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Diaphragmatic dysfunction and cardiac surgery; Perioperative assessment and effect on outcome; prospective observational study

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Abstract

While the use of ultrasound in critical care is increasing, there remains a scarcity of studies focused on assessing diaphragm dysfunction using ultrasound in cardiac surgery patients. This study aimed to investigate the incidence of diaphragm dysfunction in adult cardiac surgery patients and to assess the impact of such dysfunction on patient outcomes. A prospective observational study of 104 consecutive adult cardiac surgery patients was conducted at a single Centre. Diaphragmatic displacement (DD) or excursion and diaphragmatic thickening fraction (DTF) were measured using motion-mode ultrasound during quiet normal breathing both pre-operatively (the day before surgery) and post-operatively (during spontaneous breathing trial on continuous positive airway pressure (CPAP) mode + pressure support 10 cm H2O). Post-operative DD was significantly decreased compared to pre-operative one (mean 1.39 ± 0.42 cm vs. 2.3 ± 0.52 cm, $p < 0.001$), as was DTF (mean 23% ± 10% vs. 40% ± 13%, $p < 0.001$). The incidence of diaphragmatic dysfunction post-cardiac surgery was 17% by the definition of DD < 1cm, and 49% by the definition of DTF ≤ 20%. Diaphragmatic dysfunction was positively correlated with cardio-pulmonary bypass time, as well as total ventilation time and ICU stay, indicating a negative impact on overall patient outcomes. This study highlights the importance of diaphragmatic ultrasound as a bedside technique for detecting severe diaphragmatic dysfunction post-cardiac surgery, particularly in patients experiencing respiratory distress. Our results suggest that diaphragmatic dysfunction is positively correlated with cardiopulmonary bypass (CPB) time underscoring the importance of monitoring diaphragmatic function in this patient population, particularly those with prolonged CPB time. These findings may guide future research and clinical interventions aimed at improving outcomes in post-cardiac surgery patients.

Keywords: Cardiac surgery, Cardiopulmonary Bypass, Diaphragm dysfunction, Diaphragmatic displacement.

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1. Introduction

The diaphragm is a crucial respiratory muscle, and its dysfunction can lead to respiratory complications and prolonged mechanical ventilation [1-2]. Various insults, including hypotension, hypoxia, sepsis, and mechanical ventilation, can induce diaphragmatic dysfunction [1-5]. Therefore, evaluating diaphragmatic function is essential in many clinical situations. Sonographic evaluation of the diaphragm has recently become popular in the ICU due to its noninvasive, easy-to-use, and accurate nature. It can quantify normal and abnormal movements, diagnose diaphragmatic paralysis and recovery, screen for postoperative diaphragmatic dysfunction, and detect synchronization of spontaneous breathing efforts with the ventilator [1,6-7]. Ultrasound can measure diaphragmatic excursion, speed of diaphragmatic contraction, and diaphragmatic thickness through the diaphragmatic thickening fraction (DTF), which helps assess diaphragmatic function and its contribution to respiratory workload [8-9]. Diaphragmatic dysfunction is a common complication after cardiac surgery, leading to delayed weaning from mechanical ventilation and respiratory distress [1,5,10]. Abnormal diaphragmatic motion is observed in conditions such as phrenic nerve injury, neuromuscular diseases, and after cardiac surgery [1,3-5,8,11-13]. Evaluating diaphragmatic function before any weaning attempt could be of importance. Hypokalemia, hypophosphatemia, hypomagnesemia or placement of intercostal drainages or radiofrequency ablation used in cardiac surgery are considered potential risks for diaphragmatic dysfunction [14]. Hypothermic, mechanical, and ischemic injury are common causes of phrenic nerve damage during cardiac surgery [15]. While inflammation and oxidative stress can cause diaphragmatic weakness in critically ill patients, further research is needed to understand the effects of cardiopulmonary bypass and intraoperative complications on diaphragmatic function and the co-occurrence of certain conditions and procedures with diaphragmatic dysfunction [16]. Diaphragmatic dysfunction defined as vertical diaphragmatic displacement (DD) <10 mm is a predictor of weaning failure among patients in medical ICUs [9].

The diaphragmatic thinking fraction (DTF) is another parameter of diaphragmatic function that is significantly different between patients who failed and those who succeeded SBT. A cutoff value of a DTF >36% was associated with a successful SBT with high sensitivity, specificity, positive predictive value, and negative predictive value [17].

2. Aim of this work

The purpose of this study is to evaluate diaphragm function in postoperative cardiac surgery patients during weaning from mechanical ventilation, using non-invasive ultrasonic methods to calculate inspiratory diaphragmatic thickening fraction and diaphragmatic displacement. We also aim to identify risk factors associated with postoperative diaphragm weakness and to investigate the impact of this weakness on patient outcomes.

3. Materials and Methods

3.1. Study Design and Patient Population

This is a prospective cross-sectional observational study conducted at a tertiary-care cardiac center. Adult patients aged 18 years and above were consecutively enrolled, who were admitted to an adult cardiac surgical ICU (CSICU) between June 2016 and November 2019. Ethical committee approval was taken before the study. All patients underwent cardiac surgery with cardiopulmonary bypass and were subjected to the same protocol for general anaesthesia, including the same induction, maintenance with intravenous and inhalational (sevoflurane) anaesthesia, and neuromuscular blocker (rocuronium for induction + atracurium or cisatracurium for maintenance). In the postoperative period, all patients underwent the same protocol for weaning from mechanical ventilation.

3.2. Inclusion and Exclusion Criteria

Patients were included if they were 18 years old and above, underwent planned cardiac surgery, including elective and emergency cases without preoperative hemodynamic instability or respiratory distress requiring respiratory support, were ready for weaning from mechanical ventilation (FIO2 $\leq$ 50%, positive end-expiratory pressure level (PEEP) $\leq$ 5 cmH_2O, respiratory rate $\leq$ 30 breaths/min, PaO2/FIO2 ratio > 200mm Hg, Glasgow coma score $\geq$ 14), had stable cardiovascular (i.e., heart rate < 120 beats/min; systolic blood pressure, 90–160mmHg; and no or minimal vasopressor use, i.e., dopamine, dobutamine $\leq$ 5μg/kg/min or adrenaline, noradrenaline $\leq$ 0.05μg/kg/min), and metabolic status (i.e., electrolytes and glycaemia within normal range, body temperature < 38 °C, hemoglobinemia $\geq$ 8–10g/dL). Patients were excluded if they are refusing, or they had a history of diaphragmatic paralysis or neuromuscular disease affecting the diaphragm or evidence of pneumothorax or pneumomediastinum. Patients with low EF $\leq$ 30%, post-operative cerebrovascular stroke, or reintubation due to cardiac cause; arrest, arrhythmias, or failure, were excluded from outcome correlation.

3.3. Materials and Measurements

Transthoracic ultrasonography using a SonoSite M-Turbo was performed at the bedside in both B- and M-modes to evaluate diaphragmatic excursion and thickness in patients undergoing cardiac surgery. The patients were positioned semi-recumbent at 45°, and the ultrasound probe was placed in the right anterior axillary line between the seventh and ninth intercostal spaces to visualize the posterior third of the corresponding hemidiaphragm perpendicularly or with an angle not less than 70°, depending on the case difficulty [18]. The diaphragmatic inspiratory excursion or displacement (DD) was measured in M-mode during tidal breathing using a phased-array transducer with a frequency range of 1-5 MHz [19]. The amplitude of diaphragmatic inspiratory excursion was measured as the point of the maximal height of the diaphragm in the M-mode tracing to the baseline, expressed in cm or mm. Three consecutive tidal breaths were recorded, and the average value was used for analysis. Diaphragmatic thickness (DT) was subsequently measured at the zone of apposition (ZOA), which is the area of the diaphragm attached to the rib cage, at both end inspiration and end-expiration using a high frequency 6-15MHz ultrasound linear transducer in M-mode. The diaphragm in the ZOA appeared as a hypoechoic layer between two hyperechoic bright and parallel lines representing the pleural and peritoneal membranes. The costophrenic sinus, which is located 0.5-2cm below the ZOA, was used as a landmark to identify the transition zone between the lung cranially and the liver or spleen caudally. The diaphragm thickness was measured from the middle of the pleural line to the middle of the peritoneal line, and the diaphragmatic thickness fraction (DTF) was calculated as a percentage using the formula: (Thickness at end inspiration - Thickness at end-expiration) / Thickness at end-expiration [17,20].

3.4. Data Collection

In this study, data were collected at three time points, including baseline demographic characteristics, medical history, key laboratory results, cardiac ejection fraction (EF), and diaphragm assessment the day before the operation. We recorded the intraoperative cardiopulmonary bypass (CPB) time, aortic cross-clamp time, and any intraoperative hypotension or deep hypothermic circulatory arrest (DHCA) during the operation. After the operation, a diaphragm assessment was conducted during a spontaneous breathing trial using continuous positive airway pressure (CPAP) mode with pressure support of 10cm H2O and PEEP of 5cm H2O and compared with the preoperative assessment. Additionally, important labs and arterial blood gas (ABG) parameters before extubating were recorded. The right hemidiaphragm was evaluated by M-mode ultrasonography to record DD using a low-frequency probe and DT using a high-frequency probe. Assessing the left hemidiaphragm was technically challenging in post-cardiac surgery patients, especially those who had undergone coronary artery bypass grafting (CABG) procedures, due to intercostal drains and pleural effusion.

4. Results

4.1. Statistical Analysis

In this study, data analysis was conducted using IBM SPSS software. Descriptive statistical measures such as frequency, per cent, mean, and standard deviation were employed to interpret the results.

The reported outcomes were presented as mean ± standard deviation, median (IQR 25th to 75th percentiles), or number (proportion). To evaluate the correlation between variations in DD and DTF, Spearman correlation coefficient (rho) and Kendall's tau b correlation coefficient were utilized. The Mann-Whitney's U test was used to analyze the occurrence of diaphragmatic dysfunction, as well as male/female differences. Correlations were performed using both Pearson parametric and Kendall tau b non-parametric methods. The latter was deemed more appropriate due to the skewness of several measurements. Statistical significance was set at $p < 0.05$.

4.2. Patients' characteristics

During the study period, 104 adult patients who were admitted to the cardiac surgery intensive care unit (CSICU) following cardiac surgery were enrolled in the study. Four patients were excluded due to post-operative cardiac complications which led to reintubation or prolonged mechanical ventilation. The main clinical-demographic characteristics of the patients are summarized in Table 1, including age, sex, and body mass index (BMI) presented as numbers and percentages, and a history of smoking, hypertension, diabetes mellitus, neuro-muscular, and autoimmune diseases expressed as numbers and ratios. Table 1 showed that the study population were 100 adults, with different age groups most of them [86%] between 20-60 years, 4% <20 years, and 10% > 70 years. Of them [66%] males and [34%] females, [40%] were overweight and [26%] were obese, [40%] were smokers or ex-smokers, [34%] were diabetic, [51%] have a history of hypertension, [6%] have a history of neuromuscular deficit, and only 2 patients [2%] have a history of auto-immune disease (systemic lupus erythematosus). Table 2 showed the study population's main demographic features were age [mean 48.4, SD 16.4], and BMI [mean 26.9, SD 5.3]. Pre-operative labs were mostly normal or near normal because most the of patients were electively operated on well-prepared. Preoperative EF was normal in most of the patients [mean 50%, SD 10%] (Table 3). Table 4 presents the results of a paired sample t-test conducted to examine the statistical significance of the pre-post changes in diaphragmatic function parameters. The analysis revealed a statistically significant reduction in DD post-operatively, which indicates diaphragmatic dysfunction [mean 0.9130 ± 0.37857, $p < 0.001$]. Additionally, the analysis also revealed a statistically significant reduction in DTF post-operatively, which is also indicative of diaphragmatic dysfunction [mean 0.16720 ± 0.07284, $p < 0.001$]. These findings suggest that the surgical procedure has had a significant impact on diaphragmatic function. Results indicated a significant positive correlation between diaphragmatic dysfunction (displacement) and both duration of operation ($r = .289$, $p = .004$) and CBP time ($r = .267$, $p = .007$). Furthermore, a positive correlation was found between diaphragmatic dysfunction (displacement) and both control mode time ($r = .203$, $p = .043$) and spontaneous mode time ($r = .222$, $p = .026$). Regarding diaphragmatic dysfunction (thickening fraction), a positive correlation was found with CBP time ($r = .209$, $p = .037$) and post-operative EF ($r = .208$, $p = .038$). No significant correlations were found between diaphragmatic dysfunction and extubating time Rapid Shallow Breathing Index (RSBI) which equals respiratory rate divided by tidal volume (TV) in liters, total ventilation time, total ICU stay, or ventilation-free days. These findings provide important insights into the specific factors related to cardiothoracic surgery that contribute to diaphragmatic dysfunction (Table 5). Table 6 presents the non-parametric correlation analysis between diaphragmatic dysfunction (measured by displacement and thickening fraction) and various outcome parameters using Kendall's tau _ b correlation coefficient. Significant positive correlations were observed between DD and the duration of operation ($p < 0.01$) and CPB time ($p < 0.01$). Additionally, positive correlations were noted between DD and the total ventilation time, control mode time, and total ICU stay ($p < 0.05$). In terms of DTF, significant positive correlations were observed with the duration of operation and ventilation-free days ($p < 0.01$). Furthermore, positive correlations were noted with the total ventilation time, control mode time, spontaneous mode time, and total ICU stay ($p < 0.05$). According to our weaning protocol, patients undergoing SBTs must meet certain requirements, including a normal ABG, serum lactate ≤ 4 mmol/l, and an RSBI ≤ 80, while being fully conscious and obeying commands. Table 7 shows that the time between ICU admission and SBT was 16.6 hours (SD 12.1). Total ventilation hours were 23.5 (SD 12.5), with 21.9 (SD 12.2) hours spent on controlled mode mechanical ventilation and 1.41 (SD 0.66) hours on spontaneous mode. The mean ICU stay was 5.7 days (SD 6.6), while the mean number of ventilation-free days was 3.1 (SD 3). The mean RSBI was 46.9 (SD 14.5), while the mean PaO_2 and PCO_2 were 109.8 (SD 27.2) and 36 (SD 5) mmHg, respectively. The mean serum lactate level was 1.7 (SD 0.7) mmol/l. The hemodynamic parameters were maintained within normal ranges using inotropes or vasodilators for stable blood pressure, and fluids and diuretics for CVP and urine output (Table 8). Table 9 presents the comparison of diaphragmatic parameters (DD and DTF) between males and females. The t-test results indicate that there were no significant differences between males and females for both diaphragmatic parameters ($p = 0.223$ for DD and $p = 0.777$ for DTF). The distribution of both measures was positively skewed, but the non-parametric Mann-Whitney U test also showed no significant difference between males and females ($p = 0.355$ for DD and $p = 0.207$ for DTF). Therefore, there was no evidence of a sex difference in diaphragmatic function based on these measures. In Figure 1, the scatter plot shows that there is a positive association between BMI and diaphragmatic thickness (DT) at rest, with a statistically significant correlation observed in the total group (Pearson correlation coefficient = +0.235, $p = 0.019$) and in males (Pearson correlation coefficient = +0.272, $p = 0.027$). In females, however, this relationship appears to be non-significant (Pearson correlation coefficient = +0.171, $p = 0.333$). The lack of significance in females may be attributed to the smaller sample size of female participants, and further studies with larger samples are warranted to confirm this observation. The incidence of diaphragmatic dysfunction was determined based on the currently available criteria, which defined it as DD < 1 cm or DTF ≤ 20% [21]. The results showed that 17% of patients had diaphragmatic dysfunction based on DD, and 49% of patients had diaphragmatic dysfunction based on DTF (Table 10).

The patients were divided into two groups: group 1 with diaphragmatic dysfunction (DD < 1 cm) and group 2 without diaphragmatic dysfunction (DD > 1 cm). The statistical analysis showed a significant difference between the two groups regarding CPB in minutes (p = 0.028). The mean CPB time in group 1 was significantly higher than that in group 2 (147.24 ± 70.09 vs. 105.22 ± 44.41, respectively). This result was also confirmed by the non-parametric Mann-Whitney U test. In addition, there was no significant difference between the two groups regarding the duration of operation or total ventilation time. The mean duration of operation was 6.41 ± 2.59 hours in group 1 and 5.17 ± 1.19 hours in group 2 (p = 0.069), while the mean total ventilation time was 21.9 ± 11 hours in group 1 and 23.85 ± 12.81 hours in group 2 (p = 0.560).

5. Discussion

In a population of adult patients aged > 18 years who were admitted to adult CSICU, we have been able to describe the diaphragmatic function during spontaneous breathing, compare it with the preoperative state, and correlate it with operation-related factors. Our findings reveal that post-operative diaphragmatic function is always reduced, with an incidence of 17% of patients having diaphragmatic dysfunction based on DD, and 49% of patients based on DTF. Moreover, we observed a positive correlation between diaphragmatic dysfunction and cardio-pulmonary bypass time, the total ventilation time, control mode ventilation time, and total ICU stay. Furthermore, diaphragm displacement appears to be superior to thickening for bedside assessment. Additionally, we observed a positive association between BMI and diaphragmatic thickness at rest, especially in males. Diaphragmatic dysfunction is clinically relevant in cardiac surgery patients owing to a potentially negative impact on time to ventilator weaning, extubation success and intensive care unit length of stay [13,22]. However, the dynamic characterization of diaphragm mechanics after cardiac surgery has not been described till the time, we started our study. Fortunately, Tralhão et al., (2019) studied the time course of diaphragmatic function in this population and compared the pre-operative measurements with a series of post-operative measurements on daily basis till the 5th postoperative day. He observed a global reduction in diaphragm displacement in 36% of patients after surgery which is referred to as, apparent diaphragm stunning [23]. Anyway, he did not focus -unlike our study- on operative details and did not correlate it with a degree of diaphragm dysfunction. While Lorelle et al., (2009) studied the diaphragm of patients' post-cardiac surgery with difficult weaning from mechanical ventilation (more than 7 days on mechanical ventilation) and compared it with a group of patients extubated within 12h postoperatively (smooth ordinary post-operative course) [1]. Among patients from the latter group, a reduction in DD was also encountered on the 2nd or 3rd post-operative day [1]. However, some differences concerning our study should be noted. Excursion measurements (muscle thickness not measured) were made between forced expiration and maximal inspiration requiring patient's cooperation (post-extubation), whereas we studied patients breathing normally, without effort on CPAP mode with pressure support 10 cm H2O during SBT. This accounts for the difference between a 40% reduction in diaphragmatic displacement decrease observed in his study and the one found in this study (17% DD < 1cm). We chose to avoid forced inspiration because the ability of chest expansion to a vital capacity in the postoperative period is impaired by postoperative pain and is highly variable among patients. This also allowed us to obtain our values by averaging 3 consecutive respiratory cycles, thereby avoiding selection bias. Our analysis reveals a similar dynamic profile between excursion and muscular thickening. However, obtaining appropriate acoustic windows for thickening imaging can pose a challenge. In contrast, excursion or displacement appears to be a more accessible measurement to assess the function of the diaphragm in spontaneously breathing patients. Previous studies have shown good reproducibility for each parameter when measured individually [10,21]. The small thickness values of the diaphragm make the accurate placement of cursors critical, as any inaccuracy can result in proportionately greater errors in the percentage of thickening. This finding suggests that using excursion instead of thickening to assess diaphragmatic function may be preferable due to the potential measurement errors associated with the latter. Our study presents several notable strengths. Firstly, it is one of a limited number of studies to investigate diaphragm behavior, utilizing ultrasound as the assessment tool, in consecutive cardiac surgery patients, both pre-and post-operatively. Secondly, this study is the first to explore the correlation between cardiac operation details, such as cardio-pulmonary bypass time, and the incidence of diaphragmatic dysfunction. Thirdly, we contribute to the existing literature by demonstrating that the evaluation of diaphragmatic function is both feasible and reproducible in this patient population. Fourthly, our study includes emergency and urgent cases, allowing for confirmation of results in the face of variability in operative details and their impact on diaphragmatic function. These findings offer valuable insights into the impact of cardiac surgery on diaphragmatic function, which may inform future clinical practice and research. Several limitations of our study must be acknowledged. Firstly, the relatively small cohort and single-Centre design may limit the generalizability of our findings. Secondly, given the small sample size, caution is warranted when interpreting the lack of association between variables such as intraoperative hypotension for a certain time or DHCA, and diaphragmatic dysfunction. Thirdly, diaphragm thickness varies at different intercostal space, and different methods of measurement may yield different results; thus, precise definitions of measurement techniques are essential [24]. Fourthly, visualization of the left hemidiaphragm can be challenging, particularly for post-cardiac surgery patients with intercostal drains, which may limit our ability to accurately assess diaphragmatic function. Fifthly, diaphragmatic displacement is influenced by the subject's position and maximal voluntary inspiratory effort, which may introduce variability in our measurements, although we minimized this by using a semi-sitting position [25]. Sixthly, current reference values for diaphragmatic function are based on studies with small or moderate numbers of volunteers, which may limit their global generalizability. Finally, our study only included patients without respiratory impairment, precluding extrapolation of our findings to patients with respiratory distress or difficult weaning from mechanical ventilation following cardiac surgery.

As has been proposed by other authors in different clinical settings [1]. Despite these limitations, our study provides valuable insights into diaphragmatic function in the context of cardiac surgery.

Table 1: The main clinical-demographic characteristics of the study population.

		No	%
Age group	<20	4	4.0
	20-	15	15.0
	30-	8	8.0
	40-	20	20.0
	50-	26	26.0
	60-	17	17.0
	70+	10	10.0
Sex	Male	66	66.0
	Female	34	34.0
Body Mass Index categories	Underweight	8	8.0
	Normal	26	26.0
	Overweight	40	40.0
	Obese	26	26.0
Smoking	Yes	26	26.0
	No	60	60.0
	Ex-smoker	14	14.0
Diabetes mellites		34	34.0
History of hypertension		51	51.0

History of neuromuscular deficit	6	6.0
History of immune disease	2	2.0
History of neuromuscular disorder	2	2.0

Table 2: Demographic and pre-operative laboratory data.

	Mean	Standard Deviation	Percentile 25	Median	Percentile 75
Age	48.4	16.4	37	53	60
Weight	72.1	16.0	64	74	82
Hight	163.8	9.3	159	163	170
Body mass index	26.9	5.3	24.30	27.05	30.40
serum haemoglobin A1c	7.0	1.9	5.70	6.20	7.65
serum creatinine umol/l	96.2	54.8	71	88	106
serum calcium umol/l	2.1	0.1	2.00	2.10	2.20
serum magnesium umol/l	0.9	0.1	0.80	0.90	1.00
serum phosphorus umol/l	1.1	.2	1.00	1.10	1.30
AST u/l	26.7	14.8	15.35	23.00	31.00
ALT u/l	31.9	14.6	21	27	42
serum albumin gm/dl	3.4	.4	3.15	3.50	3.70
serum bilirubin total	9.7	5.5	5.70	8.05	11.35
serum bilirubin direct	2.6	1.6	1.65	2.15	2.90
serum haemoglobin gm/dl	13.6	2.0	12.05	13.80	15.00
platelets count	257.7	76.7	200	244	320
ejection fraction (EF)	.5	.1	.45	.50	.60

AST=aspartate trans-aminase, ALT=alanine trans-aminase.

Table 3: Descriptive statistics of diaphragmatic parameters pre- and post-operative.

	Mean	SD	Percentile 25	Median	Percentile 75
DT during expiration cm	0.24	0.07	0.19	0.23	0.27
Pre-operative DD cm	2.30	0.52	1.90	2.20	2.80
Pre-operative DTF%	0.40	0.13	0.31	0.38	0.44
Post-operative DD cm	1.39	0.42	1.10	1.30	1.65
Post-operative DTF%	0.23	0.10	0.17	0.22	0.29

DT: the diaphragmatic thickness during expiration, which represents the resting state of the diaphragm, was utilized as a baseline measure and to exclude any pre-operative diaphragmatic dysfunction. These results offer significant insights into the pre-and post-operative diaphragmatic function and will serve as the foundation for our study's conclusions.

Table 4: Pre-post changes in diaphragmatic function parameters.

	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference	Paired t-test	P value

				Lower	Upper		
DD in cm (pre-post)	0.91300	0.37857	0.03786	0.83788	0.98812	24.117	<0.001
DTF as per cent (pre-post)	0.16720	0.07284	0.00728	0.15275	0.18165	22.955	<0.001

Table 5: The relationship between diaphragmatic dysfunction (displacement and thickening fraction) and different outcome parameters using Pearson correlation (parametric).

	DD		**DTF**	
	Pearson Correlation	**p-value**	**Pearson Correlation**	**p-value**
Duration of operation in hours	.289**	0.004	0.107	0.291
CPB Time in minutes	.267**	0.007	.209*	0.037
Post-operative EF	0.140	0.163	.208*	0.038
At extubating time Rapid Shallow Breathing Index	-0.092	0.362	0.150	0.135
Total ventilation time in hours	0.194	0.054	0.138	0.170
Control mode time in hours	.203*	0.043	0.141	0.161
Spontaneous mode time in hours	.222*	0.026	0.129	0.199
Total ICU stay /days	0.194	0.054	-0.037	0.717
Ventilation free days	0.138	0.172	0.028	0.783

* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed). Diaphragmatic displacement = pre-post reduction in diaphragmatic displacement i.e., degree of diaphragmatic dysfunction in terms of diaphragmatic displacement. Diaphragmatic thickening fraction = pre-post reduction in diaphragmatic thickening fraction i.e., degree of diaphragmatic dysfunction in terms of diaphragmatic thickening fraction.

Table 6: The correlation analysis between diaphragmatic dysfunction and various outcome parameters using Kendall's tau b correlation (non-parametric).

	Kendall's tau_b			
	DD		**DTF**	
	Correlation Coefficient	**P value**	**Correlation Coefficient**	**P value**
Duration of operation in hours	.272**	0.000	.197**	0.005
CPB in minutes	.274**	0.000	0.114	0.097
Post-operative Ejection fraction	0.071	0.340	0.115	0.120
At extubating time RSBI	-0.004	0.950	0.062	0.368
Total ventilation time in hours	.151*	0.030	.176*	0.011
Control mode time in hours	.174*	0.012	.171*	0.014

spontaneous mode time in hours	0.068	0.358	.145*	0.048
Total ICU stay in days	.170*	0.025	.153*	0.043
Ventilation free days	0.068	0.377	.198**	0.009

* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed).

Table 7: Statistics of outcome parameters; ventilation parameters and ABG analysis at the time of extubating.

	Mean	**Standard Deviation**	**Percentile 25**	**Median**	**Percentile 75**
The time between ICU admission and the start of SBT / hours	16.6	12.1	9.0	13.5	19.0
Total ventilation time in hours **	23.5	12.5	15.1	19.9	27.1
Controlled mode time in hours **	21.9	12.2	13.8	18.0	25.0
Spontaneous mode time in hours **	1.41	0.66	1.00	1.25	1.71
Total ICU stay in days **	5.7	6.6	3.0	3.5	5.0
Ventilation-free days **	3.1	3.0	2.0	2.0	3.0
respiratory rate	21.0	4.1	18.0	20.0	24.0
RSBI	46.9	14.5	37.0	44.5	60.3
Partial O2 pressure (PaO2) mm Hg, ABG	109.8	27.2	90.0	104.5	128.5
Partial CO2 pressure (PCO2) mm Hg, ABG	36.0	5.0	33.6	37.0	38.0
Ph, ABG	7.4	0.1	7.4	7.4	7.4
Bicarbonate level (HCO3) mmol/l, ABG	23.2	2.0	21.7	22.8	24.6
serum lactate mmol/l	1.7	.7	1.3	1.5	2.1
GLASCO coma scale	15.0	.2	15.0	15.0	15.0
serum potassium mmol/l	4.2	.4	4.0	4.1	4.5
serum sodium mmol/l	142.2	3.9	140.0	142.0	144.0
hemoglobin level gm/dl	10.4	.8	9.8	10.4	10.8

** secondary outcome parameters.

Table 8: Hemodynamic parameters at the time of SBT.

	Mean	**Standard Deviation**	**Percentile 25**	**Median**	**Percentile 75**
Systolic blood pressure mmHg	129.6	17.5	115.0	130.0	140.0
Diastolic blood pressure mmHg	73.4	8.8	68.0	75.0	80.0
Heart rate, beat/mint	89.9	12.0	80.0	89.0	95.0

Central venous pressure (CVP) cm HO2	13.2	3.2	11.0	13.0	15.0
temperature	37.1	0.3	36.9	37.0	37.2
urine output ml/h	134.4	76.3	100.0	100.0	150.0

Table 9: Male /female differences with diaphragmatic parameters.

		Sex		**t-test**	**p-value**	**Mann-Whitney U test**
		Male (N=66)	**Female (N=34)**			
DD	**Mean**	0.95	0.85	1.225	0.223	Z= 0.925 P=0.355
	Standard Deviation	0.37	0.40			
	Percentile 25	0.70	0.60			
	Median	0.90	0.80			
	Percentile 75	1.10	1.20			
DTF	**Mean**	0.17	0.17	0.285	0.777	Z=1.262 P=0.207
	Standard Deviation	0.06	0.10			
	Percentile 25	0.13	0.11			
	Median	0.15	0.14			
	Percentile 75	0.19	0.18			

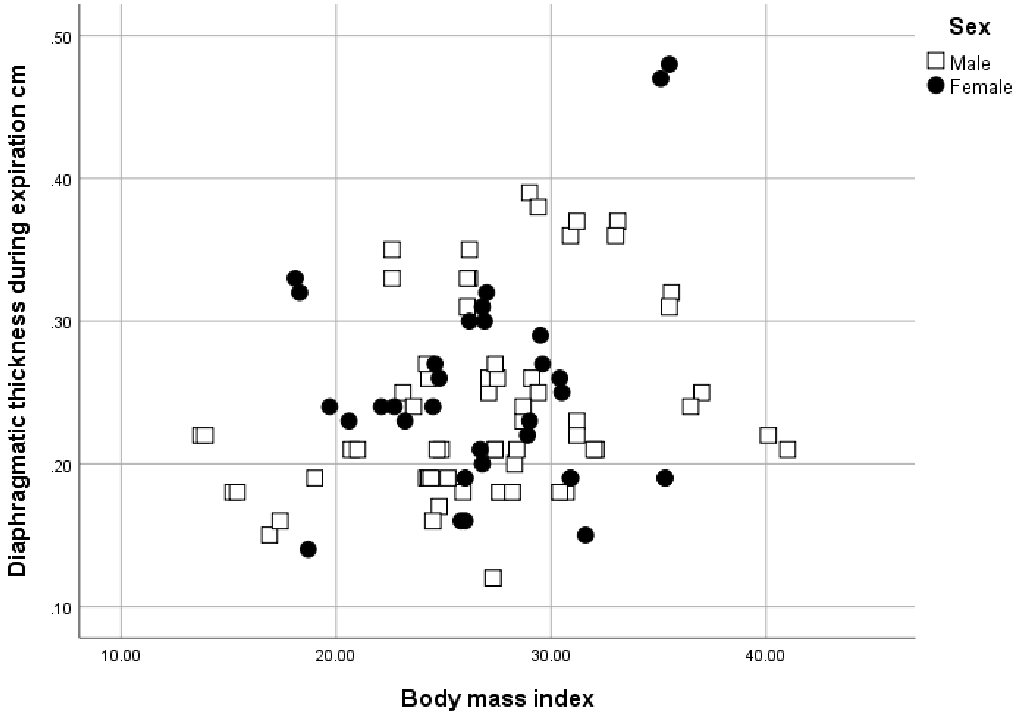

Figure 1: The correlation between male /female BMI and diaphragmatic thickness at rest.

Table 10: Incidence and degree of severity of post-operative diaphragmatic dysfunction.

		Post-operative DD cm		**Post-operative DTF**	
		<1	1+	≤ 0.20	>0.20
	No	17	83	49	51
Duration of operation in hours	Mean ± SD	6.41 ± 2.59	5.17 ± 1.19	5.56 ± 1.95	5.21 ± 1.1
	Median (IQR)	5.6 (1.4)	5 (1.75)	5 (1.25)	5.2 (1.6)
		t=1.940, p=0.069		**t=1.096, p=0.277**	
CPB Time in minutes	Mean ± SD	147.24 ± 70.09	105.22 ± 44.41	118.67 ± 60.53	106.29 ± 41.36
	Median (IQR)	122 (31)	95 (57)	108 (61)	97 (51)
		t=2.376, p=0.028		**t=1.198, p=0.234**	
Total ventilation time in hours	Mean ± SD	21.9 ± 11	23.85 ± 12.81	22.3 ± 11.23	24.69 ± 13.61
	Median (IQR)	18.8 (7.7)	20 (13.5)	18 (10.25)	21.25 (13.75)
		t=0.585, p=0.560		**t=0.959, p=0.340**	

*The use of the Mann-Whitney U test gave the same results regarding the significance.

6. Conclusions

In conclusion, our study aimed to assess diaphragmatic function using ultrasound in spontaneously breathing patients following uncomplicated cardiac surgery. We found that diaphragmatic function was reduced in almost all patients, with some patients exhibiting severe diaphragmatic dysfunction. Notably, we observed a positive correlation between diaphragmatic dysfunction and cardio-pulmonary bypass time, total ventilation time and total ICU stay which impact the overall outcomes. While diaphragm displacement and thickening showed a parallel reduction, displacement was easier to acquire and more reproducible in this population. Overall, our study highlights that ultrasonography-based determination of diaphragm function after cardiac surgery is a useful, feasible, non-invasive, bedside technique for ruling out severe diaphragmatic dysfunction, especially in the presence of respiratory distress. The findings of this study offer valuable insights into the distinct factors associated with cardiothoracic surgery that contribute to diaphragmatic dysfunction. These findings may guide future research and clinical interventions aimed at improving outcomes in post-cardiac surgery patients. Thus, this study underscores the importance of monitoring diaphragmatic function in this patient population, especially those with prolonged cardiopulmonary bypass time to facilitate optimal management and improved clinical outcomes.

7. Future research

Several research areas can be recommended for future investigation, such as the assessment of diaphragmatic relaxation. Previous research has shown that abnormalities in diaphragmatic relaxation can indicate impaired contractile performance, highlighting the importance of evaluating this aspect of diaphragmatic function [26-27]. While trans diaphragmatic pressure has traditionally been used to measure diaphragmatic relaxation rate, advances in technology now permit noninvasive evaluation of diaphragmatic sonography. Additional ultrasound techniques, such as 3D imaging and elastography, have yet to be widely implemented in clinical practice and critical care settings. Future investigations exploring these techniques may yield valuable insights into the diaphragmatic function and inform improved clinical management of patients.

8. Key messages

- Assess the diaphragm with the US after cardiac surgery in patients with respiratory distress or difficulty weaning from mechanical ventilation.
- Evaluate diaphragmatic respiratory excursion during spontaneous ventilation to identify dysfunction.
- More research is needed on the role and measurement of diaphragm thickening.
- Consider the inclusion of diaphragmatic assessment in bedside examination protocols.

9. Declarations

This study has not been previously published and is not under consideration for publication elsewhere. All authors have approved its publication, and it has been tacitly or explicitly approved by the responsible authorities where the work was carried out. If accepted, this study will not be published elsewhere in the same form, in English or any other language, including electronically, without the written consent of the copyright holder.

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Conflicts of interest

The authors declare that they have no conflicts of interest.
Availability of data and materials: All data and materials used in this study are available upon request. Please contact the corresponding author at ibrahim-shawky@outlook.com for more information.

Code availability

Not applicable.

Authors' contributions

The study was designed and led by Ibrahim S Omara, with contributions from Faten F Awadallah, Hassan K Nagi, Kamel A Mohamed, and Hazem H Abd El Haq. All authors have critically reviewed and approved the final draft and are responsible for the content and similarity index of the manuscript.

Ethics approval

This study was approved by NHI Egypt 670/2017.

Consent to participate

All participants provided written consent to participate in this study.

Consent for publication

Not applicable.

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