CHAPTER 157

Assessment of Fluid Status and Body Composition and Control of Fluid Balance With Intermittent Hemodialysis in the Critically Ill Patient

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OBJECTIVES

This chapter will:
1. Discuss body composition in health and disease.
2. Describe the current tools used in evaluation of body composition and fluid status.
3. Consider intermittent hemodialysis in the critically ill patient for control of fluid balance and prevention of intradialytic hypotension.

BODY COMPOSITION IN HEALTH AND DISEASE

Body composition can be viewed from five perspectives: atomic, molecular, cellular, tissue, and whole body levels.[1] At the atomic level, six elements form 98% of the body mass: 61% oxygen, 23% carbon, 10% hydrogen, 2.6% nitrogen, and 1.4% calcium; the remaining 2% of the mass consists of 44 other elements.

More than 100,000 distinct molecules constitute the molecular composition, ranging from simple molecules such as water to highly complex ones such as lipids and proteins. Water, which accounts for about 60% of a 70-kg "reference male" and about 50% of a "reference female," is the major chemical component of the body and essential for the interior milieu. The total body water (TBW) is distributed between two major compartments, the intracellular volume (ICV) and the extracellular volume (ECV); the latter can be divided into the interstitial compartment, which constitutes the extracellular environment of the cells, and the vascular space. Body fat depends heavily on nutrition and training status, ranging from less than 10% to more than 50%. Protein and minerals account for 15% and 5% of body composition, respectively. The 10^{18} cells forming the cellular body composition domain can be divided into connective tissue cells (fat cells, blood cells, and bone cells), epithelial cells, neural cells, and muscle cells. In terms of tissue composition, bone, adipose tissue, and muscle make up 75% of body weight. The *lean body mass* is the mass of the body minus the fat mass (storage lipid).

In healthy adults, body composition is maintained over the short term within narrow limits. Gender, age, race, nutrition, physical activity, and hormonal status are the main determinants of body composition. Illness may have a significant effect on body composition; malnutrition is a major complication. Malnutrition, which develops when nutritional intake falls short of nutritional requirements, leads to organ dysfunction, reduced body cell mass, abnormal blood chemistry, and worsened clinical outcomes.[2] Critically ill patients in particular are prone to malnutrition and consecutive unfavorable alterations in body composition. Malnutrition is observed frequently in patients regardless of type of illness.[3] An increased intake of energy and protein in critically ill patients is associated with improved outcomes at different body mass index (BMI) in a non-linear fashion; better outcomes are shown in patients with BMI less than 25 or more than 35.[4] In critically ill patients, hypermetabolism is caused by an activation of the sympathetic nervous system and the pituitary-adrenal axis, resulting in high plasma levels of catecholamines, adrenocorticotropic hormone, growth hormone, and cortisol. These metabolic adaptations contribute to protein-calorie malnutrition (defined as a negative balance of 100 g nitrogen and 10,000 kcal within a few days). Assessment of nutritional status and body composition in the critically ill patient is of major importance and guides adequate and sometimes aggressive nutritional support.

Fluid overload is very common in the intensive care unit (ICU). Impaired fluid balance is related with poor outcomes, such as an increased mortality risk.[5] In a retrospective analysis a positive fluid balance of more than 4 L was present after 12 hours of ICU admission in septic shock patients and increased further up to +11 L after 4 days.[6] A linear correlation has been described between cumulative fluid balance and risk of mortality.[7]

EVALUATION OF FLUID STATUS AND BODY COMPOSITION

The assessment of fluid status, body composition, and nutritional status is, in most instances, performed in a subjective manner by experienced healthcare workers. The fluid status can be judged clinically (with well-known pitfalls) from the presence or absence of edema, the skin turgor, jugular venous pressure, predialysis blood pressure, and changes in blood pressure and heart rate during dialysis. Imaging techniques such as chest radiography, abdominal ultrasonography to delineate the diameter of the inferior vena cava (IVC), lung ultrasound to assess the presence of "lung comets" (these are related to Kerley B-lines),[8] and echocardiography may yield additional important information. Bioimpedance techniques are capable of providing an integrative view of body composition and fluid status.

Anthropometric models have been developed to estimate body composition (see Tables 157.1 and 157.2 for a summary of anthropometric algorithms; see www.medal.org). The

TABLE 157.1

Anthropometric Algorithms

DOMAIN	MODEL
TBW (males > 16 years) in L [Hume and Weyers]	(0.194786 × [height in cm]) + (0.296785 × [weight in kg]) – 14.012934
TBW (females > 16 years) in L [Hume and Weyers]	(0.344547 × [height in cm]) + (0.183809 × [weight in kg]) – 35.270121
TBW (males) in L [Watson]	(– 0.09516 × [age in years]) + (0.1074 × [height in cm]) + (0.3362 × [weight in kg]) + 2.447
TBW (females) in L [Watson]	(0.1069 × [height in cm]) + (0.2466 × [weight in kg]) – 2.097
LBM (males > 16 years) in kg [Hume and Weyers]	(0.32810 × [body weight in kg]) + (0.33929 × [height in cm]) – 29.5336
LBM (adult males) in kg [Boer]	(0.407 × [body weight in kg]) + (26.7 × [height in m]) – 19.2
LBM (females > 30 years) in kg [Hume and Weyers]	(0.29569 × [body weight in kg]) + (0.41813 × [height in cm]) – 43.2933
LBM (adult females) in kg [Boer]	(0.252 × [body weight in kg]) + (47.3 × [height in m]) – 48.3
LBM (males) in kg [James]	(1.10 × [body weight in kg]) – (128 × ([body weight in kg]^2)/(body height in cm^2)
LBM (females) in kg [James]	$(1.07 \times [\text{body weight in kg}]) - \left(148 \times \frac{[\text{body weight in kg}]^2}{[\text{body weight in cm}]^2}\right)$
Corrected arm muscle area in cm^2 [Heymsfield]	$\left(\frac{(\text{Midarm circumference in cm}) - (\pi \times [\text{triceps skinfold thickness in cm}])^2}{4 \times \pi}\right)$ –(gender factor for bone area) Gender factor = 10 in males and 6.5 in females
Total body muscle mass in kg [Heymsfield]	(height in cm) × (0.0264 + [0.0029 × (CAMA)])

CAMA, Corrected arm muscle area; *LBM,* lean body mass; *TBW,* total body water.
Data from The Medical Algorithms Company. Available at www.medal.org.

TABLE 157.2

Anthropometric Models to Estimate Extracellular Volume and Intracellular Volume

GENDER	PARAMETER[a]	EXTRACELLULAR VOLUME (L)	INTRACELLULAR VOLUME (L)
Male	Height in m	9.78 × height	7.92 × height
	Weight in kg	0.245 × weight	0.198 × weight
	BSA in m^2	9.22 × BSA	7.45 × BSA
	LBM in kg	0.303 × LBM	0.244 × LBM
Female	Height in m	8.44 × height	7.04 × height
	Weight in kg	0.220 × weight	0.186 × weight
	BSA in m^2	8.18 × BSA	6.84 × BSA
	LBM in kg	0.302 × LBM	0.248 × LBM
Both	LBM in kg	0.3027 × LBM	0.2456 × LBM

BSA, Body surface area; *LBM,* lean body mass.
[a]LBM is computed with Boer's equation (see Table 158.1). Data from The Medical Algorithms Company. Available at www.medal.org.

anthropometric models are straightforward to apply but are not well validated in the dialysis population.

Ultrasonography is used frequently as a bedside tool to assess fluid status, and several indices related to IVC measures have been proposed (Table 157.3). The indexed vena cava diameter (VCDI) is calculated as follows:

$$\text{VCDI} = \frac{\text{maximal IVC diameter (IVCmax)}}{\text{body surface area (in m}^2\text{)}}$$

The IVC collapsibility index (IVCCI) is computed as follows:

$$\text{IVCCI}(\%) = \left[\frac{\text{IVCmax} - \text{IVCmin}}{\text{IVCmax}}\right] \times 100$$

These indices can be determined[9] easily and are a feasible option for rapid assessment of intravascular volume status in an outpatient dialysis setting by operators with limited formal training in ultrasonography, but there is a poor relationship between dry weight goals and IVC collapsibility.

TABLE 157.3

Cutoffs for Indexed Vena Cava Diameter and Inferior Vena Cava Collapsibility Index

VOLUME STATUS	VCDI CUTOFF (mm/m^2)	IVCCI CUTOFF (%)
Hypovolemia	<8	>75
Euvolemia	≥8 and ≤11.5	≥40 and ≤75
Hypervolemia	>11.5	<40

IVCCI, Inferior vena cava collabsibility index; *VCDI,* indexed vena cava diameter.

Lung ultrasound has gained interest in the ICU as a means to detect fluid overload signs. The presence of extravascular fluid in the lung detected by ultrasound is associated with increased mortality in ICU patients.[10] Interstitial-alveolar fluid is correlated with the presence of vertical ultrasound signatures arising from the pleura

detected by lung ultrasonography; these are called "lung comets" and are related to the Kerley B-lines known from conventional chest x-ray.[11] In hemodialysis patients the number of lung comets correlates with fluid overload and weight loss after ultrafiltration.[12] Lung ultrasound may be a promising novel noninvasive and feasible method to detect extravascular lung water in ICU patients.[13] Recently, a novel noninvasive ultrasonographic method to examine volume status has been introduced. This method is based on the measurement of corrected flow time (FTc) in carotid artery. The authors observed that FTc decreased between start and end of hemodialysis as a consequence of dialytic fluid removal.[14] Echocardiography is useful in determining volume status measures in addition to cardiac indices.

Biochemical markers, most prominently natriuretic peptides, have been advocated as noninvasive means to determine fluid status, but the levels of brain natriuretic peptide (BNP) correlate poorly with volume status.[15] However, N-terminal pro-BNP appears to be more accurate as an additional tool for assessing fluid status and is correlated with nutritional status parameters in hemodialysis patients.[16,17]

Bioimpedance analysis (BIA) is used increasingly in patients undergoing dialysis and in critically ill patients[18] to determine TBW, ECV, ICV, and other aspects of body composition. Body composition analysis by means of BIA has been compared with magnetic resonance imaging (MRI) analyses, and appropriate regression models have been developed to enable estimation of fat and muscle content.[19,20] Basically, impedance (Z) expresses the opposition to current flow that a system offers to injected alternating electric current; Z has two components (both expressed in ohms), resistance (R) and reactance (Xc). Resistance and reactance change with alternating current frequency and an increase in frequency results in a decrease in impedance. According to current concepts, the fluid volume component is reflected largely in the resistance, and reactance represents the cell membrane, which is related to nutrition. In biologic systems, lower-frequency currents travel preferentially in the extracellular space, whereas currents with higher frequencies pass through extracellular and intracellular compartments.

With injection of multiple-frequency currents (standard range 5 kHz to 1000 kHz), ECV and ICV can be estimated in a procedure called multifrequency bioimpedance spectroscopy (MFBIS). Single-frequency bioimpedance analysis (SF-BIA) with an injection current frequency of 50 kHz has been used for many years.[21] SF-BIA is simpler and easier to use than MFBIS. However, the inability to make accurate distinction between ECV and ICV is its major limitation. Different BIA approaches, such as wrist-to-ankle ("whole body method") and segmental methods,[2,9,22–27] have been used to measure ECV, ICV, and TBW in patients undergoing dialysis. These studies aimed to measure fluid status and estimate dry weight by employing ratios of ECV to ICV, ECV to TBW, and ECV to body weight.[28–32]

Nutritional status relates strongly to morbidity and mortality in patients undergoing dialysis. BIA-based measurement of muscle mass and of subcutaneous and total adipose tissues can be made routinely. Body cell mass (BCM) estimated by BIA is correlated with BCM determined by dual energy x-ray absorptiometry (DEXA), as is TBW estimated by BIA and determined by D_2O dilution.[32] Based on a regression equation developed for critically ill patients, an accurate BCM assessment can be obtained from BIA parameters and anthropometric variables; BCM could be less affected by massive fluid shifts than other BIA parameters especially in acute kidney injury patients. Therefore assessment of BCM should be preferred in severe fluid disturbances in ICU patients with renal failure.[33–35] Some researchers have proposed analyzing the impedance vector in the R—Xc plane to assess body composition and nutritional state according to tolerance ellipses defined in healthy subjects.[36–38] However, because patients undergoing hemodialysis have abnormal distribution of body fluid content, thus affecting resistance, the error of estimation may be significant with this approach. Therefore segmental BIA of the arm or leg has been suggested as an alternative approach.[19,39] Kaysen et al.[19] developed a model to estimate total body muscle mass on the basis of BIA-derived ICV (Table 157.4), which was as precise as methods based on total[40] K counting, a measure of body cell mass.

TABLE 157.4

Body Composition Analysis Based on Bioimpedance

TISSUE	MODEL
Fat-free mass in kg [Deurenberg]	$0.671 \times 10^4 \times \frac{(\text{height in m})^2}{\text{resistance in ohms}}$ + (3.1 × Gender value) + 3.9 Gender value = 0 if female, 1 if male
Total body water (hemodialysis patients) in kg [Chertow]	(–0.07493713 × age) – (1.01767992 × points for gender) + (0.12703384 × height) – (0.04012056 × weight) + (0.57894981 × points for diabetes) – (0.00067247 × weight × weight) – (0.03486146 × age × points for gender) + (0.11262857 × points for gender × weight) + (0.00104135 × age × weight) + (0.00186104 × height × weight) Height in cm; weight in kg; age in years Gender point = 0 if female, 1 if male Diabetes point = 1 if diabetic, 0 if not
Total body muscle mass in kg [Kaysen]	9.52 + 0.331 × ICV (by BIS; in mL) + 2.77 (male; 0 if female) + 0.180 × weight (kg) – 0.133 × age (in years)
Fat-free mass (in kg) [Chumlea]:	
Males	$-10.68 + \frac{0.65 \times \text{height (in cm)}^2}{\text{resistance (in ohms)}}$ + 0.26 × weight (in kg) + 0.02 × resistance (in ohm)
Females	$-9.53 + \frac{0.69 \times \text{height (in cm)}^2}{\text{resistance (in ohms)}}$ + 0.17 × weight (in kg) + 0.02 × resistance (in ohm)

BIS, Bioimpedance spectroscopy; *ICV,* intracellular volume.
Data from The Medical Algorithms Company. Available at www.medal.org.

INTERMITTENT HEMODIALYSIS IN THE CRITICALLY ILL PATIENT: CONTROL OF FLUID BALANCE AND PREVENTION OF INTRADIALYTIC HYPOTENSION

Removal of uremic toxins and excessive fluid are the main goals of renal replacement therapy. In contrast to continuous techniques such as continuous venovenous hemofiltration, removal of fluid with intermittent hemodialysis frequently is limited by hemodynamic instability, which manifests itself in most circumstances as intradialytic hypotension (IDH).

IDH and orthostatic hypotension after hemodialysis are independent predictors of mortality in patients undergoing chronic hemodialysis.[40]

IDH is the most common intradialytic problem, with an incidence of 5% to 40% of treatments depending on the definition of this complication, which varies from an asymptomatic percentage fall in systolic blood pressure to symptomatic hypotension requiring active treatment. Females, elderly patients with isolated systolic hypertension, patients with diabetes, and patients with autonomic neuropathy and low cardiac output at the start of dialysis[41] are at increased risk. In healthy subjects, blood pressure is maintained after removal of as much as 30% of the blood volume. In the dialysis population, however, the combination of autonomic and cardiac dysfunction, decreased venous return, and increased body temperature impairs the body's ability to cope with the hemodynamic stress caused by ultrafiltration.

Major factors determining the hemodynamic response are the ultrafiltration rate, the plasma refilling rate, and their instantaneous difference. The *plasma refilling rate* is the unit per time difference between filtration and absorption of plasma water in the capillary bed plus the lymphatic flow. Fluid dynamics in the capillary are governed by Starling forces, with the plasma oncotic pressure as a main absorptive factor.

The threat of IDH can be reduced by reduction of the ultrafiltration rate (through reduction of the interdialytic weight gain and thus the ultrafiltration volume and/or prolongation of ultrafiltration time) and by support of the body's ability to deal with the hemodynamic challenges caused by ultrafiltration—through improving vasoconstriction, treating congestive heart failure, or raising the serum albumin concentration.

Diastolic dysfunction results from impaired myocardial relaxation and reduced distensibility of the left ventricle. Systolic dysfunction in most cases is due to myocardial ischemia from coronary artery disease. Autonomic neuropathy is common in patients with diabetes. Therapy with drugs that interfere with vasoconstriction and other hemodynamic responses to ultrafiltration should be avoided immediately before or during hemodialysis.

Raising the dialysate sodium concentration to 150 mmol/L at the beginning of treatment is effective in reducing the chance of episodes of hypotension and maintaining blood pressure in chronic dialysis patients, but the price paid consists of increases in interdialytic weight gain and blood pressure as well as aggravation of the problems of overhydration. Besides that, this strategy may not be useful in critically ill patients; a retrospective cohort study in ICU patients with renal failure showed no benefit of sodium profiling.[42]

Reduction of interdialytic weight gain by reducing the sodium intake to less than 2300 mg (equivalent to 6 g sodium chloride) per day is an important preventive measure for IDH. Iatrogenic salt loading results from high dialysate sodium concentration or from application of intravenous saline solutions during dialysis.

Monitoring of relative changes in blood volume with a blood volume monitor (BVM) helps estimate plasma refilling rate in relation to ultrafiltration rate. A drop in blood volume greater than 15% during a hemodialysis session sharply raises the risk of IDH. On the other hand, IDH is unusual with a drop in blood volume smaller than 5%. An unchanged blood volume despite ongoing ultrafiltration suggests fluid overload. In a recent study predialysis fluid overload (by bioimpedance spectroscopy) and BVM data were collected in 55 chronic hemodialysis patients in 317 treatments. Average relative blood volume curves were well separated in different fluid overload groups between 0 and 5 L. Receiver-operating characteristics analysis revealed that the sensitivity of BVM was moderate in median fluid overload ranges between 1 and 3 L and highest for fluid overload more than 3 L.[43]

A novel tool used to monitor hemodynamic parameters in ICU is the transpulmonary thermodilution method; this seems to be accurate and less invasive and has been proposed for use in intermittent hemodialysis to detect risk factors for intradialytic hypotension.[44] Another study including 32 ICU patients with transpulmonary thermodilution measurements by PiCCO-device and sustained low-efficiency dialysis as renal replacement therapy reported a significant increment in cardiac index, central venous pressure, global end-diastolic volume index, and cardiac power index as a result of disconnection with re-transfusion at the end of HD treatment.[45] However, these data should be considered with caution because there is evidence of the lack of precision in some parameters detected by this method when evaluated during hemodialysis treatment.[46]

Maggiore et al.[36] first reported the beneficial effects of cooling dialysate on systematic hypotensive episodes during dialysis. A systematic review of the current literature on this issue concluded that reducing dialysate fluid temperature reduces IDH frequency by a factor of 7.1 and that postdialysis mean arterial pressure was 11.3 mm Hg higher with cool-temperature dialysis.[47] There may be an advantage in maintaining or reducing the core temperature with an automated feedback device (BTM, Fresenius Medical Care, Homburg, Germany) rather than making arbitrary reductions of dialysate temperature. Investigators in major randomized European trials concluded that active control of body temperature with an automated feedback device can improve significantly intradialytic tolerance in hypotension-prone patients, reporting a 50% reduction in rate of hypotensive episodes.[48] A recent meta-analysis included 26 trials consisting of a total of 484 patients; the results showed that in patients receiving chronic hemodialysis, reduced dialysate temperature may reduce the rate of intradialytic hypotension and increase intradialytic mean arterial pressure.[49]

Midodrine, an α_1-adrenergic receptor agonist, administered 30 minutes (5 mg orally) before the dialysis session improves intradialytic blood pressure. However, this agent should be used cautiously in patients who have congestive heart failure or who are taking beta blockers, digoxin, or a non-dihydropyridine calcium channel blocker.

Symptomatic IDH should be treated promptly through reduction of ultrafiltration rate and changing the patient to the Trendelenburg position; resistant IDH should be treated with 200 to 500 mL saline and possibly oxygen in the presence of hypoxemia. If severe IDH persists, an extended investigation including physical examination, electrocardiogram, emergency echocardiography, and laboratory studies is warranted. Arrhythmia, myocardial infarction, pericardial tamponade, hemorrhage, hemolysis, pulmonary embolism, and air embolism should be considered in the differential diagnosis. Kidney Disease Outcomes Quality Initiative (KDOQI) guidelines on the evaluation and treatment of IDH are available.[50]

Key Points

1. Knowledge of body composition is paramount in the care of critically ill patients.
2. Fluid status and nutritional condition can be delineated by clinical, anthropometric, biochemical, imaging, and bioimpedance means.

3. Body composition can be assessed reliably by bioimpedance techniques.
4. Reducing interdialytic weight gain is the cornerstone in the prevention of intradialytic hypotension (IDH). Cool dialysate has proven beneficial in IDH-prone patients.

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A complete reference list can be found online at ExpertConsult.com.

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