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Ultrasound and Computed Tomography Imaging Technologies for Nutrition Assessment in Surgical and Critical Care Patient Populations

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Abstract Modern imaging techniques, including portable bedside sonography and high-resolution computed tomography, have revolutionized our ability to diagnose and treat patients. One unique way of leveraging the availability of clinical information provided by these imaging modalities is in the areas of lean body mass and nutritional assessment. This review provides an outline of key aspects of state-of-the-art approaches to imaging-based nutritional assessment in surgical and intensive care unit populations.

Keywords Ultrasound · Computed tomography · Lean body mass · Anthropometrics · Nutrition assessment · Sarcopenia

Introduction

Muscle mass, also known as "lean body mass," is an important marker of nutritional status and is highly associated with a number of critical clinical parameters, including immune function [1] and quality of life in chronic illness [2]. In addition to serving as a surrogate for protein intake and nitrogen storage, skeletal muscle plays a role in the stress response via a number of different mechanisms [3].

Importance of Muscle Mass in Nutrition Assessment

Muscle mass, often characterized as lean body mass, serves as an important marker of nutritional status and is highly correlated to immune function. In addition to serving as a surrogate for protein intake and nitrogen storage, skeletal muscle plays a role in the stress response. Critically ill patients with sarcopenia have longer ICU stays, longer ventilator durations, and higher mortality [4••]. Patients with low muscle mass experience difficulty participating in rehabilitation activities and are either less likely or slower to recover from illness, regain their baseline functional status, or return to the home environment. Their length of stay is typically longer [5]. Nutrition screening is currently mandated by the Joint Commission and most hospitals are incorporating a variety of tools into their assessments to identify at-risk patients for additional interventions [6]. While low BMI (e.g. <18) has long been recognized as a risk for poor outcomes [7], obesity represents a more complex challenge because there is a sarcopenic subset of obese patients at high risk [8]. Visceral proteins are important predictors of risk but as acute phase reactants they do not adequately reflect nutritional status in the ill patient. For variety of reasons, there has been great interest in stratifying nutritional risk based on muscle mass. Ultrasound (US) and computed tomography (CT) have emerged as widespread technologies that can be harnessed for nutritional assessment. Their clinical applications for nutrition are emerging, and we seek to introduce to the clinician the use of these techniques in nutrition assessment.

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Introduction to Musculoskeletal Ultrasonography

Ultrasonography utilizes oscillating sound pressure waves of frequencies well above the human range of hearing. Sound waves are produced by a piezoelectric crystal transducer (commonly called a 'probe') and projected into the human body, typically through a gel medium [9]. Echoes reflecting off of the different structures of the body are collected and interpreted by the machine to produce a composite image [10••]. Structures and tissues of different compositions will reflect or conduct sound differently, which changes their appearance on the composite image. Current US systems have resolutions up to 0.1 mm [11, 12]. The time between signals determines the location and the amplitude of the signal determines its brightness. Bone reflects US, and therefore appears white, while blood transmits the US, causing the lumen of a blood vessel to appear black, for example. Soft tissues, such as liver, appear gray [13•].

The use of US in medical applications dates back to the 1950's [11, 14]. Medical ultrasonography has been used to image soft structures of the thorax, abdomen, and pelvis, as well as muscles, tendons and joint spaces in the extremities, and can also be used to evaluate subcutaneous tissue and provide imaging guidance for procedures including vascular access and nerve blocks [15•]. These various uses require the operator to be familiar with a host of different settings and parameters to achieve the best possible image, depending on the type and depth of tissue being studied, the structures that surround it, and the body habitus of the patient. Several different types of transducers or probes have been developed for these various applications. Some use lower frequencies, which in general offer greater depth but poorer resolution, and others use higher frequencies, which are capable of higher resolution but weaker penetration [10••, 16]. High-frequency probes are therefore best for visualizing detail within soft structures that are relatively superficial, while low frequency probes are best when investigating deeper structures or when performing US on an obese patient [13•]. Five to 7.5-MHz probes are normally used in muscle US to allow adequate depth penetration [11].

Several US modes have also been developed to allow for sonographic studies beyond simple imaging. 2D mode, also called B-mode or Brightness mode, the most commonly used, produces an image of a 2D plane through the body, and can be used to generate a 3D reconstruction of an image [17, 18]. A-mode (amplitude) US emits light diodes that can record changes in tissue density [19]. M-mode, or motion mode, takes serial 2D images through a particular plane to create a motion strip, showing how a particular structure moves through time. Finally, Doppler mode utilizes the Doppler effect to measure blood flow through vessels [10••]. In addition to these "expert" modes, modern US machines are also equipped with a number of functions and tools to help enhance images and make measurements. Adjustments to depth, gain, brightness, contrast, and harmonic frequencies can help improve image quality, and calipers and calculators can measure thicknesses, areas, volumes, flow, and movement [13•, 16].

Musculoskeletal ultrasonography has been utilized as a relatively inexpensive and non-invasive imaging modality to investigate joint, muscle, and subcutaneous tissue. Muscle thickness, pennation angle (the angle made by the muscle fibers (fascicles) and their intersection with a central tendon), and fiber length can all be measured, and this additional information may help quantify the ability of the muscle to generate force [18]. More recently, ultrasonography has been investigated for its use in evaluating additional pathologies including fibrillation and fasciculation, fibrosis, fat infiltration, dystrophies, and others [20••, 21–26]. Musculoskeletal US is useful for these applications because of its convenience, cost, and portability. It is also non-invasive and does not expose the patient to ionizing radiation [9]. However, musculoskeletal US is limited in its usefulness by its sensitivity, which is far less than that of magnetic resonance imaging (MRI). Also, bedside US is highly dependent on the skill of the sonographer. Since US can only image one plane at a time, the sonographer must take care to thoroughly investigate an area with the probe, or pathology may be missed more readily than on other imaging modalities. Furthermore, obesity may be associated with inferior image quality and make a thorough interrogation difficult [10••, 13•, 16]. Properly identifying anatomical landmarks poses a problem as well [27], and different equipment settings on the US may change muscle appearance. Increasing gain "whitens" the projection, which may lead to misidentification. Finally, different muscles exhibit different echoes and echogenicity increases with age, potentially creating additional confusion.

Ultrasound in Nutritional Status Assessment

Musculoskeletal US as a tool for assessment of nutritional status is a relatively new procedure, though small studies on the concept appeared as early as 1962 [28, 29]. Use of US in nutrition is aimed at measuring tissue mass in an effort to estimate body composition and direct nutritional management [29–32]. It is already well-established that imaging modalities such as CT and MRI can be reliably used to measure muscle and fat mass [23, 33]. Potential protocols for nutritional ultrasonography rely on using the caliper tool to measure thickness of tissues, and they

essentially fall into two camps. Most groups follow a strategy of attempting to measure the muscular thickness, but many have measured the thickness of subcutaneous adipose tissue (SAT).

Measurements of muscle thickness as a means to assess nutritional status have been attempted at a number of anatomic landmarks. Early research has tended to use biceps brachii and triceps brachii as well as the suprailiac region, since those sites are also standard sites for anthropometry and skin fold measurements, making for a ready comparison of the two methodologies [31, 32]. More recently, many more sites have been studied, including subscapular, abdominal, thigh, calf, as well as tongue and facial musculature [27, 34–37, 38••]. The most common sites appear to be the quadriceps, the biceps, and the triceps, and studies seem to show that all sites are roughly equivalent with respect to error. There are two different ways to measure the muscle: one is to measure the cross-sectional area, and the second is to measure the muscle thickness. Measuring muscle thickness has been shown to be more accurate in diseased subjects because increased echogenicity make cross-sectional area measurement more difficult. Some recommend quadriceps muscle layer thickness (QMLT) for screening of muscle wasting in the ICU [38••]. Others tried to create an index of lean body mass and muscle thickness using US and found that forearm, mid-thigh, and biceps muscle thickness measured together strongly predicted muscle mass loss [39]. Yet others demonstrated practical use of US in daily monitoring of ICU patients [40]. Measurements of the thickness of adipose tissue have been attempted less often, but could potentially be used. Sites studied include the triceps, biceps, mid-axilla, supraspinatus region, abdomen, suprailiac region, iliac crest, thigh, and calf [29–31, 33, 41].

Musculoskeletal US as a tool for nutritional assessment has many potential benefits, highlighting many of the advantages of general ultrasonography. US is non-invasive and involves no exposure to ionizing radiation, and therefore nutritional US creates minimal risk for the patient. US has improved drastically that it now can display muscle tissue with resolutions up to 0.1 mm, higher than a three tesla MRI [12]. US can be performed at the bedside, which avoids unnecessary patient transportation. It is also relatively inexpensive compared to other imaging modalities; therefore is potentially very cost-effective [31, 34, 42]. Ultrasonography can also be performed by any appropriately trained clinician and does not require interpretation by a radiologist. Modern US machines can rapidly store images for review, comparison, and re-assessment, thus facilitating repeat interpretation, quality control, and error checking. Because of the ease and convenience of US, measurements of muscle and fat at one or even several sites and subsequent interpretation of nutritional status can be done in a matter of minutes at the bedside. Finally, nutritional ultrasonography may discover important musculoskeletal and neurovascular incidental findings, and theoretically can be done during another US study. For example, femoral muscle mass can be quickly assessed during a scan looking for a lower extremity DVT.

Despite these potential benefits, current efforts in nutritional US have encountered several important obstacles and limitations that must be addressed. First, and most importantly, US is a unique imaging modality in that it involves direct contact between the probe and patient. Muscle and fat are compressible tissues, and the pressure applied to the probe will change how thick the tissue appears on the sonogram. Different sonographers use different amounts of pressure, and typical US machines are not equipped to measure the pressure applied to the probe, which introduces a potential for measurement bias of tissue thickness with US as compared to CT and MRI, which do not involve any instruments touching the patient [34, 41, 42]. Also in situations where tissue thickness increases such as obesity or spinal muscle atrophy, tissues may be easily compressed. Many studies have attempted to address this source of error by calling for "maximal pressure" with the probe, but this seems to be an imperfect solution as different clinicians are capable of exerting different amounts of pressure. With no objective measure for probe pressure, it will be difficult to standardize technique. Certain architectural components of the muscle may also prove problematic during US measurement. One study attempted to prove if US provided a valid estimation of fascicle length, fascicle angle, and muscle thickness in the gastrocnemius muscle in cadavers. The authors found that there are fascicle-like structures mistaken for fascicles, which leads to errors in US assessment. Fascicle-like structures appeared as hyper-echoic collagen-rich connective tissue between fascicles and obscured fascicle muscle fiber measurements, which normally appear as hypoechoic black lines [43].Tilt is another source of error that must be accounted for. One study showed that tilt of more than 5° while measuring the biceps brachii with US distorted the image because the humerus was not visualized and true fascicles could not be defined [44]. Interestingly, US calipers have been found to overestimate the thickness of subcutaneous fat because sound velocity is 1450 m/s through fat compared to an average speed of 1540 m/s in soft tissue and 1585 m/s in muscle; however, these sources of error are small, less than 6 % for subcutaneous fat, and less than 3 % for muscle [45].

Often patients most in need of nutritional assessment and management also appear to be the most difficult to evaluate with US. Critically ill patients tend to be very edematous, and edema can make interpretation of US images very difficult. In healthy young patients, it is fairly straightforward; muscle striations are readily apparent, and

there are typically clean, distinct borders visible between the various layers of tissue (Fig. 1a). However, in the critically ill ICU patient, edema can obscure the borders and characteristic appearances of each type of tissue (Fig. 1b). Muscle striations become less clear, and it is more difficult to be certain where subcutaneous fat ends and where muscle begins. Additionally, swollen and edematous tissues become even more compressible than their healthy counterparts since the fluid in and around those tissues can be displaced by pressure, compounding the error introduced by tissue compressibility. Diseased tissues can show multiple shimmering lines, which gives the muscle a whiter appearance on US potentially making assessment difficult. Diseased muscles are also known to have a different appearance than normal ones on US in terms echo intensity [46]. Normal muscle has low echo intensity, meaning it appears black (Fig. 1a). Echogenic sheets of perimysial tissue connective tissue give it a speckled appearance in the transverse plane and a pennate appearance in the longitudinal plane making the appearance distinct from surrounding structures like subcutaneous fat, bone, nerves, and blood vessels [11]. The Heckmatt score describes muscle echo intensity as described in Table 1 [47].

Different muscles have different echoes and echogenicity intensifies with age, which may make muscle harder to discern. Settings on the US may also change muscle appearance. Increasing gain whitens the projection, which may be mistaken for pathology. Bending the knee on assessment of the thigh produces a change in direction of muscle fibers in the quadriceps, which leads to increased echogenicity. Muscle contraction, on the other hand, increases muscle diameter, which decreases echogenicity. Measurements in the transverse plane must be perpendicular to the tissue otherwise it will overestimate the muscle thickness and decrease its intensity.

Special consideration of US use should be paid to mechanically ventilated patients. Mechanical ventilation may provoke diaphragm atrophy during critical illness, which may prolong duration of ventilation. Measuring diaphragm or skeletal muscle thickness may benefit these patients as skeletal muscle atrophy is a negative prognostic factor. A US study of the diaphragm in healthy volunteers created a technique to measure diaphragm thickness in unusual body positions with the hope of applying it clinically to ICU-ventilated patients [48]. Muscle mass measurement with US may also be beneficial for critically ill patients who receive neuromuscular blocking agents and corticosteroids for a prolonged period of time because of their known role in muscle atrophy [49].

Finally, approximately two thirds of the US population is obese or overweight. Obesity is a major risk factor for many diseases and ultimately for ICU admission. Not surprisingly, many patients in the ICU or critical care setting who require enteral or parenteral nutrition are obese. Therefore, obese patients will comprise a significant portion of the population undergoing nutritional US assessment, but obesity significantly complicates this procedure. In determining where to place the probe to make measurements of tissue thickness, most protocols employ the use of palpable landmarks such as the Anterior Superior Iliac Spine, the poles of the patella, the spine of the

Table 1 Heckmatt score for muscular ultrasound

Grade 1	Normal
Grade 2	Increased muscle echo intensity with distinct bone echo
Grade 3	Marked increased muscle echo intensity with a reduced bone echo
Grade 4	Very strong muscle echo and complete loss of bone echo

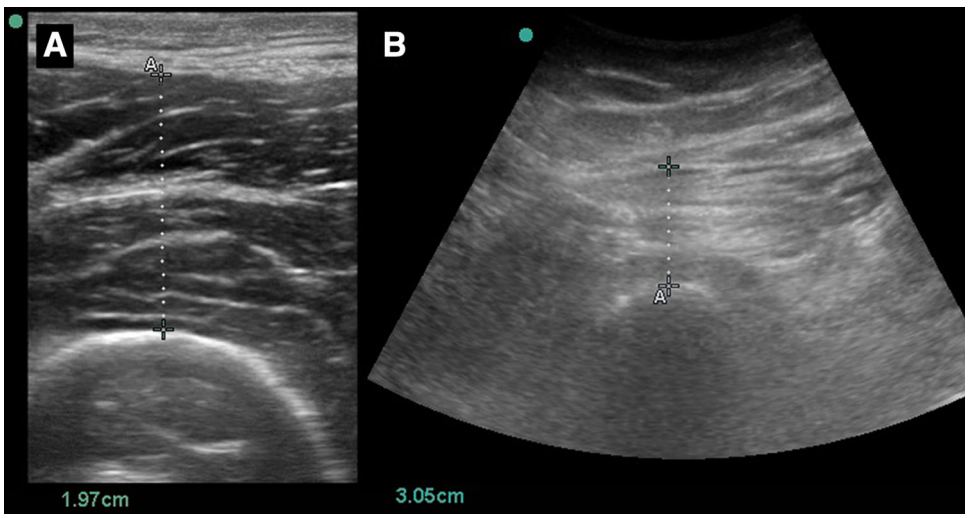

Fig. 1 Quadriceps muscle layer thickness measurement in **a** a young healthy volunteer with excellent image quality and clearly defined anatomy using a high-frequency linear ultrasound probe and in **b** a morbidly obese critically ill patient in septic shock and volume overload obtained using a lower-frequency curvilinear probe capable of deeper penetration. *Note* the reduced image quality and poorly defined anatomy on this image

scapula, etc. Above a certain BMI, these landmarks are no longer palpable, and it becomes difficult to ensure standard placement of the probe.

Computed Tomography

CT is currently considered a gold-standard imaging modality in muscle mass quantification because of its high precision, specificity, and clinical accessibility. Limitations include size and weight limits, limited field of view, and relatively high-radiation doses required. CT is not routinely used in nutrition screening; however, populations who routinely undergo CT scanning such as trauma or cancer patients may be subject to malnutrition and may benefit from early assessment and intervention. The adaptation of CT into clinical nutrition protocols should be investigated.

Assessment Techniques

The applications for CT in muscle mass quantification have evolved with its technical developments. Techniques to measure cross-sectional area of axial CT for analyzing adipose tissue, total lean tissue, and total muscle volume by measuring two consecutive CT images targeting the L3 region have become common [50, 51]. Figure 2 illustrates the range of results that can be obtained using this technique in patients with different body compositions. Other studies have targeted single images at L4–L5 regions for similar cross-sectional measurements [52, 53]. Body composition may be calculated from Hounsfield unit (radiodensity) assignment to pixels in the images for tissue type identification and multiplying the number of assigned pixels with the surface area of each tissue type. Whole-body composition may also be estimated from cross-sectional abdominal slices [54]. CT imaging for whole-body measurement has also been applied to measure cadaver adiposity through predetermined standardized positions [55, 56].

CT imaging has been explored as a potential modality for quantifying SAT. Some authors have applied CT imaging to measure SAT cross-sectional area and indicated its viability as an estimator for total SAT volume [57]. Others compared CT versus MRI and noted that SAT measurement is comparable in both imaging modalities. A disadvantage of CT imaging is radiation exposure to the patient [58••, 59].

At the same time, as intramuscular fat (intra-and extramyocellular adipose infiltrate) has been linked to several metabolic conditions, so there is an increasing interest to quantify intramuscular fat to elucidate the correlations, it may impart to muscular performance. Some reports advocated the use of CT to quantify intramuscular fat based upon attenuation values [60], correlating skeletal muscle attenuation to skeletal muscle lipid concentration; however, reports are limited in their ability to achieve direct measurement of muscle lipid content due to challenges discriminating intra- and extracellular lipid content [61, 62]. Furthermore, MRI has increasingly become the preferred modality in measuring intramuscular fat.

Role in Outcomes Prediction

As cachexia and sarcopenia are characteristic signs of malignancy and usually confer a poor prognosis, the use of CT imaging has found much application in capturing, assessing, and correlating these symptomatic indicators with clinical outcome in cancer patients. The application of CT imaging as a modality to measure muscle mass and body composition in cancer patients has been proposed in place of other tools such as DEXA, which was more widely in use in the body composition research community [50]. Further studies indicate the potential for secondary analysis of CT imaging as a diagnostic tool to identify cancer

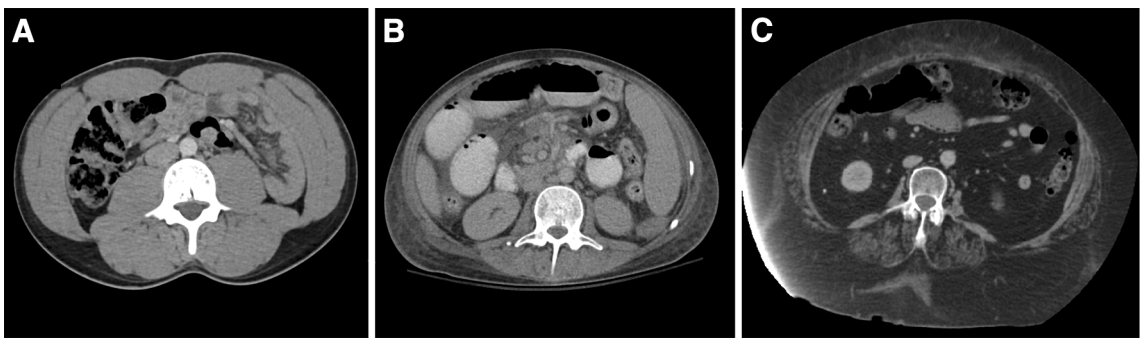

Fig. 2 Axial CT images obtained at the L3 vertebra. Variable muscle mass (*gray*) and adiposity (near-*black*) are noted in **a** healthy male who participates in high-intensity daily strength training (BMI 25), **b** cachectic male with AIDS and gastrointestinal disease (BMI 18), **c** morbidly obese female with sarcopenia and significant fatty infiltration of the paraspinous muscles (BMI 58)

cachexia in small-cell lung cancer patients [63••]. The use of secondary CT imaging has been increasingly popular in correlating muscle mass wasting and skeletal muscle density as prognostic indicators for cancer patient survival [64, 65]. PET/CT studies have been able to identify metabolic tumor volume as a viable prognostic factor in predicting cancer patient outcome undergoing chemotherapy [66, 67]. Psoas muscle cross-sectional area has been identified as a way to measure sarcopenia and a marker for mortality risk in patients undergoing surgery [68].

Role in Pharmaceutical Dosing

Initial studies have begun to establish correlation between nutritional status and pharmacokinetics, of which chemotherapeutic drug dosage and toxicity are of particular interest. Several small studies [21–23] have successfully applied CT imaging to measure body composition, showing that reduced lean tissue and skeletal muscle mass may be indicators of significant antineoplastic drug toxicity[69–71]. This has given rise to greater use of CT imaging in determining body composition in chemotherapeutic investigations [72].

Added Value of Pre-existing Clinical Imaging Data

Multiple reports describe the use of existing clinical imaging data for determining the relationships between available quantitative and qualitative patient information and the nutritional (as well as prognostic) status of various patient populations [73, 74]. Opportunities for further application to a wide variety of conditions are potentially limitless.

Conclusion

The use of modern imaging tools in nutrition assessment is still in its early phases. As US techniques are validated and software analysis for CT becomes more widespread, one may expect to see expanded incorporation of these techniques into clinical protocols.

Compliance with Ethics Guidelines

Conflict of Interest Thomas R. Wojda, Michael Scott Cardone, Wilson D. Lo, Stanislaw P. A. Stawicki, and David C. Evans declare that they have no conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been high-lighted as:

- • Of importance
- •• Of major importance

1. Roubenoff R, Kehayias JJ. The meaning and measurement of lean body mass. Nutr Rev. 1991;49(6):163–75.
2. Wilson IB, et al. Relation of lean body mass to health-related quality of life in persons with HIV. J Acquir Immune Defic Syndr. 2000;24(2):137–46.
3. Desborough JP. The stress response to trauma and surgery. Br J Anaesth. 2000;85(1):109–17.
4. •• Moisey LL, et al. Skeletal muscle predicts ventilator-free days, ICU-free days, and mortality in elderly ICU patients. Crit Care. 2013;17(5):R206. *This experiment was designed to assess if low skeletal mass had a negative affect on elderly patients after trauma. The study fins sarcopenia is highly prevalent in the elderly population after trauma and could be a predictor of increased mortality, discharge disposition, and ICU stay. The study concludes that measurement of muscularity may prove important in rehabilitation and nutrition practices.*
5. Pichard C, et al. Nutritional assessment: lean body mass depletion at hospital admission is associated with an increased length of stay. Am J Clin Nutr. 2004;79(4):613–8.
6. Evans DC, et al. Nutrition optimization prior to surgery. Nutr Clin Pract. 2014;29(1):10–21.
7. Evans DC, et al. Obesity in trauma patients: correlations of body mass index with outcomes, injury patterns, and complications. Am Surg. 2011;77(8):1003–8.
8. Prado CM, et al. Prevalence and clinical implications of sarcopenic obesity in patients with solid tumours of the respiratory and gastrointestinal tracts: a population-based study. Lancet Oncol. 2008;9(7):629–35.
9. Edelman SK. Understanding ultrasound physics. 4th ed. Woodlands: ESP; 2012.
10. •• Levitov A, Mayo P, Slonim A. Critical care ultrasonography. 2nd ed. New York: McGraw-Hill; 2014. p. 400. *This book contains comprehensive analysis of ultrasound use in critical care and provides reference guides for numerous technical interventions pertaining to ultrasound use and critically ill patients.*
11. Pillen S, Arts IM, Zwarts MJ. Muscle ultrasound in neuromuscular disorders. Muscle Nerve. 2008;37(6):679–93.
12. Cosgrove D. Ultrasound: general principles. In: Grainger RG, Allison DJ, editors. Diagnostic radiology. Edinburgh: Churchill Livingstone; 1992. p. 65–77.
13. • Hagan-Ansert SL. Textbook of diagnostic ultrasonography. Mosby: St Louis;2011. *This book contains valuable information in regards to patient care and ultrasonography. It illustrates the importance of identifying clinical landmarks and the appearance of common pathologies on ultrasound.*
14. Wild JJ, Neal D. Use of high-frequency ultrasonic waves for detecting changes of texture in living tissues. Lancet. 1951;1(6656):655–7.
15. • Stawicki SP, Bahner DP. Modern sonology and the bedside practitioner: evolution of ultrasound from curious novelty to essential clinical tool. Eur J Trauma Emerg Surg. 2014. doi:10.1007/s00068-014-0464-x. *This editorial sheds to light the growing popularity of bedside use of the ultrasound, highlights the benefits and its clinical applicability, and addresses questions and concerns about its use in critical care.*

16. Tempkin BB. Ultrasound scanning: principles and protocols. Philadelphia: Saunders; 2009. p. 672.
17. Fry NR, Gough M, Shortland AP. Three-dimensional realisation of muscle morphology and architecture using ultrasound. Gait Posture. 2004;20(2):177–82.
18. Legerlotz K, Smith HK, Hing WA. Variation and reliability of ultrasonographic quantification of the architecture of the medial gastrocnemius muscle in young children. Clin Physiol Funct Imaging. 2010;30(3):198–205.
19. Borkan GA, et al. Comparison of ultrasound and skinfold measurements in assessment of subcutaneous and total fatness. Am J Phys Anthropol. 1982;58(3):307–13.
20. •• Pillen S, van Alfen N. Skeletal muscle ultrasound. Neurol Res. 2011;33(10):1016–24. *This journal article addressess the usefulness of ultrasonography in detection of specific neuromuscular disorders, detection of fabrillations, muscle ultrasound versus other imaging techniques, and the future of ultrasound imaging.*
21. Pillen S, et al. *Assessing spinal muscular atrophy with quantitative ultrasound.* Neurology. 2011;76(10):933; **author reply 933–4**.
22. Jansen M, et al. Quantitative muscle ultrasound is a promising longitudinal follow-up tool in Duchenne muscular dystrophy. Neuromuscul Disord. 2012;22(4):306–17.
23. Janssen BH, et al. Quantitative muscle ultrasound versus quantitative magnetic resonance imaging in facioscapulohumeral dystrophy. Muscle Nerve. 2014;50(6):968–75.
24. Grimm A, et al. Ultrasound differentiation of axonal and demyelinating neuropathies. Muscle Nerve. 2014;50(6):976–83.
25. Giles LS, et al. Can ultrasound measurements of muscle thickness be used to measure the size of individual quadriceps muscles in people with patellofemoral pain? Phys Ther Sport. 2015;16(1):45–52.
26. Bickerstaffe A, et al. Quantitative muscle ultrasound and quadriceps strength in patients with post-polio syndrome. Muscle Nerve. 2015;51(1):24–9.
27. e Lima KM, da Matta TT, de Oliveira LF. Reliability of the rectus femoris muscle cross-sectional area measurements by ultrasonography. Clin Physiol Funct Imaging. 1962;32(3):221–6.
28. Whittingham GV. Measurement of tissue thickness by ultrasound. Aerosp Med. 1962;33:1121–8.
29. Bullen BA, et al. Ultrasonic reflections used for measuring subcutaneous fat in humans. Hum Biol. 1965;37(4):375–84.
30. Fanelli MT, Kuczmarski RJ. Ultrasound as an approach to assessing body composition. Am J Clin Nutr. 1984;39(5):703–9.
31. Chiba T, et al. Ultrasonography as a method of nutritional assessment. JPEN J Parenter Enteral Nutr. 1989;13(5):529–34.
32. Koskelo EK, et al. Quantitation of muscles and fat by ultrasonography: a useful method in the assessment of malnutrition in children. Acta Paediatr Scand. 1991;80(6–7):682–7.
33. Leahy S, et al. Ultrasound measurement of subcutaneous adipose tissue thickness accurately predicts total and segmental body fat of young adults. Ultrasound Med Biol. 2012;38(1):28–34.
34. Walton JM, Roberts N, Whitehouse GH. Measurement of the quadriceps femoris muscle using magnetic resonance and ultrasound imaging. Br J Sports Med. 1997;31(1):59–64.
35. MacGillivray TJ, et al. 3D freehand ultrasound for in vivo determination of human skeletal muscle volume. Ultrasound Med Biol. 2009;35(6):928–35.
36. Van Den Engel-Hoek L, et al. Quantitative ultrasound of the tongue and submental muscles in children and young adults. Muscle Nerve. 2012;46(1):31–7.
37. Alfen NV, et al. Quantitative facial muscle ultrasound: feasibility and reproducibility. Muscle Nerve. 2013;48(3):375–80.
38. •• Tillquist M, et al. Bedside ultrasound is a practical and reliable measurement tool for assessing quadriceps muscle layer thickness. JPEN J Parenter Enteral Nutr. 2014;38(7):886–90. *This experimental study identifies the interrater and intrarater reliability of ultrasonography and the measurements of quadriceps muscle layer thickness and advocates for standardizations of ultrasound use for measurement of muscle wasting in the critical care setting.*
39. Campbell IT, et al. Muscle thickness, measured with ultrasound, may be an indicator of lean tissue wasting in multiple organ failure in the presence of edema. Am J Clin Nutr. 1995;62(3):533–9.
40. Gruther W, et al. Muscle wasting in intensive care patients: ultrasound observation of the M. quadriceps femoris muscle layer. J Rehabil Med. 2008;40(3):185–9.
41. Toomey C, et al. Technical considerations for accurate measurement of subcutaneous adipose tissue thickness using B-mode ultrasound. R Soc Med J. 2011;19(2):91–6.
42. Wagner DR. Ultrasound as a tool to assess body fat. J Obes. 2013;2013:280713.
43. Bénard MR, et al. Anatomical information is needed in ultrasound imaging of muscle to avoid potentially substantial errors in measurement of muscle geometry. Muscle Nerve. 2009;39(5):652–65.
44. Herbert RD, Gandevia SC. Changes in pennation with joint angle and muscle torque: in vivo measurements in human brachialis muscle. J Physiol. 1995;484(Pt 2):523–32.
45. Shirley I, et al. A user's guide to diagnostic ultrasound. Tunbridge Wells: Pitman Medical; 1978.
46. Heckmatt JZ, Dubowitz V, Leeman S. Detection of pathological change in dystrophic muscle with B-scan ultrasound imaging. Lancet. 1980;1(8183):1389–90.
47. Heckmatt JZ, Leeman S, Dubowitz V. Ultrasound imaging in the diagnosis of muscle disease. J Pediatr. 1982;101(5):656–60.
48. Baldwin CE, Paratz JD, Bersten AD. Diaphragm and peripheral muscle thickness on ultrasound: intra-rater reliability and variability of a methodology using non-standard recumbent positions. Respirology. 2011;16(7):1136–43.
49. Moukas M, et al. Muscular mass assessed by ultrasonography after administration of low-dose corticosteroids and muscle relaxants in critically ill hemiplegic patients. Clin Nutr. 2002;21(4):297–302.
50. Mourtzakis M, et al. A practical and precise approach to quantification of body composition in cancer patients using computed tomography images acquired during routine care. Appl Physiol Nutr Metab. 2008;33(5):997–1006.
51. Heymsfield SB, et al. Accurate measurement of liver, kidney, and spleen volume and mass by computerized axial tomography. Ann Intern Med. 1979;90(2):185–7.
52. Kvist H, et al. Total and visceral adipose-tissue volumes derived from measurements with computed tomography in adult men and women: predictive equations. Am J Clin Nutr. 1988;48(6):1351–61.
53. Irving BA, et al. NIH ImageJ and Slice-O-Matic computed tomography imaging software to quantify soft tissue. Obesity (Silver Spring). 2007;15(2):370–6.
54. Shen W, et al. Total body skeletal muscle and adipose tissue volumes: estimation from a single abdominal cross-sectional image. J Appl Physiol. 2004;97(6):2333–8.
55. Sjostrom L, et al. Determination of total adipose tissue and body fat in women by computed tomography, 40 K, and tritium. Am J Physiol. 1986;250(6 Pt 1):E736–45.
56. Janssens V, et al. Post-mortem limitations of body composition analysis by computed tomography. Ergonomics. 1994;37(1):207–16.
57. Irlbeck T, et al. Association between single-slice measurements of visceral and abdominal subcutaneous adipose tissue with volumetric measurements: the Framingham Heart Study. Int J Obes (Lond). 2010;34(4):781–7.

58. •• Klopfenstein BJ, et al. Comparison of 3 T MRI and CT for the measurement of visceral and subcutaneous adipose tissue in humans. Br J Radiol. 2012;85(1018):e826–30. *This study compares CT and MRI use in visceral fat quantification and demonstrates the efficacy of MRI as a safe, accurate, and precise imaging technique for calculating visceral and subcutaneous adipose tissue deposits.*
59. Seidell JC, Bakker CJ, van der Kooy K. Imaging techniques for measuring adipose-tissue distribution—a comparison between computed tomography and 1.5-T magnetic resonance. Am J Clin Nutr. 1990;51(6):953–7.
60. Kelley DE, Slasky BS, Janosky J. Skeletal muscle density: effects of obesity and non-insulin-dependent diabetes mellitus. Am J Clin Nutr. 1991;54(3):509–15.
61. Goodpaster BH, et al. Skeletal muscle attenuation determined by computed tomography is associated with skeletal muscle lipid content. J Appl Physiol. 2000;89(1):104–10.
62. Larson-Meyer DE, et al. Muscle-associated triglyceride measured by computed tomography and magnetic resonance spectroscopy. Obesity (Silver Spring). 2006;14(1):73–87.
63. •• Baracos VE, et al. Body composition in patients with non-small cell lung cancer: a contemporary view of cancer cachexia with the use of computed tomography image analysis. Am J Clin Nutr. 2010;91(4):1133S–7S. *This study demonstrated the ability of Computer Tomography to assess muscle wasting in obese, normal, and overweight patients with non-small cell lung cancer as a nutritional risk factor, prognositic factor, and forcaster of cancer treatment toxicity.*
64. Martin L, et al. Cancer cachexia in the age of obesity: skeletal muscle depletion is a powerful prognostic factor, independent of body mass index. J Clin Oncol. 2013;31(12):1539–47.
65. Antoun S, et al. Skeletal muscle density predicts prognosis in patients with metastatic renal cell carcinoma treated with targeted therapies. Cancer. 2013;119(18):3377–84.
66. Murphy JD, et al. Postradiation metabolic tumor volume predicts outcome in head-and-neck cancer. Int J Radiat Oncol Biol Phys. 2011;80(2):514–21.
67. Castaldi P, et al. Can "early" and "late" 18F-FDG PET-CT be used as prognostic factors for the clinical outcome of patients with locally advanced head and neck cancer treated with radiochemotherapy? Radiother Oncol. 2012;103(1):63–8.
68. Peng P, et al. Impact of sarcopenia on outcomes following resection of pancreatic adenocarcinoma. J Gastrointest Surg. 2012;16(8):1478–86.
69. Prado CM, et al. Body composition as an independent determinant of 5-fluorouracil-based chemotherapy toxicity. Clin Cancer Res. 2007;13(11):3264–8.
70. Antoun S, et al. Low body mass index and sarcopenia associated with dose-limiting toxicity of sorafenib in patients with renal cell carcinoma. Ann Oncol. 2010;21(8):1594–8.
71. Cushen SJ, et al. Body composition by computed tomography as a predictor of toxicity in patients with renal cell carcinoma treated with sunitinib. Am J Clin Oncol. 2014. doi:10.1097/COC.0000000000000061.
72. Prado CM. Body composition in chemotherapy: the promising role of CT scans. Curr Opin Clin Nutr Metab Care. 2013;16(5):525–33.
73. Englesbe MJ, et al. Sarcopenia and mortality after liver transplantation. J Am Coll Surg. 2010;211(2):271–8.
74. Miller BS, et al. A quantitative tool to assess degree of sarcopenia objectively in patients with hypercortisolism. Surgery. 2011;150(6):1178–85.