Usefulness of US imaging in overhydrated nephropathic patients

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Abstract Achievement of a normal hydration status is one of the major targets of hemodialysis. It is based on the estimation of “dry weight”, the term used to define normal body fluid content. The concept of dry weight in hemodialysis patients is clinically undisputed, but it is not always easy to achieve in this population. Assessment of hydration status by clinical evaluation is imprecise and often unreliable. Measurement of the inferior vena cava (IVC) diameter has been shown to reflect individual fluid status. The relationship between variation in IVC diameter before and after hemodialysis session and weight loss has been

investigated. Ultrasound (US) measurement of the IVC diameter is considered a valid measure of the hydration status and is routinely used in hemodialysis patients. Moreover, a relationship between IVC diameter, respiratory activity and hydration status, evaluated by considering both plasma volume and central venous pressure, has been demonstrated. In conclusion, assessment of hydration status based on blood pressure and central venous pressure can be considered reliable only in patients without signs of heart failure.

Keywords Hemodialysis · Ultrasonography · Overhydration · Chronic kidney disease

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Sommario Il raggiungimento di un normale stato di idratazione è di fondamentale importanza nei pazienti in emodialisi e si basa sulla stima del “peso secco”, che indica il normale contenuto corporeo di fluidi. Il “peso secco” non è sempre facile da ottenere in questa popolazione di pazienti. La valutazione clinica dello stato di idratazione è spesso imprecisa e talvolta inaffidabile. Il diametro della vena cava inferiore (VCI) sembra riflettere lo stato di idratazione del paziente. La relazione tra la variazione del diametro della VCI prima e dopo la seduta emodialitica e la perdita di peso è già stata studiata. La misurazione ecografica del diametro della VCI è un valido strumento per la stima dello stato di idratazione ed è utilizzato quotidianamente nei pazienti in emodialisi. Inoltre, è stata dimostrata una relazione tra il diametro della VCI, l'attività respiratoria e lo stato di idratazione, considerando sia il volume plasmatico che la pressione venosa centrale. Concludendo, la valutazione dello stato di idratazione, basata sulla pressione arteriosa e sulla pressione venosa centrale, può essere considerata affidabile solo nei paziente senza scompenso cardiaco.

Introduction

Overhydration is a clinical condition characterized by an increased amount and altered distribution of body fluids; evaluation is essential for a correct diagnosis and appropriate treatment. In the field of nephrology, numerous clinical situations may lead to overhydration, and the importance of a correct evaluation of volume status is supported by studies showing that fluid overloaded patients on dialysis have an increased mortality risk compared to those who are normohydrated [1, 2]. Assessment of hydration status in uremic patients is therefore an important task for the nephrologist both in the conservative phase and in patients undergoing renal replacement therapy. Physical examination is still the first and most important tool in the assessment of hydration status, although it is based on “empirical” data presenting a low specificity.

The so-called “dry weight” of dialysis patients is clinically defined as the lowest weight tolerated without developing unacceptable clinical symptoms (cramps, nausea, vomiting, hypotension). The “dry weight” may vary in the same patient because of intercurrent diseases (e.g., diarrhea, vomiting, malnutrition, infection, etc.), but also owing to changes in the hemoglobin values.

Physical examination permits evaluation only of advanced states of overhydration (due to the presence of edema), and early stages of overhydration cannot be recognized. Edema located in the sloped spaces is clinically evaluable only when accumulated interstitial fluid exceeds 2–2.5 l, i.e., a total increase in body liquids of not less than 5–6 l [3].

It is therefore important to identify features, which allow early recognition of overhydration in order to reduce the risk linked to this disorder. The methods currently available include monitoring of the blood volume, ultrasound (US) imaging, natriuretic peptide testing and bioimpedentiometric analysis [4, 5]. In this paper the usefulness of US imaging is analyzed.

US patterns in overhydrated patients

During US examination, the probe emits US beams with a uniform speed of 1,340 m/s; the speed and intensity of sound propagation are constant. The beams interact with the anatomical structures under examination and return to the probe at a different speed with a varying frequency, intensity and duration [6]. In other words, during the passage through the tissues the US beams are modified by physical phenomena, such as absorption, reflection, refraction and diffusion, which are characteristic of the analyzed anatomical structures. These variations are detected by the probe and

converted into an electrical signal processed by the “beamformer” resulting in a gray-scale image on the monitor (ranging from black to white) [6].

The image may be completely anechoic (black, the so-called absolute acoustic vacuum) in the presence of only fluids. It may also be completely hyperechoic (white), if the analyzed structures present numerous interfaces. The interfaces may be so many that they do not permit the passage of the US signal, thereby causing the formation of posterior signal void areas (e.g., an anechoic area behind calcified structures such as bones and stones). Between these two extremes, there are different shades of gray that allow differentiation of the examined structures. Anatomic regions with numerous interfaces will reflect large amounts of the emitted energy, whereas tissues containing few interfaces will return small amounts of energy [6].

The US beams undergo changes while crossing the tissues and this causes a progressive attenuation of the original signal: this beam attenuation is related to the wavelength (a greater attenuation when a higher frequency is used) and the composition of the tissues (e.g., nearly no absorption in fluids, whereas the lung presents high values) [6, 7].

Evaluation of patients with suspected overhydration

In the assessment of hydration status, physical examination should precede US imaging. All regions which may contain accumulation of fluid should be evaluated, as involvement is quantitatively and qualitatively different as a result of the disorder that has generated it, such as cardiac, renal, hepatic, nutritional, thyroid or lymph node disorders [7, 8]. Excess fluid may be located in the vascular compartment (the first space), in the interstitial compartment (the second space) and in the cavities (the third space). The following anatomic structures should therefore be assessed: subcutaneous tissues, lungs, myocardium, veins and the splanchnic region.

Diagnosis of overhydration is not difficult in the presence of edema and/or fluid collections, but in the absence of these signs, diagnosis is more complex. As previously mentioned, edema is detected at physical examination only if plasma fluid collection in the interstitial space exceeds 2–2.5 l [2, 3]. However, in the absence of clinical signs, US diagnosis of overhydration may allow prompt intervention with therapy leading to a rapid change in hydration status and the patient’s weight as well as a reduced risk of developing complications.

US evaluation of overhydrated patients

The subcutaneous tissue is easily explored at physical examination and this is the earliest location of excess body

fluid build-up; edema is the clinical expression of this condition. US imaging of the subcutaneous tissues is furthermore simple and repeatable using a high-frequency linear probe that allows detection of variation in the thickness of the dermis suggesting an early stage of fluid overload, which is not detectable at physical examination. The pre-tibial extensor surface is the anatomical site, which is most easily studied [9, 10] (Fig. 1).

The venous axes used in the US study to assess variations in the hydration status are the inferior vena cava (IVC), the hepatic vein and the jugular vein [4, 11, 12]. The vein is chosen according to the patient's physical characteristics. However, usually the jugular vein is preferred as it runs superficial to the muscle and is easily studied using a high-frequency linear probe in the region near the common carotid arteries. The IVC and suprahepatic veins are studied with a convex probe, selecting liver segment 1 (caudate lobe) as the anatomical landmark. A transverse subcostal scan is obtained to the right of the vena cava by gently rocking the probe cranially to the suprahepatic veins. The venous regions may provide useful information on the hydration status by showing the ability of the veins to collapse during respiratory movements.

Static and dynamic imaging provides information, which is useful for estimating overhydration using the venous collapsibility index (CI), i.e., the difference between the vessel diameter in the expiratory and inspiratory phases compared to that of the expiratory phase (Table 1). The normal values of this index vary between 0.75 and 0.40, which correlate with the blood pressure within the right atrium taken as a reference value [12]. CI values greater than 0.75 are a sign of overhydration, whereas CI values less than 0.40 indicate dehydration [12, 13] (Fig. 2). However, the CI of the vena cava does not reflect the real hydration status in uremic patients right after the hemodialysis session; probably because the

refilling process occurring after hemodialysis treatment is still not completed [14].

Lung US imaging provides information about the hydration status through the study of both the lung and the pleural cavity. A convex, linear or sector probe can be used, and the patient can be studied in the supine or sitting position; preferably a study of the posterior thoracic region. The areas to be studied can be traced by the paravertebral, scapular and posterior axillary lines in order to obtain transverse and longitudinal scans in the intercostal spaces. The most representative of these areas may be the mid-basal posterior segments (Fig. 3).

Under normal conditions, the pleural cavity appears as an exogenous, sometimes double, line (the pleural parenchymal line) representing the two pleurae (parietal and visceral) of the lungs (Fig. 4). The visceral pleura moves with the lung (the so-called “pleural curtain”), and it is disconnected from the parietal pleura in the presence of pleural effusion. In this case, a more or less conspicuous anechoic appearance will be visible between the two pleurae depending on the amount of pleural fluid (Fig. 5). Pleural effusion can also be diagnosed by studying the anterior subcostal plane which will present anechoic areas

Table 1 Estimation of the right atrial pressure on the basis of volume and respiratory dynamics of the inferior vena cava (IVC)

IVC diameter	% Inspiratory reduction	Right atrial pressure
<1.5 cm	Collapse	0–5 mmHg
1.5–2.0 cm	>50 %	5–10 mmHg
1.5–2.0 cm	33–50 %	10–15 mmHg
2.0–2.5 cm	0–33 %	15–20 mmHg
>2.5 cm	Absent	>20 mmHg

Evaluation of volume and dynamics of the IVC can provide an accurate estimation of the right atrial pressure. Right atrial pressure is a reliable indicator of hydration status

Fig. 1 Anterior view of the tibia; longitudinal (*left*) and transverse (*right*; stronger magnification) showing thickened subcutaneous tissue owing to the presence of numerous hypoechoic areas (suggesting fluid collections) separating more echoic areas

Fig. 2 Calculation of the collapsibility index (CI) of the inferior vena cava (IVC). The study of the veins can provide information required in the assessment of hydration status by evaluating the ability of the veins to collapse during respiration. The static and dynamic observation provides indicators for the estimation of overhydration using the collapsibility index (CI), i.e., the difference between the vessel diameter in the expiratory and inspiratory phases compared to that of the expiratory phase. The normal values of this index vary between 0.75 and 0.40, which correlate with the blood pressure within

the right atrium taken as a reference value. The IVC is measured during the tele-inspiratory and tele-expiratory phases. The difference between vessel diameter in the expiratory phase and vessel diameter in the inspiratory phase indexed for the expiratory vessel diameter expresses the CI (in the example CI is 0.69). Longitudinal anterior view: measurement of the IVC diameter immediately below the outlet of the suprahepatic veins in the expiratory phase (a) and in the inspiratory phase (b)

Fig. 3 A linear probe with trapezoidal field-of-view; longitudinal posterior thoracic view shows the different US appearance of the ribs, intercostal muscle and pleura (the bat sign, where the wings are the ribs and the body is the intercostal muscle and the pleura)

of different dimensions above the spleen and to the left and to the right of the liver depending on the amount of fluid [6, 13] (Figs. 6, 7).

The lungs are characterized by reverberations, which under normal conditions appear as A-lines, i.e., thick horizontal hyperechoic lines [14, 15]. In the presence of lung edema, US imaging reveals reverberation artifacts (ring-down artifacts, also known as vertical B-lines) starting in the pleura and extending down to the lower edge of the screen. These reverberation artifacts mask the A-lines (Fig. 8). In the presence of edema, B-lines are generated

Fig. 4 Posterior intercostal view obtained using a linear probe shows a continuous hyperechoic image (white arrows) that moves with respect to the external layers, attributable to the visceral pleura in the healthy lung. The black arrows indicate thin hypo-anechoic areas evidencing the presence of pleural fluid

from the thickened alveolar walls and there is a correlation between the number of B-lines and the extent and degree of pulmonary edema [15, 16].

The peritoneum is a virtual cavity, which is not visible under normal conditions. However, in case of overhydration it can easily be assessed for the presence of fluid in the peritoneal spaces, also referred to as the pouches, such as the hepatorenal pouch (Morrison's pouch), the splenorenal pouch, the rectovesical pouch and the rectouterine pouch (pouch of Douglas, the deepest point of the peritoneal

Fig. 5 Intercostal view obtained using a linear probe shows a small collection of pleural fluid (anechoic)

Fig. 6 Posterior longitudinal view shows a large anechoic area (asterisk) above the spleen indicating a large collection of pleural fluid in the left lung

cavity). In the presence of liquid in these pouches, there may be concomitant fluid collections in the intestinal and perirenal spaces.

Generally, a low-frequency convex probe is used. However, a study of the peritoneum and bowels in search of edema can also be performed with a high-frequency linear probe. The upper abdominal planes are studied in lateral and oblique views with the patient lying in the supine and lateral position. The lower abdominal planes adjacent to the hypogastric region are studied in central views with the probe positioned on the pubic symphysis and in lateral views with the iliac axes as an anatomical landmark to assess the intestinal peritoneum [17, 18] (Fig. 9).

Fig. 7 Ascending right subcostal view of the liver showing the vena cava and the dilated suprahepatic veins as well as the presence of an anechoic area (asterisk) attributable to right side basal pleural effusion

Fig. 8 Intercostal transverse view obtained using a linear probe shows the presence of “ring-down” artifact, the so-called B-lines (horizontal arrows) starting from the pleura and extending along the entire US image masking the normal echostructure of the lung, the so-called A-lines (vertical arrows). The B-lines are a sign of pulmonary edema

The pericardium may contain excessive pericardial fluid and should be studied in epigastric views obtained in connection with abdominal US imaging by positioning a cranially tilted probe on the subxiphoid site. These views permit evaluation of the pericardial line, the pericardial space and very frequently also the four chambers of the heart and the cardiac motility. The pericardial space is

Fig. 9 Abdominal trapezoidal view obtained using a linear probe shows accumulation of hematic and fibrin-rich fluid in the abdominal cavity during paracentesis in peritoneal carcinomatosis; the bowel loops (asterisks) and the thoracentesis needle (arrow)

Fig. 10 Left subcostal ascending view of the four chambers of the heart obtained using a convex probe that shows detachment of the two pericardial sheets owing to the presence of pericardial effusion (asterisk); also septal and left ventricular hypertrophy is visible; the patient is on hemodialysis

generally scarcely visible, but US imaging may show the presence of fluid (anechoic) which suggests a number of different conditions according to the amount of fluid [19, 20] (Fig. 10).

Conclusions

The need for assessment of hydration status using a safe, fast, and easily repeatable method such as US imaging is a

valid reason for performing this examination in patients with kidney diseases, particularly in the presence of suspected overhydration. However, there are currently no studies in the literature reporting statistically significant data on the accuracy of US imaging in the assessment of hydration status in uremic patients. On the other hand, clinical experience has shown the usefulness of US imaging in the assessment of overhydration. Further randomized controlled trials are required to confirm the accuracy of this method, which has already proved useful in daily clinical practice. This would be an additional tool in the hands of the nephrologists, who perform US imaging, in order to optimize management of patients with chronic kidney disease.

Conflict of interest The authors (Michele Prencipe, Antonio Granata, Alessandro D'Amelio, Giulia Romano, Filippo Aucella, Fulvio Fiorini) have no conflict of interest.

Ethical statements All human and animal studies have been approved by the appropriate ethics committee and have therefore been performed in accordance with the ethical standards laid down in the Helsinki Declaration of 1975 and its late amendments

Human and animal studies The study described in this article does not contain studies with human or animal subjects performed by any of the authors.

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