ISSN: 1607-8322, e-ISSN: 2220-5799 **Anaesthesia, Pain & Intensive Care**
Vol 28(5); October 2024 DOI: 10.35975/apic.v28i5.2555

ORIGINAL RESEARCH **CARDIAC ANESTHESIA**

Perioperative assessment of diaphragmatic dysfunction in cardiac surgery patients and its effect on outcome; a prospective observational study

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ABSTRACT

Objectives: While the assessment of the diaphragm in different clinical scenarios is quite frequent, there remains a scarcity of studies focused on assessing diaphragm dysfunction using ultrasound in cardiac surgery patients. We investigated the impact of cardiopulmonary bypass (CPB) surgery on diaphragm function and evaluated its effects on mechanical ventilation.

Methodology: A prospective cohort study, on 100 consecutive adult cardiac surgery patients, was conducted at National Heart Institute. Diaphragmatic displacement (DD) or excursion and diaphragmatic thickening fraction (DTF) were measured using motion-mode ultrasound during quite normal breathing pre-operatively (the day before surgery) and post-operatively on mechanical ventilation, while the patient was fully conscious and spontaneously breathing on continuous positive airway pressure (CPAP) mode + pressure support 10 cmH_2O. Then, the results were correlated to CBP time and important patient outcomes.

Results: Post-operative DD was significantly less as compared to the pre-operative reading; (1.39 ± 0.42 cm vs. 2.3 ± 0.52 cm; $P < 0.001$), as was DTF (23% ± 10% vs. 40% ± 13%; $P < 0.001$). The incidence of diaphragmatic dysfunction post-cardiac surgery was 17% by the definition of DD < 1 cm, and 49% by the definition of DTF ≤ 20%. DD was positively correlated with CBP time, as well as total ventilation time and ICU stay, indicating a negative impact on overall patient outcomes.

Conclusion: The results suggest that diaphragmatic dysfunction is positively correlated with CPB time, total ventilation time and ICU stay, underscoring the importance of monitoring diaphragmatic function in post-operative patients, who are difficult to wean from mechanical ventilation with apparently normal chest X-ray, particularly those with prolonged CPB time.

Keywords: cardiac surgery; cardiopulmonary bypass; diaphragm dysfunction; diaphragmatic displacement; diaphragm ultrasound; mechanical ventilation.

Citation: Omara ISM, Nagi HK, Mohamed KAA, Abd El Haq HH, Awdallah FF. Perioperative assessment of diaphragmatic dysfunction in cardiac surgery patients and its effect on outcome; a prospective observational study. Anaesth. pain intensive care 2024;28(5):816−823; **DOI:** 10.35975/apic.v28i5.2555

Received: June 28, 2024; **Reviewed:** September 04, 2024; **Accepted:** September 06, 2024

1. INTRODUCTION

The diaphragm is a crucial respiratory muscle, and its dysfunction can lead to respiratory complications and can prolong mechanical ventilation.[1,2] Numerous factors, such as hypotension hypoxia, sepsis and mechanical ventilation, have the potential to cause diaphragmatic dysfunction. [3,4,5] Consequently, assessing diaphragmatic function becomes crucial in various clinical scenarios.

Sonographic evaluation of the diaphragm has recently become popular in the ICU, due to its being noninvasive, easy-to-use, and accurate. It can assess both typical and atypical movements, diagnose diaphragmatic paralysis and detect recovery, screen for postoperative diaphragmatic dysfunction, and identify if the patient's spontaneous breathing efforts are synchronized with the ventilator.[1,6,7] It can measure diaphragmatic excursion, speed of diaphragmatic contraction,[8] and diaphragmatic thickness through the diaphragmatic thickening fraction (DTF), which helps assess diaphragmatic function and its contribution to respiratory workload.[9]

Postoperative diaphragmatic dysfunction is a prevalent complication following cardiac surgery, resulting in prolonged dependence on mechanical ventilation and respiratory distress.[1,5,10] Anomalous diaphragmatic movement is detected in conditions such as phrenic nerve injury, neuromuscular diseases,[3,4,5,8,11,12] and after cardiac surgery.[1,13] 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,[16] 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. Diaphragmatic dysfunction defined as vertical diaphragmatic displacement (DD) < 10 mm is an extubation failure predictor among patients in medical ICUs.[9] DTF is an additional diaphragmatic function parameter that exhibits statistically significant differences between patients who succeeded spontaneous breathing trials (SBT) and those who couldn't pass. A DTF cutoff exceeding 36% was associated with a successful SBT with high sensitivity, specificity, positive predictive value, and negative predictive value.[17]

1.2. Study objectives

This study aimed to assess diaphragm function using ultrasound in postoperative cardiac surgery patients during mechanical ventilation weaning. The incidence of diaphragmatic dysfunction was measured. Cardiac surgery risk factors are co-related to postoperative diaphragm dysfunction and its impact on patient outcomes.

2. METHODOLOGY

2.1. Study design & patient population

This was a prospective cohort study conducted at National Heart Institute, Giza, Egypt. The research committee used the Cochrane formula to calculate the essential sample size for the required level of precision, confidence level and the estimated proportion of the attribute present in the population. According to Aguirre et al.,[15] the prevalence of diaphragmatic dysfunction after cardiac surgery was up to 60%. So, the estimated sample size according to the equation was 96 patients. After adding 10% dropout, the calculated sample size was 100. Adult patients aged ≥ 18 y were consecutively enrolled and were admitted to adult cardiac surgical ICU (CSICU). 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 anesthesia, propofol 0.2-0.5 mg/kg IV, fentanyl 5-25 µg/kg/h infusion, sevoflurane 0.5-1%, and rocuronium 0.6-0.8 mg/kg for induction, and atracurium 0.06-0.12 mg/kg/h or cisatracurium for maintenance. During the postoperative phase, all patients followed a standardized weaning protocol from mechanical ventilation.

2.2. Patient selection

Patients included were aged 18 y 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, had stable cardiovascular status, no or minimal vasopressor use, and normal metabolic status.

Patients were excluded if they refused to participate, or they had a history of diaphragmatic paralysis or neuromuscular disease impacting the diaphragm or pneumothorax evidence. Patients with low EF ≤ 30%, post-operative cerebrovascular stroke, or reintubation due to cardiac arrest, arrhythmias, or failure, were excluded from outcome correlation were also excluded.

2.3. Materials and Measurements

Transthoracic ultrasonography with SonoSite M-Turbo Ultrasound system B (2012-09, WA 98021 USA, SN: WK19HL) was performed at the bedside in both B- and

M-modes to evaluate diaphragmatic displacement and thickness in patients undergoing cardiac surgery. The patients were examined in a semi-recumbent position at 45°, and the ultrasound probe was placed in the right anterior axillary line between the seventh and ninth intercostal spaces to target the posterior third of the corresponding hemidiaphragm perpendicularly,[18] or with an angle not less than 70°, depending on the case difficulty. 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 6-15 MHz ultrasound linear transducer in M-mode. The diaphragm in the ZOA is identified as a hypoechoic (dark) layer between two hyperechoic (bright) and parallel lines representing the pleural and peritoneal membranes. The costophrenic sinus, which is located 0.5-2 cm below the ZOA, was used as a landmark to pinpoint the transition zone between the lung cranially and the liver caudally. The measurement of the diaphragm thickness was from the middle of the pleural line to the middle of the peritoneal line, [17, 20] then calculating the diaphragmatic thickness fraction (DTF) as a percentage using the following formula:

(thickness at end inspiration - thickness at end-expiration) / thickness at end-expiration.

Measurements were made at two time points; First - pre-operatively the day before operation during quite normal breathing. DD and DTF were recorded. Second - post-operatively while the patient was on mechanical ventilation during SBT. DD and DTF were recorded.

Diaphragmatic dysfunction was defined as DD < 10 mm and /or DTF ≤ 20%.[21] According to this definition, patients will be sub-grouped into two categories: those with diaphragmatic dysfunction and those without. The dysfunction group will be correlated to cardiopulmonary bypass time, total ventilation time, and ICU length of stay.

2.4. Data collection

We collected the data at three time-points.

First: Day before the operation; baseline demographic characteristics, medical history, key laboratory results, cardiac ejection fraction (EF), and diaphragm measurements.

Second: During the surgery; intraoperative cardiopulmonary bypass (CPB) time, aortic cross-clamp time, and any intraoperative hypotension or deep hypothermic circulatory arrest (DHCA) during the operation.

Third: 6-12 h post-operatively; diaphragm measurements (DD and DTF) recorded during a spontaneous breathing trial. Lab tests and arterial blood gas (ABG) were recorded before extubation.

The right hemidiaphragm was more feasible and practical in this patient category. Evaluating the left hemidiaphragm posed technical challenges in post-cardiac surgery patients, particularly those who had undergone coronary artery bypass grafting (CABG) procedures, due to the presence of intercostal tubes and potential pleural effusion.

2.5. Statistical analysis

Data was analyzed with IBM SPSS software. Descriptive statistical measures such as frequency, per cent, mean, and standard deviation were employed to describe the results. The reported outcomes were presented as mean ± standard deviation, median (IQR 25th to 75th percentiles), or number (proportion). Utilizing Spearman correlation coefficient (rho) and Kendall's tau-b, we evaluated the correlation between variations in DD and DTF. The Mann-Whitney 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 $P < 0.05$.

3. RESULTS

3.1. Patients' characteristics

104 adult patients admitted to the cardiac surgery intensive care unit (CSICU) following cardiac surgery were enrolled during the study period. 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. Table 1 shows the study population demographic data, including age group, gender distribution, BMI category, and history of smoking, diabetes, hypertension, neuromuscular deficit, and a history of auto-immune disease (systemic lupus erythematosus).

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

Parameters		No (%)
Age group (y)	18-20	4 (4)
	20-	15 (15)
	30-	8 (8)
	40-	20 (20)
	50-	26 (26)
	60-	17 (17)
	70+	10 (10)
Gender	Male	66 (66)
	Female	34 (34)
Body Mass Index categories	Underweight	8 (8)
	Normal	26 (26)
	Overweight	40 (40)
	Obese	26 (26)
Smoking	Yes	26 (26)
	No	60 (60)
	Ex-smoker	14 (14)
Diabetes mellites		34 (34)
History of hypertension		51 (51)
History of neuromuscular deficit		6 (6)
History of immune disease		2 (2)
History of neuromuscular disorder		2 (2)

Table 2 shows the main demographic features were mean age (48.4 ± 16.4 y), and mean BMI (26.9 ± 5.3 kg/m^2). Preoperative labs were mostly normal or near normal because most of the patients were electively operated and well-prepared. Preoperative EF was normal in most of the patients (50 ± 10%).

Table 3 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 [0.9130 ± 0.37857; P < 0.001]. Furthermore, the analysis showed a significant decrease in DTF after the operation, indicating diaphragmatic dysfunction [0.16720 ± 0.07284, P > 0.001]. These results imply that the surgical procedure has significantly affected diaphragmatic function.

Table 2: Demographic and pre-operative laboratory data.

Parameters	Mean ± (SD)	Median (IQR)
Age (y)	48.4 ± 16.4	53 (37 – 60)
Weight (kg)	72.1 ± 16	74 (64 – 82)
Height (cm)	163.8 ± 9.3	163 (159 – 170)
Body mass index (kg/m^2)	26.9 ± 5.3	27.05 (24.3 – 30.4)
Serum HbA1c (%)	7.0 ± 1.9	6.20 (5.7 – 7.65)
Serum creatinine (µmol/L)	96.2 ± 54.8	88 (71 – 106)
Serum calcium (µmol/L)	2.1 ± 0.1	2.10 (2 – 2.2)
Serum magnesium (µmol/L)	0.9 ± 0.1	0.90 (0.8 – 1)
Serum phosphorus (µmol/L)	1.1 ± 0.2	1.10 (1 – 1.3)
AST U/L	26.7 ± 14.8	23 (15.35 – 31)
ALT U/L	31.9 ± 14.6	27 (21 – 42)
Serum albumin (gm/dL)	3.4 ± 0.4	3.5 (3.15 – 3.7)
Serum bilirubin, total (µmol/L)	9.7 ± 5.5	8.05 (5.7 – 11.35)
Serum bilirubin, Direct (µmol/L)	2.6 ± 1.6	2.15 (1.65 – 2.9)
Serum hemoglobin (gm/dL)	13.6 ± 2	13.80 (12.05 – 15)
Platelets count	257.7 ± 76.7	244 (200 – 320)
Ejection fraction (EF)	.50 ± 0.20	0.50 (0.45 – 0.60)

AST; aspartate trans-aminase, ALT; alanine trans-aminase. Data presented as mean ± SD,

Median with interquartile range (IQR).

The incidence of diaphragmatic dysfunction was 17% of patients based on DD, and 49% of patients based on DTF. 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

Table 3: pre-post changes in diaphragmatic function parameters.

Parameter	Mean ± SD	Std. Error Mean	95% CI		Paired t-test	P value
			Lower	Upper		
DD in cm (pre-post)	0.913 ± 0.37857	0.03786	0.83788	0.98812	24.117	< 0.001
DTF as % (pre-post)	0.1672 ± 0.07284	0.00728	0.15275	0.18165	22.955	< 0.001

P < 0.05 considered as significant; DD - diaphragm displacement; DTF - diaphragmatic thickening fraction

Table 4: Incidence of post-operative diaphragmatic dysfunction and its correlation to surgery-related potential risk factors.

Risk factors		Post-operative DD cm		Post-operative DTF	
		<1	1+	≤ 0.20	>0.20
		17	83	49	51
Duration of operation (h)	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 (min)	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.*

between the two groups regarding CPB in min (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). The result was also verified by using the non-parametric Mann-Whitney U test. There was no significant difference between the two groups regarding the duration of operation or total ventilation time (P = 0.069, P = 0.560 respectively).

Table 5 presents the non-parametric correlation analysis between diaphragmatic dysfunction (measured as DD and DTF) and various outcome parameters using Kendall's tau-b correlation coefficient. We used a non-parametric test due to mild skewness in the distribution of these variables. Significant positive correlations were observed between diaphragmatic dysfunction (DD and the duration of operation (P < 0.01) and CPB time (P < 0.01). Additionally, positive correlations were observed with the total ventilation time, control mode time, and total ICU stay (P < 0.05). Diaphragmatic dysfunction in terms of DTF, significant positive correlations with the duration of operation and ventilation-free days (P < 0.01) was observed. 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 5: the correlation analysis between diaphragmatic dysfunction and various outcome parameters using Kendall's tau b correlation (non-parametric).

Parameters	Kendall's tau_b			
	DD		DTF	
	Correlation Coefficient	P value	Correlation Coefficient	P value
Duration of operation (h)	.272**	0.000	.197**	0.005
CPB (min)	.274**	0.000	0.114	0.097
Total ventilation time (h)	.151*	0.030	.176*	0.011
Control mode time (h)	.174*	0.012	.171*	0.014
spontaneous mode time (h)	0.068	0.358	.145*	0.048
Total ICU stay (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 6: Statistics of outcome parameters; ventilation parameters and ABG analysis at the time of extubation.

Parameters	Mean ± SD	Median (IQR)
Time between ICU admission and the start of SBT (h)	16.6 ± 12.1	13.5 (9 – 19)
Total ventilation time (h)**	23.5 ± 12.5	19.9 (15.1 – 27.1)
Controlled mode time (h)**	21.9 ± 12.2	18 (13.8 – 25)
Spontaneous mode time (h)**	1.41 ± 0.66	1.25 (1 – 1.71)
Total ICU stay (days)**	5.7 ± 6.6	3.5 (3 – 5)
Ventilation-free (days)**	3.1 ± 3	2 (2 – 5)
RSBI	46.9 ± 14.5	44.5 (37 – 60)
PaO_2 (mmHg)	109.8 ± 27.2	104.5 (90 – 128)
PCO_2 (mmHg)	36 ± 5	37 (33.6 – 38)
Ph	7.4 ± 0.1	7.4
HCO_3 (mmol/L)	23.2 ± 2	22.8 (21.7 – 24.6)
Serum lactate (mmol/L)	1.7 ± 0.7	1.5 (1.3 – 2.1)

*** Secondary outcome parameters*

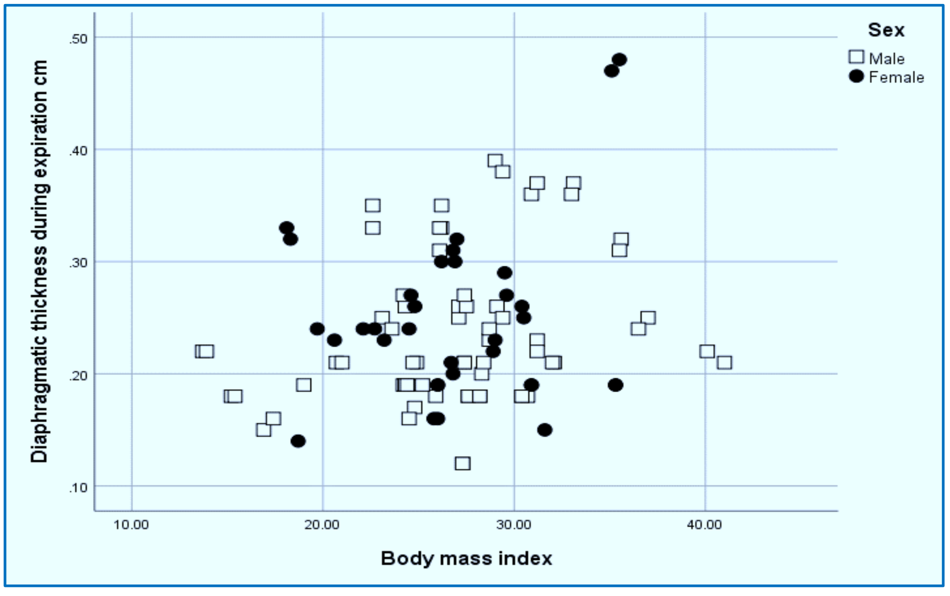

Figure 1: Correlation between male /female BMI and diaphragmatic thickness at rest.

Table 6 shows that the time between ICU admission and SBT was 16.6 ± 12.1 hours. Total ventilation hours were 23.5 ± 12.5. The mean ICU stay was (5.7 ± 6.6) days. The hemodynamic parameters were maintained within normal ranges using inotropes or vasodilators.

Table 7 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 gender-based differences in diaphragmatic function based on these measures.

The scatter plot shows that there is a positive association between BMI and diaphragmatic

Table 7: Male /Female differences with diaphragmatic parameters

Parameter		Gender		t-test	P-value	Mann-Whitney U test
		Male 66 (66%)	Female 34 (34%)			
DD	Mean ± SD	0.95 ± 0.37	0.85 ± 0.40	1.225	0.223	Z = 0.925
	Median (IQR)	0.90 (0.70 – 1.10)	0.80 (0.60 – 1.20)			P = 0.355
DTF	Mean ± SD	0.17 ± 0.06	0.17 ± 0.10	0.285	0.777	Z = 1.262
	Median (IQR)	0.15 (0.13 – 0.19)	0.14 (0.11 – 0.18)			P = 0.207

P < 0.05 considered as significant; DD - diaphragm displacement; DTF - diaphragmatic thickening fraction 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.

4. DISCUSSION

In a population of adult patients aged ≥ 18 y, 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 indicate 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. Diaphragm displacement appears to be superior to thickening for bedside assessment. And there is a positive association between BMI and diaphragmatic thickness at rest, especially in males.

Diaphragmatic dysfunction significantly affects ventilator weaning time, extubation success, and ICU length of stay in cardiac surgery patients.[13,22] However, the diaphragm mechanics pattern characterization after cardiac surgery has not been well described till now. Fortunately, Tralhão et al. studied diaphragmatic function in this cohort in timeline manner and compared the pre-operative measurements with a series of post-operative measurements daily 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. studied the diaphragm function post-cardiac surgery in patients with difficult weaning from the ventilator (more than 7 days on mechanical ventilation) and compared it with patients who extubated smoothly within 12 h postoperatively.[1] In the latter group, they also found a reduction in diaphragmatic function on the 2nd or 3rd postoperative day.[1]

Noteworthy distinctions exist in our study. While excursion measurements (excluding muscle thickness) were conducted post-extubation during forced expiration and maximal inspiration, our investigation involved patients breathing normally in CPAP mode with 10 cm H_2O pressure support during SBT. This accounts for the disparity between the 40% diaphragmatic displacement reduction observed in the referenced study and the 17% reduction (< 1 cm) found in our study. We deliberately avoided forced inspiration due to postoperative pain impairing chest expansion and the vital capacity, which varies significantly among patients. Our approach allowed us to derive values by averaging three consecutive respiratory cycles, minimizing selection bias. Our analysis showed synchronized changes between muscular thickening and displacement. However, obtaining suitable acoustic windows for thickening imaging remains challenging. In contrast, excursion or displacement emerges as a more accessible metric for assessing diaphragm function in spontaneously breathing patients. Previous studies have demonstrated good reproducibility for each parameter when measured individually.[10,21] Given the diaphragm’s small thickness, precise cursor placement is critical to avoid proportionately greater errors in thickening percentage. Consequently, utilizing excursion rather than thickening may be preferable for assessing diaphragmatic function, considering potential measurement errors associated with the latter.

4.1. Strengths of the study

Our study presents several notable strengths. Firstly, it is one of a limited number of studies to investigate diaphragm behavior, utilizing ultrasound as an 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 assessing diaphragmatic function is both achievable and replicable 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 effect on diaphragmatic function. These findings offer valuable insights into the side effects of cardiac surgery on diaphragmatic function, which may inform future clinical practice and research.

5. LIMITATIONS

Several limitations of our study must be acknowledged. First; the relatively small cohort and single-center design may limit generalization of our findings. Second; given the small sample size, caution is warranted when interpreting the absence of association between variables such as intraoperative hypotension for a certain time or DHCA, and diaphragmatic dysfunction. Third; diaphragm thickness varies at different intercostal spaces, and different methods of measurement may yield different results; thus, precise definitions of measurement techniques are essential. Fourth; 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. Fifth; diaphragmatic displacement is affected 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. Sixth; 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. Despite these limitations, our study provides valuable insights into diaphragmatic function in the context of cardiac surgery.

5. CONCLUSION

In conclusion, we found that diaphragmatic function was reduced in almost all patients post-operatively, with some patients exhibiting significant reduction, enough to be addressed as diaphragmatic dysfunction. Notably, we found a positive correlation between diaphragmatic dysfunction and cardio-pulmonary bypass time, total ventilation time, and total ICU stay which impact the overall outcomes. Despite parallel reduction of both diaphragmatic displacement and thickening, measuring diaphragm displacement was more achievable and more replicable in this population. Overall, our study highlights that ultrasonography-based assessment of diaphragm function after cardiac surgery serves as a valuable, feasible, non-invasive bedside technique for excluding severe diaphragmatic dysfunction, especially in the presence of respiratory distress with apparently normal chest x-rays. The findings of this study offer valuable insights into potential risk factors associated with cardiothoracic surgery that contribute to diaphragmatic dysfunction, especially prolonged cardiopulmonary bypass time. These findings may guide future research and clinical studies, especially in cardiac Centers operating off-pump surgeries to assess diaphragm function without exposure to cardiopulmonary bypass and then compare the results to this study. Thus, this study underscores the importance of monitoring diaphragmatic function to facilitate optimal management and improved clinical outcomes in post-cardiac surgery patients.

6. Future research

Several research areas can be recommended for future investigation, such as the assessment of diaphragm muscle 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. 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.

7. 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.

8. Availability of data

All data and materials used in this study are available with the corresponding author.

9. Conflict of interests

The authors declare that they have no conflicts of interest. This study did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

10. Ethics approval

This study was approved by NHI Egypt 670/2017. Clinical trials.gov Identifier: NCT03126838

11. Consent to participate

All participants provided written consent to participate in this study.

12. 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.

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