Original Article

Investigation of diaphragmatic motion and projected lung area in diaphragm paralysis patients using dynamic chest radiography

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Background: Dynamic chest radiography (DCR) is a novel and supplementary examination in respiratory diseases. The investigation of other chest diseases using DCR has been explored, identifying a certain correlation of the pulmonary function test (PFT). However, there is a lack of research using DCR parameters to quantitatively evaluate chest disease. The purpose of this study was to investigate the diagnostic value of DCR for diaphragm paralysis (DP).

Methods: This retrospective study recruited 118 participants, which include 18 patients with DP, 48 healthy volunteers, and 52 patients with respiratory disease. Comparison of DCR parameters relationships among 3 groups was performed using one-way analysis of variance (ANOVA) and Kruskal-Wallis test. The receiver operating characteristic (ROC) curve was used to compare the value of the DCR parameters to diagnose DP.

Results: The differences of excursion of diaphragm (ED) in normal (nb) and forced breathing (fb), ED(fb)–ED(nb), and the parameters of projected lung area (PLA) in inspiratory (ins) and expiratory phase (exp), PLA.exp(fb), PLA.ins(fb)–PLA.ins(nb), and PLA.exp(fb)–PLA.exp(nb) among the 3 groups were statistically significant. The highest area under the curve (AUC) of right-side parameter was the ED(fb)–ED(nb), for which the AUC was 0.8950 [95% confidence interval (CI): 0.7618–1.000], whereas that of the left-side parameter was ED(fb), for which the AUC was 0.9176 [95% confidence interval (CI): 0.8524–0.9829].

Conclusions: The parameters of DCR have good diagnostic value for DP. The highest diagnostic efficiency for DP on the right side is the ED(fb)–ED(nb), with a sensitivity of 95% and a specificity of 78.6%, whereas on the left side is ED(fb), with a sensitivity of 80% and a specificity of 88.2%.

Keywords: Diaphragm paralysis (DP); chest; digital radiography; dynamic chest radiography (DCR)

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Introduction

The diaphragm is the most important skeletal muscle for human breathing and is innervated by the phrenic and vagus nerves. The phrenic nerve originates from the C3–C5 nerve root, mainly from the C4 nerve root (1). Patients with diaphragm paralysis (DP) are often characterized by dyspnea, vital capacity, and decreased ventilation (2). Their respiratory function is affected generally, and in severe cases, it will develop into systemic diseases such as respiratory failure. Transdiaphragmatic pressure measurement is the gold standard for the diagnosis of DP, but it is an invasive, painful and lengthy procedure, making it difficult for patients to accept. Dynamic chest radiography (DCR) as a novel, high-speed, low-dose pulsed X-ray flat plate detection device (3), can collect dynamic images in different states. After the analysis and processing through the post-processing workstation, we can obtain the excursion of diaphragm (ED), projected lung area (PLA), and PLA rate of change from the dynamic images. It has important clinical value in evaluation of diaphragm movement, chest wall movement, airway diameter, bone joint, lung ventilation/perfusion, and so on (4-6). Previous studies have confirmed its clinical value in restrictive (7) and obstructive (8) pulmonary diseases, pulmonary vascular diseases (9), and establishing a dynamic digital radiography-forced vital capacity (DDR-FVC) estimation model (10). The purpose of this study was to explore the diagnostic value of DCR for DP. We present this article in accordance with the STARD reporting checklist (available at https://qims.amegroups.com/article/view/10.21037/qims-24-90/rc).

Methods

Population selection

The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). This retrospective study was approved by the Scientific Research Ethics Review Committee of The First Affiliated Hospital of Guangzhou Medical University (No. G-59, 2023). Informed consent was provided by all the participants. DP and respiratory disease patients were recruited from June 2022 to September 2023, whereas healthy screening volunteers were recruited from June 2022 to October 2022. Common inclusion criteria for all the participants were as follows: (I) ≥18 years old adults with informed consent; (II) scheduled for DCR; (III) comprehension and ability to follow instructions for normal and forced breathing (fb); (IV) no status of pregnancy, potential pregnancy, or lactation. The additional inclusion criteria for DP patients were as follows: (I) clinical diagnosis of DP based on clinical course, symptoms, electromyography, or transdiaphragmatic ultrasound; (II) no evidence of other respiratory disease. For healthy screening volunteers: (I) no combination of neuromuscular or skeletal disorders; (II) never smokers; (III) no past medical history of respiratory diseases. For respiratory disease participants: (I) clinical diagnosis of common respiratory diseases, such as chronic obstructive pulmonary disease (COPD), interstitial lung disease (ILD).

Therefore, a total of 118 individuals, including 18 patients with DP, 48 healthy volunteers, and 52 patients with respiratory disease, were enrolled in this study. According to the affected diaphragm classified into left and right groups, there were 13 patients with DP involving both sides, 4 with the left side, and 1 with the right side. Totally, 14 affected diaphragms of the right side and 17 affected diaphragms of the left side were classified. Additionally, according to the classification of respiratory diseases, there were 20 cases of pulmonary arterial hypertension (PAH), 14 cases of COPD, 4 cases of ILD, 6 cases of infectious pulmonary disease, and 8 cases of other respiratory disease. Ultimately, we classified a DP group and a non-DP group which includes 2 subgroups, healthy volunteers, and patients of respiratory disease.

DCR

DCR imaging using a Digital Radiography X-ray System (KONICA MINOLTA Inc., Tokyo, Japan), composed of a flat-panel detector and a pulsed X-ray generator, was performed in the posteroanterior standing position. All the participants took normal breath and forced breath separately (*Figures 1,2*). We required at least 3 cycles of normal breathing (nb) and mixed inspiratory/expiratory phases in fb. Conditions for DCR examination were different from the previous reports: tube voltage: 110 kV; tube current:100 mA; pulse duration of pulsed X-ray: 2 ms; source-to-image distance:1.8 m; additional filter: 1.0 mm aluminum + 0.5 mm copper; exposure time: 7–15 s. The additional filter was used to remove soft X-rays. The dynamic image data, captured at 15 frames/s, were synchronized with the pulsed X-ray, which could prevent excessive radiation exposure to the participants within the tolerant range from 0.3 to 1.0 mGy. The effective dose was approximately 0.2 mSv.

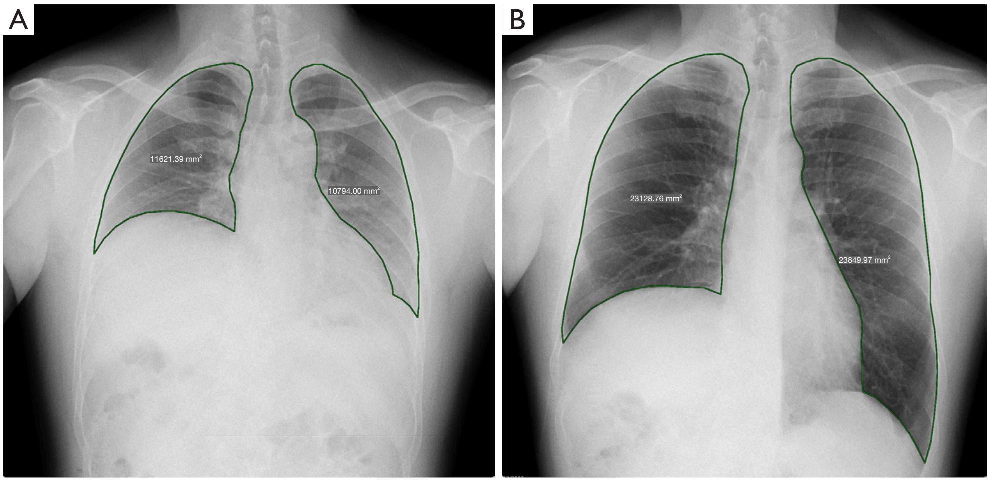

Figure 1 PLA of DP patient (right). (A) Expiratory phase in forced breathing; (B) inspiratory phase in forced breathing. PLA, projected lung area; DP, diaphragm paralysis.

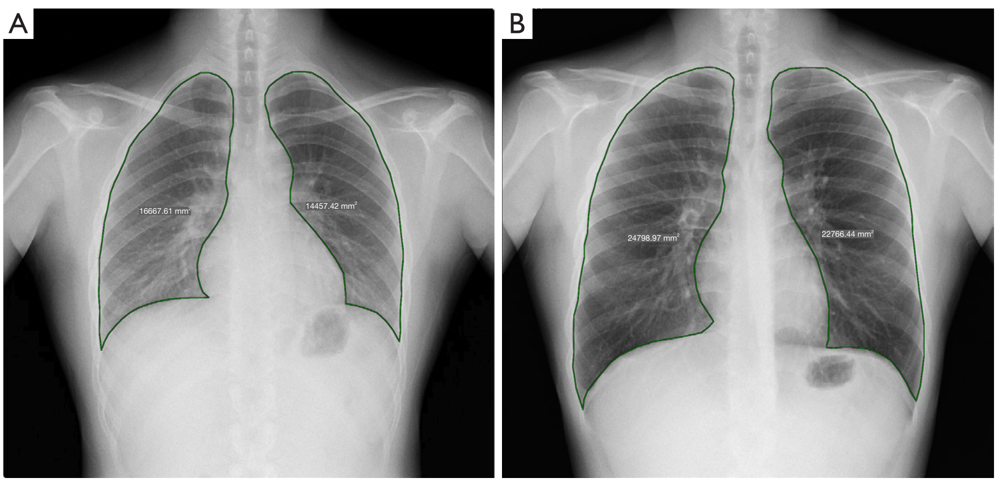

Figure 2 PLA of healthy volunteer. (A) Expiratory phase in forced breathing; (B) inspiratory phase in forced breathing. PLA, projected lung area.

Image analysis

DCR images were automatically transmitted to IWS post-processing workstation and analyzed using prototype software (KONICA MINOLTA Inc., Japan) which can indicate diaphragmatic motion, and mark the bilateral apex of the lung and superior plane of diaphragm (*Video 1*). The template matching technique was used to automatically track the highest point of bilateral diaphragms throughout the respiratory phase and calculate the vertical excursion of bilateral diaphragms. Bilateral lung fields of DCR images were contoured with full automation by post-processing software, and PLA were automatically measured (*Figure 3*). Richly experienced technologists and radiologists manually contoured the border of bilateral lung fields with the exclusion of both heart and mediastinum. DCR images were evaluated independently and randomly by 2 radiologists who were blinded to the clinical information of all individuals. If the results of evaluation were inconsistent between the 2 radiologists, a final consensus was reached through negotiation.

Video 1 Dynamic process of forced breathing in a patient with right diaphragm paralysis.

Statistical analysis

For this study, all statistical analysis using the software SPSS 27.0 (IBM Corp., Armonk, NY, USA) and GraphPad Prism 9.5.1 (GraphPad Software, San Diego, CA, USA), and $P<0.05$ was regarded as statistically significant. Data that conformed to normal distribution were expressed as the mean ± standard deviation (SD), one-way analysis of variance (ANOVA) and homogeneity of variance test were used for comparison between multiple groups, whereas the skew distribution data were expressed as the median (interquartile range), and Kruskal-Wallis test was used for comparisons between 3 groups. The receiver operating characteristic (ROC) curve was used to evaluate the efficacy

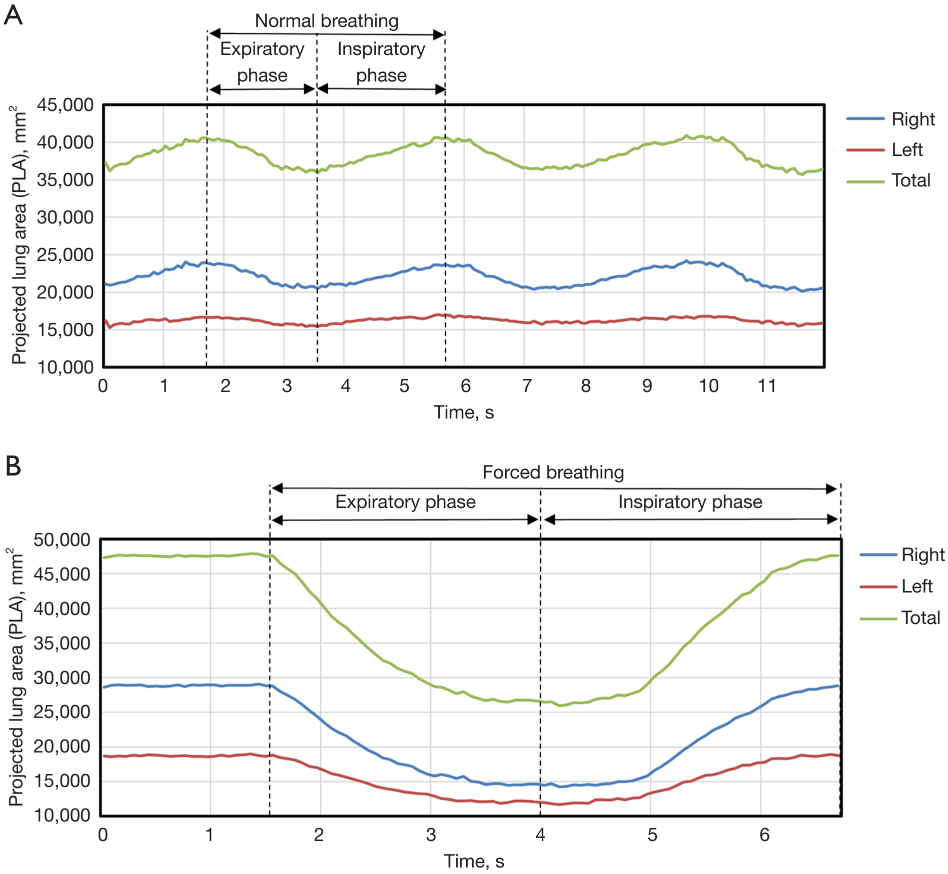

Figure 3 Patient of DP. (A) PLA in normal breathing; (B) PLA in forced breathing. DP, diaphragm paralysis; PLA, projected lung area.

Table 1 Demographic data

Parameter	Diaphragm paralysis	Healthy volunteer	Respiratory disease	P value
Sex (male)	14 (77.8%)	14 (29.2%)	24 (46.2%)	0.02
Age (years)	55.72±14.90	50.00 (9.00)	50.50 (22.00)	0.043
Weight (kg)	63.50±14.01	58.49±8.14	59.00 (16.25)	0.373
Height (cm)	168.5 (6.75)	157.02±8.11	162.35±7.34	<0.001
BMI (kg/m^2)	23.19±5.46	23.73±2.89	22.33±3.62	0.116

Data are presented as No. (%), the mean ± standard deviation or median (interquartile). BMI, body mass index.

Table 2 Comparison of the DCR parameters among the 3 groups

DCR parameter	Side	Diaphragm paralysis	Healthy volunteer	Respiratory disease	P value
ED(nb) (mm)	Right	11.86±8.31	14.99±4.13	16.96±3.73	0.015
	Left	12.91±4.91	18.24±4.72	19.26±4.12	<0.001
ED(fb) (mm)	Right	24.37±19.05	58.02±12.56	39.60 (19.8)	<0.001
	Left	26.70±9.52	57.64±11.63	41.20 (17.4)	<0.001
ED(fb)−ED(nb) (mm)	Right	9.40 (5.50)	43.03±11.49	23.60 (14.30)	<0.001
	Left	10.80 (9.00)	39.41±10.16	22.20 (15.50)	<0.001
PLA.ins(nb) (mm^2)	Right	20,156.77±6,557.60	18,723.66±3,101.75	19,472.64 (3,588.34)	0.312
	Left	16,142.21±5,345.52	14,854.66±2,952.05	15,427.28 (3,196.70)	0.196
PLA.exp(nb) (mm^2)	Right	18,478.86±6,886.72	1,6912.20±2,983.89	16,859.28 (3,518.12)	0.693
	Left	14,141.93±5,727.70	13,631.95±2,699.90	13,738.01 (3,097.26)	0.957
PLA.ins(fb) (mm^2)	Right	21,361.17±6,584.00	21,393.96±3,197.66	21,479.89±5,215.82	0.991
	Left	17,031.26±5,125.96	17,131.52±3,115.08	17,705.48 (3,263.10)	0.257
PLA.exp(fb) (mm^2)	Right	17,195.86±6,625.32	12,828.12±2,261.04	14,602.76 (4,442.62)	0.001
	Left	12,819.16±5,644.00	10,033.81±2,019.57	11,514.80 (3,092.94)	0.002
PLA.ins(fb)−PLA.ins(nb) (mm^2)	Right	1,132.97±1,395.90	2,670.29±1,106.42	1,713.80 (7,213.92)	0.001
	Left	889.04±1,132.33	2,276.85±926.97	1,719.60 (1,644.60)	<0.001
PLA.exp(fb)−PLA.exp(nb) (mm^2)	Right	−921.08 (1,539.62)	−4,084.08±1,349.54	−2,226.85±1,317.45	<0.001
	Left	−1,322.77±1,845.66	−3,598.15±1,361.02	−1,949.40±1,207.01	<0.001

Data are presented as the mean ± standard deviation, median (interquartile). DCR, dynamic chest radiography; ED, excursion of diaphragm; PLA, projected lung area; nb, normal breathing; fb, forced breathing; ins, inspiratory phase; exp, expiratory phase.

of diagnosis value of DP in DCR and visual assessment. The agreements in evaluation of DP between 2 radiologists were assessed using Cohen kappa (k) coefficients.

Results

Clinical data and demographic characteristics of patients

The demographic characteristics of all participants are summarized in *Table 1*. According to the above criteria, 118 participants were recruited in this study, including 18 patients with DP, 48 healthy volunteers, and 52 patients with respiratory disease. Among the 3 groups, there were statistical differences in age and height, but no statistical differences in weight and body mass index (BMI).

Comparison of ED and PLA area among 3 groups

Table 2 summarizes the measurement of ED and PLA using DCR. The bilateral ED during normal and forced

Table 3 Multiple comparison of DCR parameters among the 3 groups

DCR parameter	Side	DP patients to healthy volunteers	DP patients to respiratory disease patients	Healthy volunteers to respiratory disease patients
ED(nb) (mm)	Right	0.474	0.119	0.042
	Left	<0.001	<0.001	0.253
ED(fb) (mm)	Right	<0.001	0.007	<0.001
	Left	<0.001	<0.001	<0.001
ED(fb)−ED(nb) (mm)	Right	<0.001	0.006	<0.001
	Left	<0.001	0.005	<0.001
PLA.exp(fb) (mm^2)	Right	0.002	0.372	0.001
	Left	0.016	0.937	0.001
PLA.ins(fb)−PLA.ins(nb) (mm^2)	Right	<0.001	0.035	0.016
	Left	<0.001	0.002	0.107
PLA.exp(fb)−PLA.exp(nb) (mm^2)	Right	<0.001	0.039	<0.001
	Left	<0.001	0.106	<0.001

DCR, dynamic chest radiography; DP, diaphragm paralysis; ED, excursion of diaphragm; nb, normal breathing; fb, forced breathing; PLA, projected lung area; ins, inspiratory phase; exp, expiratory phase.

respiration and the difference of the ED between normal and forced breathing [ED(fb)−ED(nb)] of DP patients were lower than those of healthy volunteers and respiratory disease patients, and there was a statistical difference among the 3 groups (P<0.05); bilateral ED(fb) and ED(fb)−ED(nb) had a statistical difference in a pairwise comparison among the 3 groups (P<0.05) (*Table 3*). During nb, the PLA of DP patients in inspiratory and expiratory phase was slightly larger than that of healthy volunteers and respiratory disease patients, but there was no statistical difference among the 3 groups (P>0.05). During fb, bilateral PLA in the inspiratory phase had no statistical difference among the 3 groups (P>0.05), whereas that of DP patients in the expiratory phase was larger than the others and showed a statistical difference among the 3 groups. The difference of the PLA between normal and fb in the inspiratory/expiratory phase [PLA.ins(fb)−PLA.ins(nb), PLA.exp(fb)−PLA.exp(nb)] has a statistical significance among the 3 groups (P<0.05).

The value of the DCR parameters and visual assessment to diagnose DP

To investigate the diagnostic efficiency of DCR parameters, parameters which had statistical difference in a pairwise comparison among the 3 groups were used to draw the ROC curve (*Figure 4*). The results are shown in *Table 4*. The areas under these parameter curves were greater than 0.7, indicating good diagnostic value for DP. The highest area under the curve (AUC) of the right-side parameter was that of the ED(fb)−ED(nb), at 0.8950 [95% confidence interval (CI): 0.7618–1.000], whereas that of the left-side parameter was ED(fb), at 0.9176 (95% CI: 0.8524–0.9829). As for visual assessment, the kappa coefficients, sensitivity, and specificity of right side were 0.495, 0.643, and 0.913, and those of left the side were 0.648, 0.588, and 0.980, respectively (*Table 5*).

Discussion

In this study, we used the imaging technology of DCR, obtained a large number of parameters regarding diaphragm movement and changes in lung field area, and found that parameters of DCR have good diagnostic value for DP. The highest diagnostic efficiency for DP on the right side was the ED(fb)−ED(nb), with a sensitivity of 95% and a specificity of 78.6%, whereas that on the left side was ED(fb), with a sensitivity of 80% and a specificity of 88.2%. Compared with DCR, a lower sensitivity but a higher specificity was shown under the visual assessment. Nevertheless, the consistency of objective evaluation is poor.

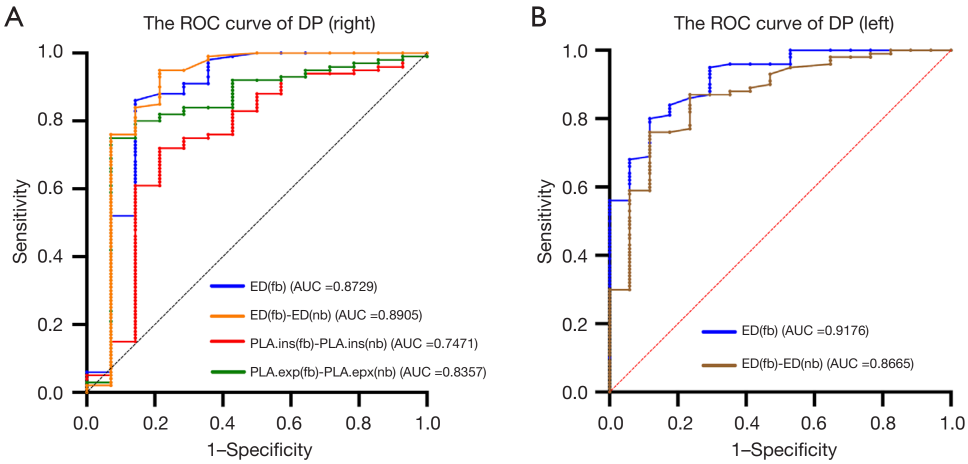

Figure 4 The ROC curve of DP, parameters with statistical difference in a pairwise comparison in DCR were included in ROC curve analysis. (A) The ROC curve of DP (right); (B) the ROC curve of DP (left). ROC, receiver operating characteristic; DP, diaphragm paralysis; ED, excursion of diaphragm; fb, forced breathing; AUC, area under the curve; nb, normal breathing; PLA, projected lung area.

Table 4 Diagnostic efficacy of DCR parameters

Side	DCR parameter	AUC (95% CI)	Cut-off value	Sensitivity	Specificity
Right	ED(fb)	0.8729 (0.7364–1.000)	32.6	86%	85.71%
	ED(fb)–ED(nb)	0.8950 (0.7618–1.000)	12.39	95%	78.57%
	PLA.ins(fb)–PLA.ins(nb)	0.7471 (0.5909–0.9034)	1408	75%	71.43%
	PLA.exp(fb)–PLA.exp(nb)	0.8357 (0.7056–0.9658)	2249	75%	92.86%
Left	ED(fb)	0.9176 (0.8524–0.9829)	36.41	80%	88.24%
	ED(fb)–ED(nb)	0.8665 (0.7744–0.9586)	15.40	87%	76.47%

DCR, dynamic chest radiography; AUC, area under the curve; CI, confidence interval; ED, excursion of diaphragm; fb, forced breathing; nb, normal breathing; PLA, projected lung area; ins, inspiratory phase; exp, expiratory phase.

Table 5 Contingency table of agreement between consensus diagnosis of visual assessment and clinical diagnosis

	Clinical diagnosis	
	DP	Non-DP
Visual assessment		
DP	R 9/L 10	R 9/L 2
Non-DP	R 5/L 7	R 95/L 99

DP, diaphragm paralysis; R, right; L, left.

DP is an unusual neuromuscular disease which is often easily misdiagnosed (11). Due to the blocked motor conduction or the damage of phrenic paralysis, the unilateral or bilateral diaphragm would be in a state of dyskinesia. Except for neuromuscular atrophy and idiopathic phrenic paralysis, neuromuscular disease, cervical spondylosis (12), surgical operation (13), tumor compression, and infectious and inflammatory diseases (14) are the causes of DP. Kara *et al.* (15) reported a case of DP in which phrenic nerve was involved by multiple myeloma. The causes of DP are variable and complicated. The common clinical manifestation of DP is the abnormal diaphragmatic movement during nb/fb (16). FitzMaurice *et al.* (17) examined 14 patients whose diaphragms exhibited paradoxical motion using DCR, which comprised an investigation of hemidiaphragm that mainly discussed the affected and unaffected sides in diaphragmatic dysfunction. Considering the cardiac effect to the PLA between the left and right lung, our study finally classified L/R sides rather than affected/unaffected sides. Transdiaphragmatic pressure measurement is the basic diagnostic method for DP, which involves low repeatability and suffering for patients. Crowe *et al.* (18) directly stimulated the phrenic nerve during operation as the gold standard to diagnose the DP but found that this method was invasive and prohibitively uncomfortable for patients. Ultrasound is a convenient method to evaluate the diaphragmatic morphology and function. B mode ultrasound can measure the thickness of the diaphragm (19,20) whereas M mode can be used to evaluate diaphragm movement (21,22). Ultrasound is non-invasive and free of ionizing radiation and can be carried out in the ward, but has higher operational requirements for the physician and does not enable intuitive observation of the diaphragm image. Traditional chest X-ray can be used as a screening method for diaphragm dysfunction but cannot diagnose DP (23). Although traditional chest radiography also can detect ED and PLA at mixed inspiratory and expiratory phases, nevertheless, it likely cannot capture the actual mixed inspiratory and expiratory phases, especially in patients with hemidiaphragm-paralysis, who show abnormal and slow diaphragmatic movement in the affected side (*Figure 1A,1B*). Computed tomography (CT) can determine the cause of abnormal shape and positioning of the diaphragm, moreover, can measure the thickness and density of diaphragm, but is not used in conventional screening methods due to the high dose of radiation and expensive cost (8,24,25). Dynamic magnetic resonance imaging (MRI) can quantitatively evaluate diaphragm function (26), but the technology of MRI is relatively complex, expensive, and time-consuming. Traditional fluoroscopy, particularly fluoroscopic sniff test, has represented the gold standard for visual assessment in the past (27); it provides detection of hemidiaphragm paralysis patients with paradoxical diaphragm motion, but a higher radiation dose is involved, and it requires both compliant patients and experienced radiologists.

DCR is a novel inspection method which involves a low dose of radiation, is low cost, takes a short time, and allows convenient observation of the dynamic image of diaphragm motion. Through the computer algorithm, DCR automatically characterizes the motion of the chest structure after image acquisition. Although there have been numerous studies on diaphragm function in COPD patients (28,29), many of which used DCR to evaluate diaphragm function (30-32), there is a lack of relevant research on DP.

In this study, all participants underwent DCR during nb and fb, because different degrees of DP patients showed various characteristics under nb/fb. Moreover, the parameters we chose included ED(fb)–ED(nb), PLA.ins(fb)–PLA.ins(nb), and PLA.exp(fb)–PLA.exp(nb), which have statistical differences. Definitely, it is necessary to investigate whether fb alone or nb can detect DP beneficially. In comparison with traditional chest X-ray, dynamic chest imaging can directly observe the change of diaphragm and PLA in different breathing patterns. The findings of our study indicated that bilateral ED of DP patients in fb was obviously smaller than that of others. The results of this research align with those of Yajima *et al.*, who reported the excursion of diaphragmatic paralysis (33). We also found that bilateral ED(fb)–ED(nb) of DP was significantly lower than those of healthy volunteers and respiratory disease patients. However, during nb, patients with DP showed no significant difference on PLA in the inspiratory and expiratory compared to healthy volunteers and other control groups. Only under fb, PLA.exp(fb) was significantly larger than that of the healthy screening group. When exhaling forcefully, the diaphragm in the health screening group contracted and lifted significantly, resulting in a relatively small area of the expiratory lung field. However, patients with DP still had a larger PLA in the expiratory phase due to the abnormal motor conduction of the phrenic nerve and the lack of significant upward movement of the diaphragm. Moreover, in other control groups, all cases had certain potential lung diseases, changes in lung or chest structure, or respiratory compensation, which affected PLA. Therefore, there was no significant difference in PLA between the DP group and other control groups. It is thus clear that although PLA can reflect the diaphragm movement status of patients with DP to a certain extent, it is not as effective as the diagnosis of diaphragm movement. Therefore, we further explored the differences in PLA.ins(fb)–PLA.ins(nb) and PLA.exp(fb)–PLA.exp(nb) among the 3 groups in this study, and found that PLA.ins(fb) had no statistical significance between the 3 groups, but PLA.ins(fb)–PLA.ins(nb) between the 3 groups was statistically significant and it of DP significantly smaller than the other 2 groups. It can be seen that the reliability of the PLA-related parameter as a diagnostic criterion for DP still needs further verification.

This study has the following limitations: (I) this study is a retrospective, single-center study, and the sample size of patients with DP included in the study is relatively small. (II) At present, there is scanty literature about using DCR to evaluate diaphragm function, and the study on evaluation of DP patients. (III) The data in this study are limited to the standing chest position, and lack of diaphragm movement data in other positions and other states. (IV) Future research related to PLA parameters will need a larger sample size. (V) The data of the respiratory diseases group were not representative, and therefore unsuitable as a comparison.

Conclusions

The quantitative acquisition of ED and PLA and dynamic observation are the unique advantage of the DCR technology compared with the above auxiliary diagnostic methods. The defect of this examination technology was filled in the field of DP. DCR is considered a convenient method to evaluate patients with DP combining quantitative analysis and visual assessment, and the diagnostic efficacy of ED (fb) and ED(fb)–ED(nb) is the best.

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Footnote

Reporting Checklist: The authors have completed the STARD reporting checklist. Available at https://qims.amegroups.com/article/view/10.21037/qims-24-90/rc

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://qims.amegroups.com/article/view/10.21037/qims-24-90/coif). The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Scientific Research Ethics Review Committee of The First Affiliated Hospital of Guangzhou Medical University (No. G-59, 2023) and written informed consent was provided by the participants.

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