination (Minami et al., 2018; Bordoni and Morabito, 2019), RTG (Minami et al., 2018; Ricoy et al., 2019), fluoroscopy (Kokatnur and Rudrappa, 2018; Minami et al., 2018; Ricoy et al., 2019), CT (Umbrello and Formenti, 2016; Minami et al., 2018; Uhlich et al., 2018; Sekusky and Lopez, 2020), MR (Nason et al., 2012; Sarwal et al., 2013; Umbrello and Formenti, 2016), EMG (Yoshioka et al., 2007; Sarwal et al., 2013; Boon et al., 2014), nerve conduction studies (Pinto et al., 2016), spirometry (Kokatnur and Rudrappa, 2018) and ultrasonography (US) (Matamis et al., 2013; Sarwal et al., 2013; Fantini et al., 2016; Fantini et al., 2019; Mandoorah and Mead, 2019; Ricoy et al., 2019; Vetrugno et al., 2019; Santana et al, 2020). The latter can determine TD thickness and movement (Boon et al., 2014) and therefore atrophy and paresis (Mandoorah and Mead, 2019). Normative values are crucial to determine TD dysfunction. Therefore, the aim of present study was to gathered standard data for specific US parameters necessary for the evaluation of TD function.

2. METHODS

Participants
Healthy adult volunteers without any respiratory or neurological disorders, age matched with patients with spinal muscle atrophy and amyotrophic lateral sclerosis, were recruited.

Assessment
Measurements were taken between September 2020 and May 2021 at the Institute of Clinical Neurophysiology, University Clinical Centre Ljubljana, Slovenia. Healthy adult volunteers were in supine position with arms extended (Fayssoil et al., 2019; Vetrugno et al., 2019). The right side of the TD thickness was assessed with 13 MHz linear probe in M-mode (Aloka UST-5412) between 8th and 9th or 9th and 10th rib in anterior axillary line (Vivier et al., 2012; Sarwal et al., 2013; O'hara et al., 2020) (Figure 1A). Only thickness of hipoehoic (muscle) layer was measured (Matamis et al., 2013). The right side of the TD motion (TD amplitude and TD velocity) was measured with 2-5 MHz convex probe (Aloka UST-9119-5) under right rib cage between middle clavicle and anterior axillary line through the liver window (Matamis et al., 2013; Sarwal et al., 2013) (Figure 1B). Under xiphoid approach or between the ribs were used when TD through liver window was not visible (colon).

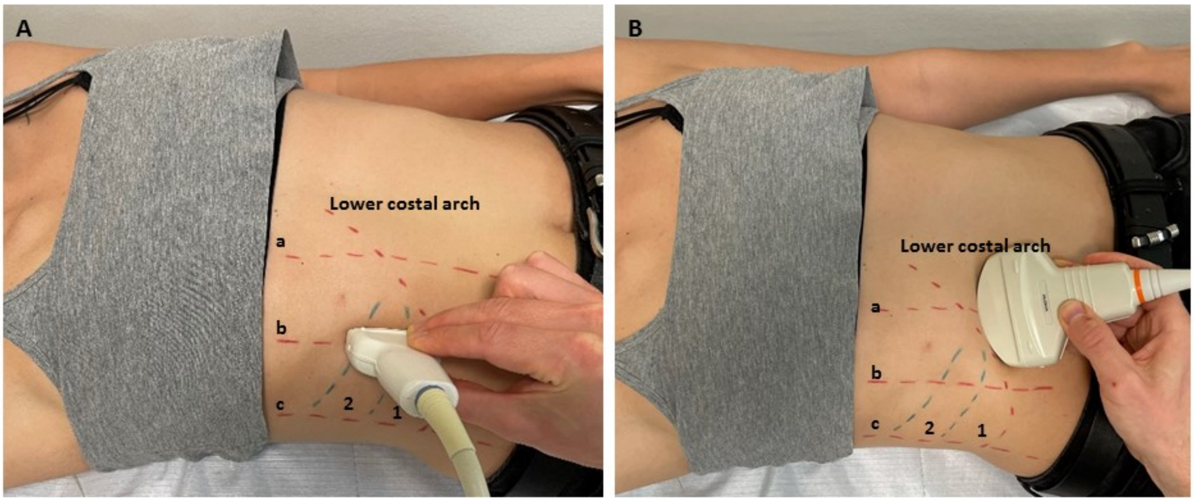

Figure 1: A – Position of the linear probe during TD thickness measuring; B – Position of the convex probe during TD motion measuring. A – Middle clavicle line; B – anterior axillary line; C – posterior axillary line; 1 – 9/10 intercostal space; 2 – 8/9 intercostal space.

US measurements

We measured TD thickness at functional residual capacity (FRC) (Kim et al., 2017) (Figure 2A) and total lung capacity (TLC) (Kim et al., 2017) (Figure 2B). TD thicknening fraction (Δd) was calculated as (thickness at TLC – thickness at FRC) / thickness at FRC (Santana et al., 2020).

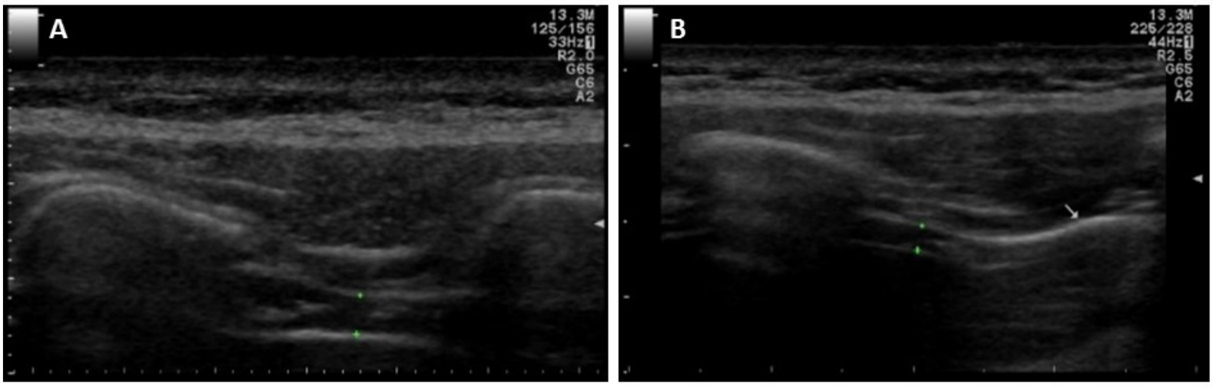

Figure 2: TD thickness at functional residual capacity (A) and TD at total lung capacity (B). Arrow is showing the lungs.

Furthermore, TD amplitude between quiet breathing (QB) (distance between tidal volume) (Santana et al., 2020) (Figure 3A), TD amplitude between deep breathing (DB) (distance between TD place at FRC in TPC) (Santana et al., 2020) (Figure 3B) and velocity of the TD between sniff maneuver (that is fast breath through nose) (Scott et al., 2006) (Figure 3C) was measured. Three consecutive measurements were performed and averaged.

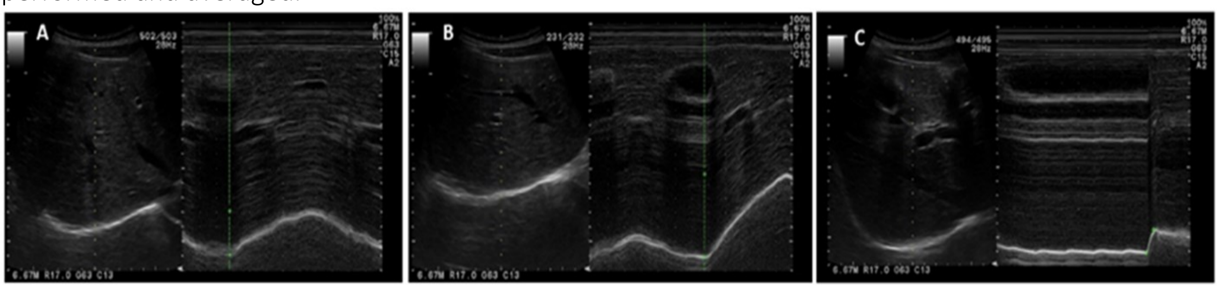

Figure 3: A – Amplitude during quiet breathing; B – Amplitude during deep breathing; C – sniff maneuver. The left image side shows breathing in B mode and the right side in M-mode.

Statistics

Statistics were made using IBM SPSS Statistics 26 (Chicago, IL, USA). Lower limits of normal were calculated as mean-1.96×SD. 5th percentile and frequency distribution was also calculated. Furthermore, correlation between dependent (US measurements) and independent variables (sex, age, height, weight, BMI were defined using simple linear regression model.

3. RESULTS

In our research 80 healthy volunteers were participated (51.7 years old ± 17.0; 33 men). Table 1 shows demographic characteristics for all participants and separately for men and women. Statistical differences (p <0.0001) were found between men and women in height and weight. Men are higher and heavier than women. Table 2 shows descriptive statistics for TD thickness and motion. Considerable differences between 5th percentile and LLN were calculated. Furthermore, frequency distribution for US variables was also calculated (Table 3).

Table 1: Demographic characteristics of 33 man and 47 women healthy volunteers

Demographic data	Men and women	Men	Women
Age [year]; mean ± SD (95% CI)	52 ± 17 (48-56)	49 ± 17 (43-55)	54 ± 17 (49-59)
Height [m]; mean ± SD (95% CI)	1.7 ± 0.08 (1.69-1.75)	1.8 ± 0.05 (1.77-1.81)*	1.7 ± 0.05 (1.65-1.68)*
Weight [kg]; mean ± SD (95% CI)	74 ± 14 (71-77)	83 ± 14 (78-88)*	68 ± 10 (65-71) *
BMI [kg/m²]; mean ± SD (95% CI)	24.9 ± 3.9 (24-26)	25.9 ± 4.0 (24.4-27.3)	24.3 ± 3.7 (23.2-25.4)
Smoking; n (%)			
Yes	13 (16 %)	6 (18%)	7 (15%)
Ex-smoker	15 (19 %)	6 (18%)	9 (19%)
No	52 (65 %)	21 (64%)	31 (66%)

*SD – standard deviation; CI – confidence interval; n – number of participants; BMI – body mass index; * – statistical difference (p < 0.0001).*

Table 2: Descriptive statistics

Measurements	Men and women	Men	Women
Thoracic diaphragm thickness at functional residual capacity [mm]			
n; mean ± SD	80; 1.5 ± 0.4	33; 1.7 ± 0.4	47; 1.4 ± 0.3
SE; 95% CI	0.1; 1.5–1.6	0.1; 1.6–1.9	0.1; 1.3-1.5
2.5-5 perc.	1.0-1.0	1.0-1.1	0.6-1.0
LLN	0.7	0.9	0.8
KS_{test} (p)	0.001	0.200	0.039
Thoracic diaphragm thickness at total lung capacity [mm]			
n; mean ± SD	80; 2.7 ± 0.9	33; 3.0 ± 1.0	47; 2.5 ± 0.7
SE; 95% CI	0.1; 2.5–2.9	0.2; 2.7-3.4	0.1; 2.3-2.7
2.5-5 perc.	1.2-1.6	1.8-1.9	1.0-1.3
LLN	0.9	1.0	1.1
KS_{test} (p)	0.002	0.009	0.186
Thoracic diaphragm thickening fraction [mm]			
n; mean ± SD	80; 0.8 ± 0.4	33; 0.8 ± 0.5	47; 0.8 ± 0.4
SE; 95% CI	0.1; 0.7–0.9	0.1; 0.6-1.0	0.1; 0.7-0.9
2.5-5 perc.	0.2-0.3	0.2-0.3	0.1-0.2
LLN	0.2	-0.2	0.2
KS_{test} (p)	0.003	< 0.0001	0.032
Thoracic diaphragm amplitude during quiet breathing [mm]			
n; mean ± SD	77; 13.5 ± 4.7	30; 15.0 ± 4.1	47; 12.6 ± 4.9
SE; 95% CI	0.5; 12.5–14.6	0.8; 13.4-16.5	0.7; 11.2-14.0
2.5-5 perc.	6.0-6.9	8.0-8.6	6.0-6.2
LLN	4.3	7.0	3.0
KS_{test} (p)	0.032	0.200	0.024

Thoracic diaphragm amplitude during quiet breathing [mm]			
n; mean ± SD	75; 51.1 ± 16.1	28; 54.9 ± 17.5	47; 48.8 ± 15.0
SE; 95% CI	1.9; 47.3–54.6	3.3; 48.1-61.7	2.2; 44.4-53.2
2.5-5 perc.	23.7-27.0	29.5-30.2	22.4-25.2
LLN	19.5	20.6	19.4
KS_{test} (p)	0.200	0.200	0.200
Velocity of the TD during sniff maneuver [mm]			
n; mean ± SD	69; 85.1 ± 32.9	25; 87.7 ± 34.2	44; 83.5 ± 32.4
SE; 95% CI	4.0; 78.1–92.9	6.8; 74.0-101.8	4.9; 73.7-93.4
2.5-5 perc.	37.2-39.5	35.0-36.5	38.1-39.5
LLN	20.6	20.7	20.0
KS_{test} (p)	0.200	0.200	0.200

n – number of the participants; SD – standard deviation; SE – standard error; CI – confidence interval; perc. – percentile; LLN – lower limit of normal (mean-1.96×SD); KS_{test} – Kolmogorov-Smirnov test; p – p value.

Table 3: Frequency distribution

TD thickness			TD motion		
FRC; n (%) [mm]	TPC; n (%) [mm]	Δd; n (%) [mm]	QB; n (%) [mm]	DB; n (%) [mm]	SM; n (%) [mm/s]
1.0; 4 (5.1)	0.9; 1 (1.3)	0.1; 1 (1.3)	6.0; 2 (2.6)	22.0; 1 (1.4)	35.0; 1 (1.5)
1.1; 7 (13.9)	1.2; 1 (2.6)	0.2; 2 (3.8)	6.5; 1 (3.9)	24.0; 1 (2.7)	38.0; 1 (2.9)
1.2; 9 (25.3)	1.5; 1 (3.8)	0.3; 6 (11.3)	7.0; 1 (5.3)	27.0; 2 (5.5)	39.0; 1 (4.4)
1.3; 8 (35.4)	1.6; 1 (5.1)	0.4; 16 (31.3)	8.0; 4 (10.5)	28.0; 1 (6.8)	40.0; 1 (5.9)
1.4; 11 (49.4)	1.7; 1 (6.4)	0.5; 6 (38.8)	9.0; 5 (17.1)	29.5; 1 (8.2)	41.0; 1 (7.4)
≥ 1.5; 40 (50.6)	1.8; 2 (9.0)	0.6; 5 (45.0)	9.3; 1 (18.4)	31.0; 2 (11.0)	41.5; 1 (8.8)
	1.9; 4 (14.1)	0.7; 3 (48.8)	10.0; 11 (32.9)	32.0; 2 (13.7)	43.0; 1 (10.3)
	2.0; 4 (19.2)	≥ 0.8; 41 (51.2)	11.0; 6 (40.8)	35.0; 2 (16.4)	46.0; 1 (11.8)
	2.1; 5 (25.6)		12.0; 5 (47.4)	36.0; 2 (19.2)	48.0; 2 (14.7)
	2.2; 5 (32.1)		≥ 13.0; 40 (52.6)	37.0; 1 (20.5)	53.0; 3 (19.1)
	2.3; 6 (39.7)			38.0; 1 (21.9)	57.0; 1 (20.6)
	2.4; 4 (44.9)			38.3; 1 (23.3)	58.0; 1 (22.1)
	2.5; 4 (50.0)			39.0; 5 (30.1)	59.0; 1 (23.5)
	≥ 2.6; 39 (50.0)			39.5; 1 (31.5)	62.0; 1 (25.0)
				40.0; 2 (34.2)	66.0; 1 (26.5)
				41.0; 1 (35.6)	68.0; 1 (27.9)
				42.0; 2 (38.4)	69.0; 2 (30.9)
				43.0; 1 (39.7)	72.0; 2 (33.8)
				44.0; 2 (42.5)	73.0; 3 (38.2)
				46.0; 1 (43.8)	74.0; 2 (41.2)
				47.0; 1 (45.2)	76.0; 2 (44.1)
				48.0; 1 (46.6)	77.0; 2 (47.1)
				49.0; 3 (50.7)	78.0; 1 (48.5)
				≥ 50.0; 36 (49.3)	79.0; 1 (50.0)
					≥ 80.0; 34 (50.0)

Values above 5th percentile are bolded. TD – thoracic diaphragm; n – number of the participants; FRC – functional residual capacity; TPC– total lung capacity; Δd – TD thickening fraction; QB – quiet breathing; DB – deep breathing; SM – sniff maneuver.

Frequency distribution (Figure 3) shows that normative values for men and women are as follows: FRC < 1.1 mm; TLC < 1.7 mm; Δd < 0.3; QB < 8.0 mm; DB < 28.0 mm and sniff maneuver < 40.0 mm/s. Normative values for men defined as 5th percentile are as follows: FRC < 1.1 mm; TPC < 1.9 mm; Δd < 0.3; QB < 8.6 mm; DB < 30.2 mm, and sniff maneuver < 36.5 mm/s.

Normative values for women defined as 5th percentile are as follows: FRC < 1.0 mm; TPC < 1.3 mm; Δd < 0.2; DB < 6.2 mm; DB < 25.2 mm, and sniff maneuver < 39.5 mm/s. Results of simple linear regression model showed significant differences between TD thickness and BMI (Table 4).

Table 4: Linear regression model

	TD thickness			TD movement		
	FRC [mm]	TPC [mm]	Δd [mm]	QB [mm]	DB [mm]	SM [mm/s]
Sex (p-value)	<0.0001	0.005	0.991	0.030	0.117	0.615
Age (p-value)	0.808	0.239	0.385	0.036	0.002	0.075
Height (p-value)	0.019	0.135	0.380	0.056	0.673	0.501
Weight (p-value)	<0.0001	0.012	0.036	0.476	0.555	0.540
BMI (p-value)	<0.0001	0.030	0.046	0.732	0.615	0.784

n – number of the participants; TD – thoracic diaphragm; FRC – functional residual capacity; TPC– total lung capacity; Δd – thoracic diaphragm thickening fraction; QB – quiet breathing; DB – deep breathing; SM – sniff maneuver; BMI – body mass index.

4. DISCUSSION

The aim of present study was to gather standard data for specific US parameters necessary for the evaluation of TD function. We included 80 healthy participants. TD amplitude between QB could not be assessed in 3.8 %, DB in 6.3 % and sniff maneuver in 15.8 % participants. The main reason was colon obstructed the view on TD. One research reported that the number of patients in which US of TD could not be assessed is even higher (28-63 %) (Sarwal et al., 2013). We calculated normative value for TD thickness at FRC 1.1 mm (men 1.1 mm and women 1.0 mm). Two other studies reported normative value for both sexes at 1.5 mm (Boon et al., 2013), and for women 1.5 mm and men 1.7 mm (Spiesshoefer et al., 2020). The most likely reason for reported differences is measurement protocol. TD is composed by 3 layers; (1) pleural membrane, (2) peritoneale membrane and diaphragm muscle. Thickness can be defined as distance between both membranes (muscle thickness) and distance including both membranes (Matamis et al., 2013). Our results show that the difference between two different techniques can be up to 51 % (Matamis et al., 2013). We also noticed that measurements of TD thickness can vary significantly between different measurement places. The normative value for TD thickness at TLC was 1.7 mm. One other study reported normative value for men 4.6 mm and for women 3.5 mm (Spiesshoefer et al., 2020). The difference in results is significant and the most probable reason measurement protocol (Matamis et al., 2013). We noticed that thickness of TD at TLC vary significantly between different measurement places, similar to thickness of the TD at FRC. It is possible to calculate TD thickening fraction from TD thickness at FRC and TLC. The normative value was 0.3 (men 0.3 mm and women 0.2 mm). The movement of the TD can be assessed in M mode. Normative value for amplitude during QB was 8.00 mm (men 8.6 mm and women 6.2 mm). Other studies reported normative values for men 10.0 mm (Boussuges et al., 2009), 12.0 mm (Spiessoefer et al., 2020) and 17.7 mm (Scarlata et al., 2018) and for women 9.0 mm (Boussuges et al., 2009), 12.0 mm (Spiessoefer et al., 2020) and 13.3 mm (Scarlata et al., 2018). Most probable explanation for differences is unknown. Normative value for TD amplitude during DB was 28 mm, while other studies reported higher values; for men 47.0 mm (Boussuges et al., 2009), 62.6 mm (Scarlata et al., 2018) and 79.0 mm (Spiesshoefer et al., 2020), and for women 36.0 mm (Boussuges et al., 2009), 49.6 mm (Scarlata et al., 2018) and 64.0 mm (Spiesshoefer et al., 2020). Again, the most probable explanation for those differences is unknown. Normative value for TD velocity during sniff maneuver was 40.0 mm/s (men 36.5 mm/s and women 39.5 mm/s). One other study reported normative value for men 67.0 mm/s and for women 52.0 mm/s (Spiesshoefer et al., 2020). Again, the most probable explanation for those differences is unknown. It is possible that differences in volunteers' characteristics are responsible for disproportions between our results and results of other authors. Furthermore, results of linear regression model show that the TD thickness is influenced by sex (FRC: $p < 0.0001$, TLC: $p = 0.005$), weight (FRC: $p < 0.0001$, TLC: $p = 0.012$), and BMI (FRC: $p < 0.0001$, TLC: $p = 0.030$); TD thickening fraction by weight ($p = 0.036$), and BMI ($p = 0.046$);

amplitude by sex (QB: p = 0.030) and age (QB: p = 0.036, DB: p = 0.002). Other results show positive correlation between weight and amplitude, height and amplitude (Haris et al., 1983; Boussuges et al., 2009) and negative correlation between age and amplitude (Orde et al., 2016; Fayssoil et al., 2019). Further studies are necessary to better understand not only the normative values but value of US in diagnosis of TD function.

5. CONCLUSION

US is perspective methods for assessing TD function mainly in neuromuscular patients (mostly patients with amyotrophic lateral sclerosis), patients with lung and internal diseases and patients in intensive care units. Further studies on healthy volunteers and patients are necessary to define the true usability of US in TD dysfunction. We suggest the enlargement of study sample and controlling the variability of US parameters in further investigations.

6. REFERENCES

1. *Boon, A. J., Harper, C. J., Ghahfarokhi, L. S., Strommen, J. A., Watson, J. C., & Sorenson, E. J. (2013). Two-dimensional ultrasound imaging of the diaphragm: quantitative values in normal subjects. Muscle & nerve, 47(6), 884-889.*
2. *Boon, A. J., Sekiguchi, H., Harper, C. J., Strommen, J. A., Ghahfarokhi, L. S., Watson, J. C., & Sorenson, E. J. (2014). Sensitivity and specificity of diagnostic ultrasound in the diagnosis of phrenic neuropathy. Neurology, 83(14), 1264-1270.*
3. *Bordoni, B., Marelli, F., Morabito, B., & Sacconi, B. (2016). Manual evaluation of the diaphragm muscle. International journal of chronic obstructive pulmonary disease, 11, 1949.*
4. *Bordoni, B., & Morabito, B. (2019). The Diaphragm Muscle Manual Evaluation Scale. Cureus, 11(4).*
5. *Boussuges, A., Gole, Y., & Blanc, P. (2009). Diaphragmatic motion studied by m-mode ultrasonography: methods, reproducibility, and normal values. Chest, 135(2), 391-400.*
6. *Caleffi-Pereira, M., Pletsch-Assunção, R., Cardenas, L. Z., Santana, P. V., Ferreira, J. G., Iamonti, V. C., ... & Albuquerque, A. L. P. (2018). Unilateral diaphragm paralysis: a dysfunction restricted not just to one hemidiaphragm. BMC pulmonary medicine, 18(1), 126.*
7. *Fantini, R., Mandrioli, J., Zona, S., Antenora, F., Iattoni, A., Monelli, M., ... & Marchioni, A. (2016). Ultrasound assessment of diaphragmatic function in patients with amyotrophic lateral sclerosis. Respirology, 21(5), 932-938.*
8. *Fantini, R., Tonelli, R., Castaniere, I., Tabbì, L., Pellegrino, M. R., Cerri, S., ... & Marchioni, A. (2019). Serial ultrasound assessment of diaphragmatic function and clinical outcome in patients with amyotrophic lateral sclerosis. BMC pulmonary medicine, 19(1), 1-8.*
9. *Fayssoil, A., Nguyen, L. S., Ogna, A., Stojkovic, T., Meng, P., Mompoint, D., ... & Lofaso, F. (2019). Diaphragm sniff ultrasound: Normal values, relationship with sniff nasal pressure and accuracy for predicting respiratory involvement in patients with neuromuscular disorders. PLoS One, 14(4), e0214288.*
10. *Harris, R. S., Giovannetti, M., & Kim, B. K. (1983). Normal ventilatory movement of the right hemidiaphragm studied by ultrasonography and pneumotachography. Radiology, 146(1), 141-144.*
11. *Kim, M., Lee, K., Cho, J., & Lee, W. (2017). Diaphragm thickness and inspiratory muscle functions in chronic stroke patients. Medical science monitor: international medical journal of experimental and clinical research, 23, 1247.*
12. *Kokatnur, L., & Rudrappa, M. (2018). Diaphragmatic palsy. Diseases, 6(1), 16.*
13. *Mandoorah, S., & Mead, T. (2020). Phrenic nerve injury. StatPearls [Internet].*
14. *Matamis, D., Soilemezi, E., Tsagourias, M., Akoumianaki, E., Dimassi, S., Boroli, F., ... & Brochard, L. (2013). Sonographic evaluation of the diaphragm in critically ill patients. Technique and clinical applications. Intensive care medicine, 39(5), 801-810.*

15. *Minami, T., Manzoor, K., & McCool, F. D. (2018). Assessing diaphragm function in chest wall and neuromuscular diseases. Clinics in chest medicine, 39(2), 335-344.*
16. *Nason, L. K., Walker, C. M., McNeeley, M. F., Burivong, W., Fligner, C. L., & Godwin, J. D. (2012). Imaging of the diaphragm: anatomy and function. Radiographics, 32(2), E51-E70.*
17. *O'Hara, D. N., Pavlov, A., Taub, E., & Ahmad, S. (2020). Ultrasonographic modeling of diaphragm function: A novel approach to respiratory assessment. Plos one, 15(3), e0229972.*
18. *Orde, S. R., Boon, A. J., Firth, D. G., Villarraga, H. R., & Sekiguchi, H. (2016). Use of angle-independent M-mode sonography for assessment of diaphragm displacement. Journal of Ultrasound in Medicine, 35(12), 2615-2621.*
19. *Pinto, S., Alves, P., Pimentel, B., Swash, M., & de Carvalho, M. (2016). Ultrasound for assessment of diaphragm in ALS. Clinical Neurophysiology, 127(1), 892-897.*
20. *Ricoy, J., Rodríguez-Núñez, N., Álvarez-Dobaño, J. M., Toubes, M. E., Riveiro, V., & Valdés, L. (2019). Diaphragmatic dysfunction. Pulmonology, 25(4), 223-235.*
21. *Santana, P. V., Cardenas, L. Z., Albuquerque, A. L. P. D., Carvalho, C. R. R. D., & Caruso, P. (2020). Diaphragmatic ultrasound: a review of its methodological aspects and clinical uses. Jornal Brasileiro de Pneumologia, 46(6).*
22. *Sarwal, A., Walker, F. O., & Cartwright, M. S. (2013). Neuromuscular ultrasound for evaluation of the diaphragm. Muscle & nerve, 47(3), 319-329.*
23. *Scarlata, S., Mancini, D., Laudisio, A., Benigni, A., & Incalzi, R. A. (2018). Reproducibility and clinical correlates of supine diaphragmatic motion measured by M-mode ultrasonography in healthy volunteers. Respiration, 96(3), 259-266.*
24. *Sekusky, A. L., & Lopez, R. A. (2020). Diaphragm Trauma. In StatPearls [Internet]. StatPearls Publishing.*
25. *Spiesshoefer, J., Herkenrath, S., Henke, C., Langenbruch, L., Schneppe, M., Randerath, W., ... & Boentert, M. (2020). Evaluation of respiratory muscle strength and diaphragm ultrasound: normative values, theoretical considerations, and practical recommendations. Respiration, 99(5), 369-381.*
26. *Uhlich, R., Kerby, J. D., Bosarge, P., & Hu, P. (2018). Diagnosis of diaphragm injuries using modern 256-slice CT scanners: too early to abandon operative exploration. Trauma Surgery & Acute Care Open, 3(1).*
27. *Umbrello, M., & Formenti, P. (2016). Ultrasonographic assessment of diaphragm function in critically ill subjects. Respiratory care, 61(4), 542-555.*
28. *Urfy, M. Z., & Suarez, J. I. (2014). Breathing and the nervous system. Handbook of clinical neurology, 119, 241-250.*
29. *Vetrugno, L., Guadagnin, G. M., Barbariol, F., Langiano, N., Zangrillo, A., & Bove, T. (2019). Ultrasound imaging for diaphragm dysfunction: a narrative literature review. Journal of cardiothoracic and vascular anesthesia, 33(9), 2525-2536.*
30. *Vivier, E., Dessap, A. M., Dimassi, S., Vargas, F., Lyazidi, A., Thille, A. W., & Brochard, L. (2012). Diaphragm ultrasonography to estimate the work of breathing during non-invasive ventilation. Intensive care medicine, 38(5), 796-803.*
31. *Yoshioka, Y., Ohwada, A., Sekiya, M., Takahashi, F., Ueki, J., & Fukuchi, Y. (2007). Ultrasonographic evaluation of the diaphragm in patients with amyotrophic lateral sclerosis. Respirology, 12(2), 304-307.*