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ORIGINAL ARTICLE

Lung ultrasound methods for assessing fluid volume change and monitoring dry weight in pediatric hemodialysis patients

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Abstract

Background The value of lung ultrasound in adult hemodialysis has been confirmed. The determination of dry weight in children remains challenging. This study explores the usefulness of lung ultrasound in assessing fluid volume change and the possibility of pulmonary ultrasound as a method to monitor dry weight in pediatric dialysis patients.

Methods This was a prospective observational study. We compared the predialysis and postdialysis B-line scores of the dry-weight group and non-dry-weight group. Changes in body weight and B-line scores were recorded during the dialytic period and interdialytic period, and the correlation was analyzed. Lung ultrasound was performed after the dialysis session every Friday, and B-line score < 10 was considered to indicate that there was no volume overload; the weight was recorded as the target weight.

Results Fourteen patients were included. A total of 78 ultrasound assessments were performed: 30 in the dry-weight group and 48 in the non-dry-weight group. The B-line scores decreased after dialysis in all patients ($p < 0.001$). Thirty-three assessments were performed in the interdialytic period, and 40 assessments in the dialytic period were performed within 1 week. Linear regression showed that changes in B-line number were directly and positively correlated with interdialytic weight gain ($r = 0.517$, $p = 0.002$) and dialytic weight loss ($r = 0.558$, $p < 0.001$). The weight of the children increased gradually without volume overload in two patients during follow-up.

Conclusion Lung ultrasound can assess the fluid volume change of pediatric dialysis patients in real time. Lung ultrasound could be a valuable method for monitoring dry weight in pediatric dialysis patients.

Keywords Lung ultrasound · Children · Dry weight · Dialysis

Introduction

Dry weight is one of the primary treatment goals for hemodialysis patients. The definition of dry weight by Sinha and Agarwal is widely accepted at present [1]. Dry weight is a volumetric state without hypovolemia or hypervolemia. Chronic hypovolemia and hypervolemia due to an incorrect estimation of dry weight can lead to chronic dehydration or long-term cardiovascular complications [2]. In the pediatric population, the determination of dry weight remains challenging. In children, weight increases due to growth. Therefore, a child's dry weight is usually more difficult to assess than that of an adult and usually requires an objective assessment. Dry weight, which is usually determined on the basis of blood pressure (BP) control in children, remains normotensive during the interdialytic period without the use of antihypertensive medications [3]. BP is the most widely used objective evaluation method in clinical practice, but it can often be inaccurate because of a wide range of fluctuations and various interfering factors. Other objective techniques include lung ultrasound (LUS), brain natriuretic peptide (BNP), the inferior vena cava collapsibility index (IVCCI), and bioimpedance analysis (BIA). Each technology has its advantages and disadvantages.

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Compared with the traditional physical examination, lung ultrasound is a noninvasive, easy-to-use technique for detecting extravascular lung water (EVLW) [4]. It evaluates the volume status of dialysis patients by counting the number of B-lines (B-line scores) [5]. In 2009, Noble et al. first reported that a reduction in B-line scores postdialysis correlates with the volume of ultrafiltration and weight reduction [6]. In recent years, lung ultrasound has been widely used to assess volume status in adult dialysis patients. In these patients, lung ultrasound is reliable for assessing tissue fluid overload [7, 8], which can detect real-time changes in volume during dialysis [6, 9, 10].

Lung ultrasound has been used in adult maintenance dialysis for 10 years; however, its application in children and infants was first reported in 2016. Allinovi et al. considered lung ultrasound to be a practical and sensitive method for the quantitative assessment of fluid overload in pediatric hemodialysis patients [11]. Another study showed that lung ultrasound is superior to echocardiography and BIA in detecting volume overload in children with stage 5 chronic kidney disease (CKD 5) [12].

At present, the use of lung ultrasound to evaluate the dry weight of pediatric dialysis patients has not previously been studied. In this study, we evaluated the difference in B-line scores between dry-weight and non-dry-weight pediatric cases. We explored the correlation between body weight and B-line score during the dialytic period and interdialytic period. The dry weight of pediatric dialysis patients with B-line scores was monitored.

Methods

Patients

We included children (< 18 years) receiving dialysis for CKD 5 between 1 May 2019 and 1 February 2020 at Beijing Children's Hospital Affiliated to Capital Medical University. The study protocol was approved by the Ethics Committee of Beijing Children's Hospital Affiliated to Capital Medical University (IEC No. 2019-k-336). The exclusion criteria were (i) lung fibrosis, atelectasis, lymphangitis, or interstitial lung disease; (ii) cardiac failure; (iii) acute respiratory distress syndrome; (iv) intradialytic hemodynamic instability; (v) inadequate lung scanning; (vi) severe mental disorder; or (vii) active severe infection.

Equipment and measurements

Lung ultrasounds were performed with the HI VISION Avius L (Hitachi Ltd., Chiba-ken, Japan) in both lungs, using a high-frequency (8.0–12.5 MHz) linear probe. The lung ultrasound measurements were performed at the bedside by a fixed nephrologist who had undergone ultrasound training for 1 year. An ultrasound scanning section was performed for each patient 15 min before dialysis and 15 min after dialysis. All patients underwent lung ultrasound in the supine position. As previously reported, lung scans proceeded from the 2nd to the 5th intercostal space on the right side and from the 2nd to the 4th on the left side, and the transducer was along the parasternal, mid-clavear, anterior axillary, and mid-axillary lines [13, 14]. The default scan depth was set at 4 to 8 cm starting from the pleural line. The focus of the image was set at the level of the pleural line [15]. B-lines were defined as a hyperechoic vertical linear artifact arising from the pleural line, moving with lung sliding and spreading to the end of the screen, erasing any A line that it crosses [16, 17].With a linear probe, B lines are parallel lines. In each intercostal position, B-lines were quantified from 0 to 10. B-line scores were the total number of B-lines visualized in 28 intercostal positions.

Study protocol

Children who were on maintenance HD were enrolled in the study. Children received 3 weekly dialysis sessions on Monday, Wednesday, and Friday. The duration of treatment was 4 h. Patients were not allowed to drink, eat, or infuse during dialysis treatment. Patients wore fixed light fitting clothes. Dry weight was the target weight of each dialysis session. However, there was one condition: the ultrafiltration volume of each dialysis session was less than 7% of the body weight before dialysis. During the session, dehydration or treatment was stopped in advance when symptoms, such as headache or BP reduction, became intolerable.

Dry weight was defined as the lowest tolerated postdialysis weight achieved via a gradual change in postdialysis weight at which patients experienced minimal signs or symptoms of either hypovolemia or hypervolemia [1]. Patients remain normotensive during the interdialytic period without the use of antihypertensive medications [3]. According to the definition of dry weight, patients were divided into a dry-weight group and a non-dry-weight group. Lung ultrasounds were performed before and after dialysis in the two groups.

The dialysis period was from the beginning to the end of a dialysis session. The interdialytic period was from the end of one dialysis session to the beginning of the next dialysis session. The time difference between the dialysis period and the interdialytic period of the same patient was less than 1 week. Changes in body weight (ΔWeight) and B-line scores (ΔB line) were recorded during the dialytic period and interdialytic period. In this part of the study, no patients were grouped to dry weight and non-dry weight groups.

BP was recorded every 30 min during the dialytic period in the hospital, and three times per day during the interdialytic period at home. Hypertension was defined as an average clinic measured SBP and/or DBP ≥ 95th percentile (on the basis of age, sex, and height percentiles) [18].

Each patient was in a different volume state during each dialysis cycle, and there was no relevant statistical effect based on individual patients; therefore, each dialysis cycle could be considered an individual measurement.

Follow-up

Follow-up of pediatric patients was performed by measuring weight gain and volume status. Two children were followed up for more than 3 months. Lung ultrasound examinations were performed after the dialysis session every Friday. A B-line score < 10 was considered to indicate that there was no volume overload, and the weight was recorded as the target weight. The weight in cases of dizziness, BP reduction, or other forms of hypovolemia was not considered the target weight. B-line scores > 10 were considered volume overload, in which ultrafiltration was intensified and the weight reduction with a maximum ultrafiltration rate was 7% of the predialysis weight per session. BNP was performed once per month. The spKt/V was evaluated once per month, and was calculated according to the Daugirdas formula [19]: spKt/V = −ln (R − 0.008 t) + (4 – 3.5 R) × (UF/BW), where ln = natural logarithm, t = time of dialysis treatment (h), R = predialysis BUN/postdialysis BUN, UF = ultrafiltration volume (L), and BW = weight after dialysis (kg).

Statistical analysis

A Wilcoxon rank test (non-normally distributed data) was used to compare changes in the number of B-lines predialysis and postdialysis in the dry weight and non-dry-weight groups. Relationships between variables were tested with the Pearson product-moment correlation coefficient. Correlations were calculated for ΔB-line scores and ΔWeight in the interdialytic period and dialytic period. A p value < 0.05 was considered to indicate statistical significance. All statistical analyses were performed using Statistical Package for Social Sciences 22 (IBM Corp., Armonk, NY).

Results

Fourteen patients were enrolled in the study. Of these, 7 (50%) were male. The median age was 11.66 (range 7.5–16) years. The median follow-up time was 4 (range 1–9) months. Kidney dysplasia was the most common cause of CKD in this study. Table 1 shows the baseline characteristics of the study population.

Thirty and forty-eight lung ultrasound assessments were performed in the dry-weight group and non-dry-weight group, respectively. All patients had decreased B-line scores after dialysis. B-line scores were significantly reduced after dialysis in the dry-weight group ($p < 0.001$) and non-dry-weight group ($p < 0.001$). The mean B-line scores of the dry-weight group were lower than those of the non-dry-weight group, and the difference between the two groups was statistically significant ($p < 0.001$). The B-line score postdialysis in the dry-weight group was 8.5 (3–19). Table 2 shows the B-line scores of the dry-weight group and non-dry-weight group.

Among the 14 patients, 33 assessments were performed in the interdialytic period and 40 lung ultrasound assessments (within 1 week of interdialytic data acquisition) were performed in the dialytic period. In the dialytic period, the median volume overload by weight (ultrafiltration volume) was 5.23% of the pre-hemodialysis bodyweight per dialysis session. The median B-line reduction per 1% predialysis weight of removal was 3.6. The median number of B-line scores fell from 54 before hemodialysis to 31 post-hemodialysis. In the interdialytic period, the median volume overload by weight was 4.66% post-hemodialysis. The median number of B-line scores increased from 28 post-hemodialysis to 53 pre-hemodialysis. Linear regression showed that changes in the B-line scores (ΔB line) were directly and positively correlated with

Table 1 Baseline characteristics of the study population

	Total (n = 14)
Male gender	7 (50%)
Age, y	11.67 (7.5–16)
Height, m	1.41 (1.20–1.69)
Weight, kg	32.1 (20.5–61.2)
BMI, kg/m^2	15.15 (12.95–21.43)
Follow-up, m	4 (1–9)
Oligoanuria (< 0.5 ml/kg/h)	8 (57.14%)
Hypertension requiring antihypertensive drugs	11(78.57%)
Cause of CKD	
Kidney dysplasia	5 (35.71%)
ANCA-associated vasculitis	3 (21.43%)
Focal segmental glomerulosclerosis	2 (14.29%)
Henoch-Schönlein purpura nephritis	1 (7.14%)
Membranous nephropathy	1 (7.14%)
Obstructive uropathy	1 (7.14%)
Unknown	1 (7.14%)

Table 2 B-line scores of the dry weight and non-dry weight groups

	Dry weight (n = 7)	Non-dry weight (n = 11)
B-line scores predialysis	23.5 (10–45)	56.5 (14–176)
B-line scores postdialysis	8.5 (3–19)	32 (5–115)
P value	< 0.001	< 0.001

interdialytic weight gain ($r = 0.517$, $p = 0.002$) and dialytic weight loss ($r = 0.558$, $p < 0.001$) (Figs. 1 and 2).

Weight gain was observed in two patients who were followed up for more than 3 months. Case 1 was a 14.6-year-old girl who was followed up for 36 weeks. She had anuria. Her systolic BP was 79–105 mmHg, her diastolic BP was 46–68 mmHg, and her monthly spKt/V was 1.33–1.55. The median B-line score was 8 (4–9). Her weight increased by 5.2% (38.2 kg to 40.2 kg). Case 2 was a 13.2-year-old girl who was followed up for 17 weeks. Her urine volume was 100–200 ml per day. Her systolic BP was 90–116 mmHg, her diastolic BP was 49–89 mmHg, and her monthly spKt/V was 1.33–1.55. Her median B-line score was 6.5 (6–9). Her weight increased by 2.6% (34.3 kg to 35.2 kg). Neither patient had signs of edema. BNP was measured once a month, and the results were normal (< 150 pg/ml) (Figs. 3 and 4).

Discussion

Lung ultrasound can assess the fluid volume change of pediatric dialysis patients in real time. Weight can represent total body volume, but the short-term weight change is mainly due to fluid volume change. B-lines are strongly correlated with extravascular lung water, which is one of the fundamental components of fluid volume [20]. Several studies have described a positive relationship between B-line scores and weight during the dialytic period [21, 22]. The role of lung ultrasound for the assessment of weight variation was also confirmed in studies of pediatric cases [11]. Similar to prior studies, our study shows that rapid weight loss during the dialytic period is directly and positively correlated with B-line score variation. In addition, slow weight gain during the interdialytic period has the same relationship with B-line score change. We calculated the quantitative relationship between volume removed and B-line score decrease in the dialytic period without intake or excretion in children. The study of Noble et al. showed that there was a decrease of 2.7 in the B-line score per 500 ml of volume removed [6]. The weight of children of different ages differs over time. The relationship between the absolute changes in body weight and the change in body fluid state is not suitable for children. In our study, the median B-line reduction per 1% of predialysis weight removal was 3.6.

The dry weight of children increases with growth, but B-line scores are not affected. The number of B-lines in the dry-weight state is helpful for assessing a child's volume state. In an adult study, the B-line score of healthy patients was 0–5 (0 for 77 patients, 5 for 5 patients) [21]. In the research of Arun Thomas, the number of B-lines before and 30 min after hemodialysis based on clinically defined dry weight was reduced from 12.7 ± 9.7 to 4.8 ± 6.6 [23]. In our study, the median

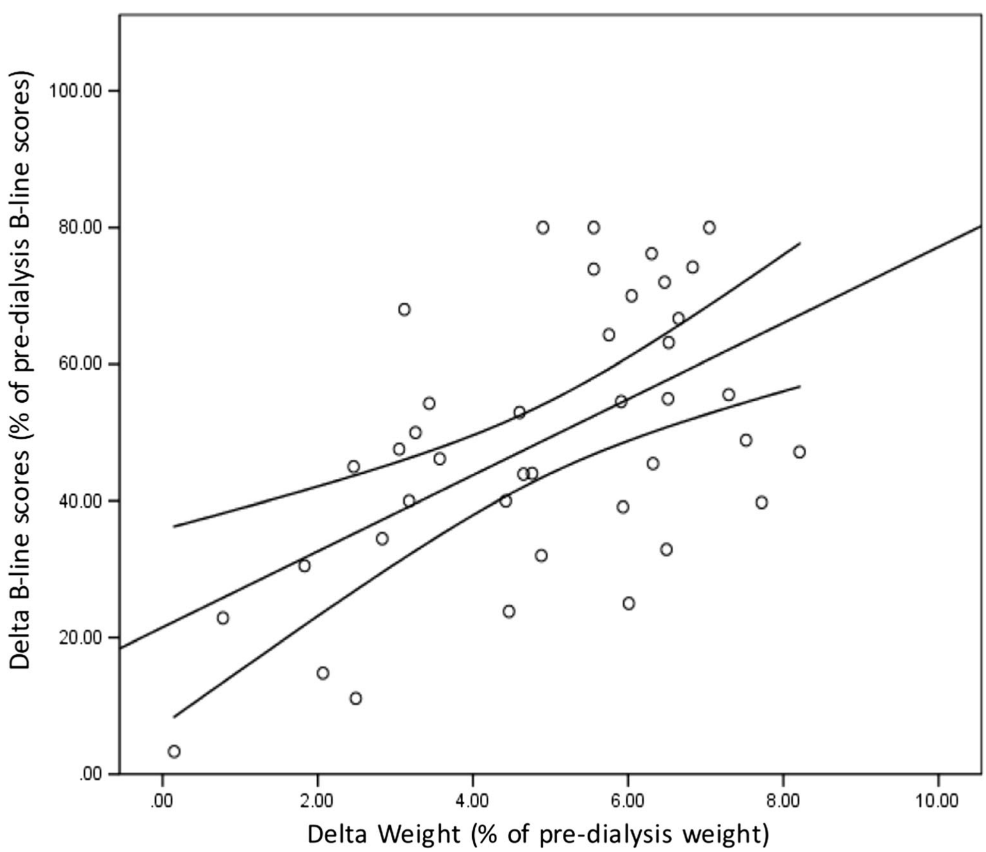

Fig. 1 Dialytic period: changes of B-line scores (ΔB line) directly positively correlate with weight loss (ΔWeight) ($r = 0.558$, $p < 0.001$)

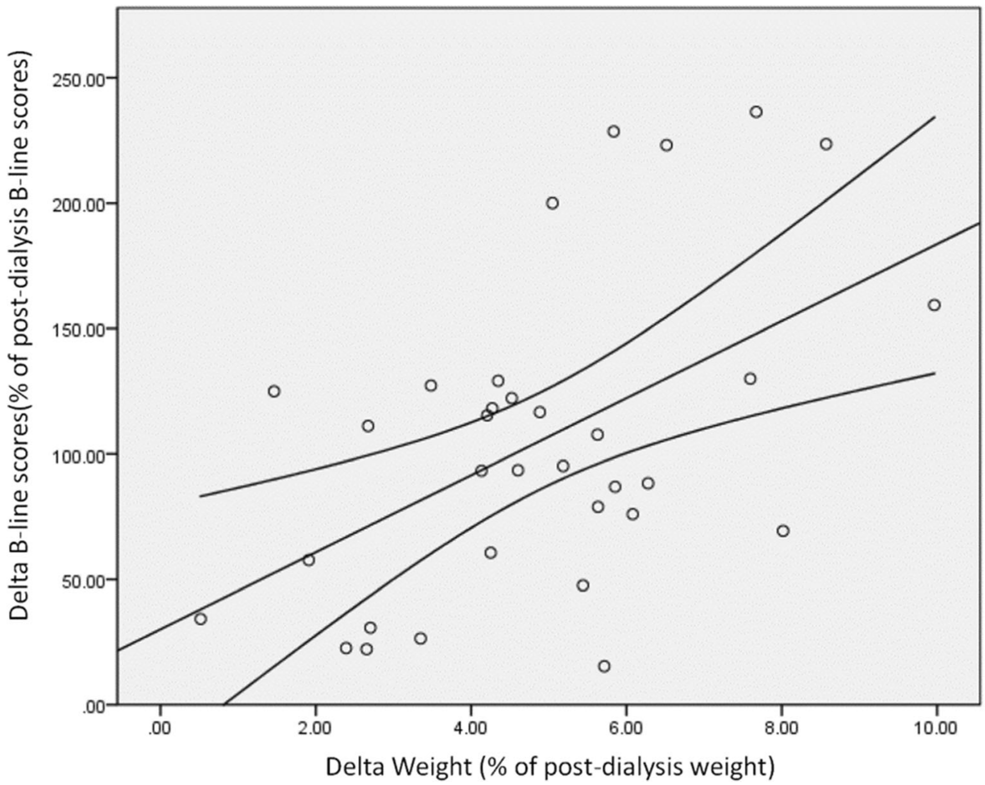

Fig. 2 Interdialytic period: changes of B-line scores (ΔB line) directly positively correlate with weight gain (ΔWeight) ($r = 0.517$, $p = 0.002$)

number of postdialysis B-lines in children with dry weight was 8.5 (3–19). The average or median B-line scores of children and adults with dry weight after dialysis were less than 10. The reference for B-line scores < 10 was used as the standard in the follow-up observation of this study.

The evaluation of dry weight in children with heart failure is difficult. The B-line scores for dry weight in pediatric dialysis patients with heart failure were not clear. In these patients, heart failure confounded the assessment of fluid overload, so they were not included in our study. Compared with those with normal heart function, children with heart failure have a higher B-line score. In a randomized controlled study of lung ultrasound-guided monitoring of dry weight reduction, patients with a background of cardiovascular disease had a higher B-line score than patients without a history of cardiovascular disease (15 vs. 5) [24]. This suggests that we should

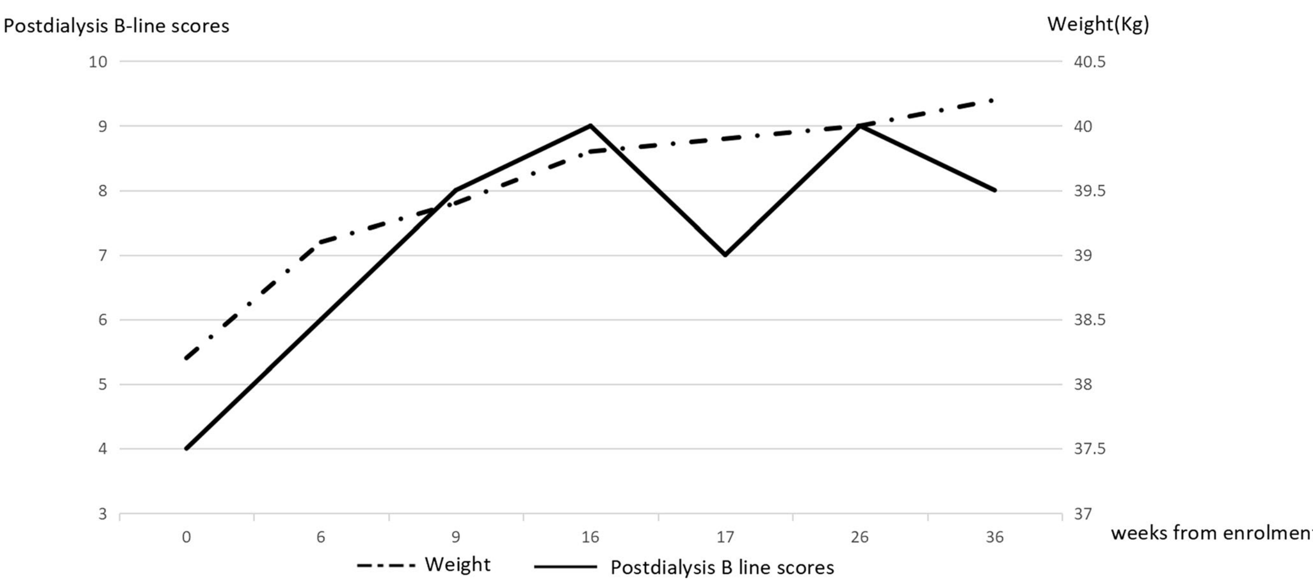

Fig. 3 Case 1: trend of postdialysis B-line scores and dry weight change during follow-up

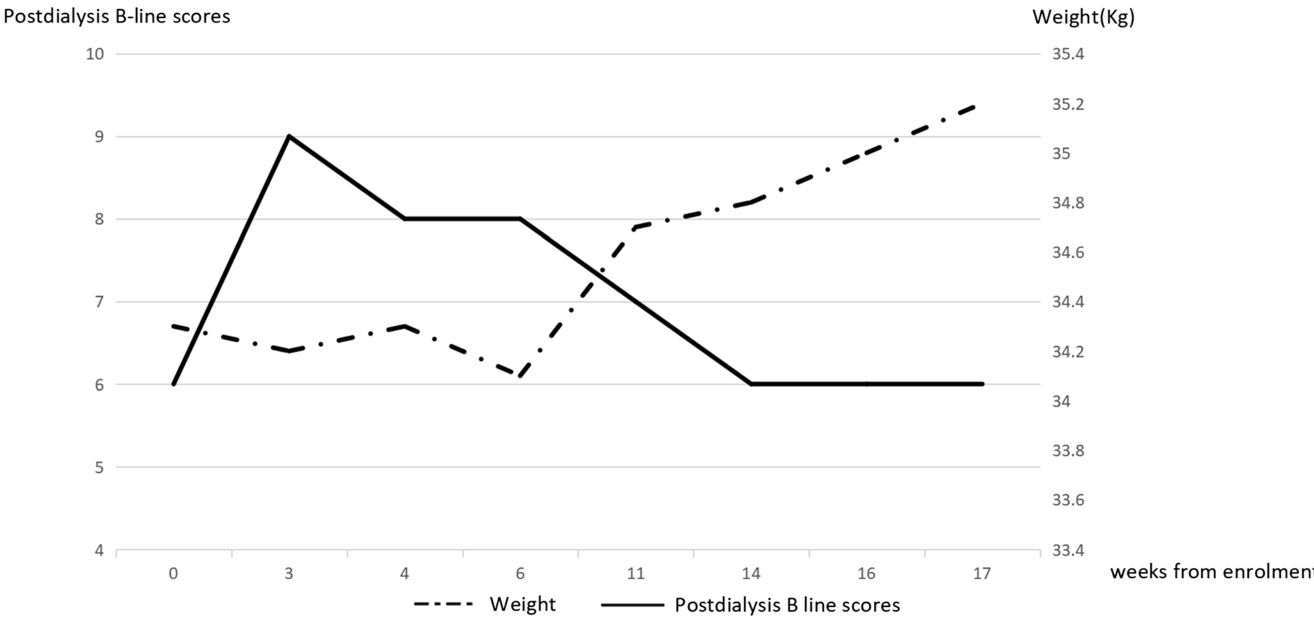

Fig. 4 Case 2: trend of postdialysis B-line scores and dry weight change during follow-up

pay attention to the impact of cardiac function on the B-line score when using lung ultrasound to assess volume status.

Although there are numerous confounding factors regarding BP, it is still a classic indicator used in volume status assessment. Pediatric dialysis patients with blood volume overload have the highest risk of hypertension [25–28].There have been a few studies on the relationship between B-line scores and BP. We defined dry weight primarily as the reference BP. In our study, the B-line scores of the non-dry-weight group were significantly higher than those of the dry-weight group. We speculated that children with hypertension had higher B-line scores than children with normal blood pressure. The relationship between BP and B-line scores should be analyzed individually in clinical applications.

The evaluation method for dry weight in dialysis children should not be affected by age, height, or weight. Lung ultrasound has advantages in the evaluation of dry weight in children undergoing maintenance hemodialysis. For children undergoing hemodialysis, weight gain needs to be differentiated between volume overload and dry weight gain [29]. A randomized controlled trial showed that compared with usual therapy, a lung ultrasound-guided fluid removal strategy results in better BP control among patients with hypertension receiving long-term hemodialysis [24]. The short-term weight gain of pediatric dialysis patients is mainly due to fluid volume overload [30]. In our study, we found that the increased fluid volume during the interdialytic period was directly and positively correlated with B-line score variation. Dry weight gain, however, is a slow and continuous process that requires regular assessment in a growing child [31]. During follow-up, two patients were in puberty and had rapid weight gain due to growth. The results showed that during the observation period, a B-line score < 10 was judged to be the capacity standard. The weight of the children increased gradually without volume overload symptoms (BP, BNP, and signs of edema), and monthly spKt/V continuously reached the standard; thus, we judged that it was dry weight gain. Lung ultrasound can directly reflect the increase in short-term volume while indirectly monitoring the increase in dry weight. We suggest that lung ultrasound could be a method to judge dry weight and volume change in children undergoing maintenance hemodialysis. A large-sample control study is needed to test the utility of this novel technique [32].

There are few studies on lung ultrasound in children with hemodialysis. In two studies, Allinovi et al. reported that the numbers of cases of hemodialysis in children were 5 and 6, respectively [11, 12]. All patients in our study were diagnosed with CKD 5 and on maintenance hemodialysis. We enrolled 14 patients, and the conclusion was more meaningful for hemodialysis patients. The definition of dialytic period and interdialytic period only apply to children with hemodialysis. Lung ultrasound can assess a change in fluid status during the dialytic period and interdialytic period in children. Pulmonary ultrasound can assess volume changes during the dialytic period; Allinovi et al. reached the same conclusion [11]. In this study, lung ultrasound can assess volume changes during the interdialytic period which reflects its potential to indirectly monitor dry weight gain. In the study of hemodialysis in children, the evaluation of dry weight is difficult. The dry weight was that prescribed by using clinical manifestations and physician experience. In the study of Allinovi et al., the target weight (dry weight) was that prescribed by the responsible physician using clinical data synthesized with trends in nutrition and growth [12]. In our study, we assumed that B-line scores were < 10 as the dry weight standard. The dry weight of patients continued to increase and there was no manifestation of volume overload. Thus, we proposed that lung ultrasound can be a valuable method for monitoring dry weight in pediatric dialysis cases.

This study has a number of limitations. First, in this study, which excluded infants, the minimum age of the patients was 7.5 years. More age groups need to be included. Second, only two children were followed up for more than 3 months, and further large-sample studies are needed. Moreover, we observed the clinical indicators of pediatric dialysis patients whose B-line scores were < 10 as the monitoring standard. Further large-sample randomized controlled studies are needed to determine the most suitable B-line score standard for monitoring dry weight in pediatric dialysis patients. Finally, lung ultrasound does not directly monitor dry weight gain, and dry weight is an ideal state that cannot be absolutely determined. Therefore, the target weight assessed by lung ultrasound is not equal to the ideal dry weight, and the difference needs further study.

Our data demonstrate that lung ultrasound can assess the fluid volume change of pediatric dialysis patients in real time. In our study, B-line scores were reduced postdialysis. Lung ultrasound reflected rapid volume changes during the dialytic period and slow volume changes during the interdialytic period. Lung ultrasound-based monitoring showed that the dry weight of the children increased gradually without volume overload symptoms. Thus, lung ultrasound can be a valuable method for monitoring dry weight in pediatric dialysis cases.

Compliance with ethical standards

Ethical approval The study protocol was approved by the Ethics Committee of Beijing Children's Hospital Affiliated to Capital Medical University (IEC No. 2019-k-336).

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