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REVIEW

Application of imaging methods and the latest progress in sarcopenia

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Abstract
Sarcopenia is a syndrome described as a progressive and generalized loss of muscle mass and strength, with decrease in physical performance. It is related to an increased risk of many adverse events, such as falls, fractures, osteoporosis, major postoperative complications, loss of quality of life, prolonged hospital stay, disability, and even death. Although sarcopenia can also be assessed using a handheld dynamometer and a short physical performance battery (SPPB); it has lower accuracy, sensitivity, and specificity. Previous studies confirmed that imaging methods can serve as an important tool in the assessment of muscle mass and quality, and can even detect microscopic changes in muscle, achieving an early diagnosis of sarcopenia. Therefore, this article reviews the advantages and disadvantages of clinical and imaging assessment methods, specific applications, and the development of imaging techniques for the assessment of sarcopenia, including the currently unresolved problems.

Keywords Sarcopenia · Imaging methods · Dual-energy X-ray absorptiometry · Computed tomography · Magnetic resonance imaging · Ultrasound

Introduction

Sarcopenia has currently received an increasing interest in the research field, due to its higher prevalence with aging and people's growing awareness of sarcopenia. The concept of sarcopenia was first defined in 1988, by American scholar Irwin Rosenberg, as an age-related loss of skeletal muscle mass and function [1]. The widely used definition of sarcopenia, which refers to a syndrome associated with progressive and general loss of skeletal muscle mass and strength with a risk of adverse outcomes, was developed by the European Working Group on Sarcopenia in Older People (EWGSOP) in 2010 [2]. EWGSOP has emphasized that decreased muscle function is essential to the diagnosis of sarcopenia. Sarcopenia is now formally considered a muscle disease (muscle failure) rooted in adverse muscle changes that accrue across a life [3]. Sarcopenia is a multifactorial disorder involving a reduction of physical activity, protein intake, vitamin D levels [4], and anabolic hormonal activity (especially testosterone, estrogen, and growth hormone) [5] Besides, it is also related to pro-inflammatory status [6]. Previous studies found the prevalence of sarcopenia among hospitalized older adults (14–33%) is higher than that in community-dwelling older adults (1–29%), and the global prevalence of sarcopenia is expected to increase from 50 million in 2010 to 200 million in 2050 [8]. Therefore, the country will spend higher healthcare costs regarding days of hospitalization, nursing home placement, and ambulatory care [7, 8]. In addition to increasing social and economic costs [9], sarcopenia is associated with adverse outcomes in patients, mainly including falls, fractures, osteoporosis, major postoperative complications, loss of quality of life, prolonged hospital stay, disability, and mortality [3, 10–12]. Therefore, using relevant clinical and imaging assessment enables to the achievement of early diagnosis of sarcopenia, which can lead to early intervention, treatment, and a delay of adverse outcomes in patients with sarcopenia improving the quality of life and reducing national health care costs. The most commonly used imaging techniques to evaluate sarcopenia are dual X-ray absorptiometry (DXA), computed tomography (CT), magnetic resonance imaging (MRI), and ultrasonography (US). In addition, we also briefly introduce the application of Peripheral Quantitative Computed

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Tomography (pQCT), High-resolution peripheral quantitative computed tomography (HR-PQCT) in sarcopenia in the review. The imaging techniques mentioned above are mainly used to measure body composition to assess muscle mass and quality in patients with sarcopenia. Combined clinical evaluation and imaging indicators can improve the sensitivity and specificity of sarcopenia diagnosis [13]. Nowadays, imaging methods in diagnosis of sarcopenia have received growing attention, so this article mainly reviews the currently used and latest imaging techniques that can detect muscle changes in sarcopenia and serve as fundamental tools in the diagnosis of sarcopenia.

Assessment methods of sarcopenia

According to the recently updated diagnostic criteria by EWGSOP [2], the assessment of muscle strength and muscle mass is essential to the diagnosis of sarcopenia. Measuring muscle strength with a handheld dynamometer is a simple and easy method and is easily applied in the community and clinical environment. However, for patients with upper limb disability, this test cannot be performed. EWGSOP also recommends that chair standing tests can be used to assess muscle strength. Physical performance can be assessed using the short physical performance battery (SPPB) and gait speed [2]. Bioelectrical impedance analysis (BIA) and imaging methods such as DXA, CT, MRI, and US can be used to measure muscle mass (Table 1). According to the latest consensus of EWGSOP and AWGSOP, BIA is considered the main clinical evaluation method for sarcopenia because it is cost-effective and portable [14]. However, BIA measurement is susceptible to various factors such as age, race, gender, electrode position, fat content, and hydration status of the patient [15], so its value is not accurate. However, imaging biomarkers measured by imaging methods are relatively objective and are rarely affected by acute disease and cognitive dysfunction [16]. Especially, CT and MRI, as the gold standard for quantifying muscle mass and visceral fat area or volume [17], can improve the sensitivity and specificity of the diagnosis of sarcopenia. Notably, Faron et al. have confirmed that CT and MRI have good consistency in the assessment of muscle mass, so CT and MRI have interchangeability [18]. The following sections describe in detail the main applications and recent advances of imaging techniques for the assessment of sarcopenia.

Imaging assessment methods and the latest development of sarcopenia

Dual-energy X-ray absorptiometry

Characteristics, principles, and application fields of DXA

DXA is more favored by clinicians and working groups as compared to other imaging methods for the quantitative analysis of muscle and is commonly used for body composition analysis at the molecular level. It can be widely used in clinical environments because of lower radiation, cost effectiveness, simple operation, short scanning time, and high accuracy [19]. Messina et al. have demonstrated lean mass

Table 1 Strengths and weak points of the main imaging technique of assessment for sarcopenia

Technique	Strengths	Weak points
Dual-energy X-ray absorptiometry	Low radiation Low cost Simple operation Short scanning time High accuracy Reproducibility	Difficult of assessment for intramuscular fat Inconsistency of results among different devices Influence of body thickness and hydration status
Computed tomography	Higher accuracy Reproducibility Cross-sectional imaging	High cost Larger radiation dose Complex post-processing
Peripheral quantitative computed tomography	Lower radiation Low cost Portability	Lack of standard scanning conditions Lack of standard scanning sites and cut-off points
Magnetic resonance	No radiation Higher spatial resolution Detection of muscle microstructure	Low accuracy of assessment for IMAT No clear low muscle mass thresholds High equipment costs Many contraindications
Ultrasound	Low cost Portability No radiation Reproducibility	Lack of standardized conditions Poor accuracy Operator skills required

(LM) and fat mass (FM) measured by DXA are strongly correlated with LM and FM by CT and MRI [20]. The measurement of bone mineral density (BMD) was performed using DXA [21]. Tegola et al. have proposed that combined appendicular skeletal muscle mass index (ASMMI) with BMD of the femoral neck to assess the risk of fracture in the elderly [22]. With the development of technology, it has also been gradually applied in the measurement of muscle mass. The principle of DXA is the transmission and attenuation of energy when an X-ray penetrates tissues of the human body at two different energy levels (40 kv and 70 kv) [7, 8, 23]. Based on the above principles, DXA can be used to indirectly measure focal and total body composition. Commonly used indicators include appendicular lean mass, appendicular lean mass index (ALMI), appendicular skeletal muscle mass (ASMM), ASMMI, fat mass index, and Android/Gynoid ratio (A/G ratio). A multicenter and large cohort study confirmed that DXA measured ALMI was strongly associated with the risk of mortality in patients with sarcopenia [24].

Specific application and limitation of DXA in sarcopenia

The ASMM is the most widely used parameter. However, because ASMM is susceptible to the body size, most guidelines recommend the use of ASMM adjusted for height, which is also known as ASMM index (ASMMI) [20]. When ASMMI is lower than the cut-off point defined by relevant guidelines (Table 2) [16], the low muscle mass can be diagnosed. In addition to the diagnosis of sarcopenia, DXA can be used for follow-up of patients, because repeatable assessment can be performed using the same equipment and cut-off point in a short time [3]. Kim et al. demonstrated using the AWGS ASMMI can predict perioperative complication risk of malignant tumor in recent study [25]. Therefore, we can distinguish the subjects with "physiological" loss of muscle mass from those with "pathological" impoverishment due to the short-term changes in muscle mass [26]. Furthermore, the assessment of resting energy expenditure (REE) by DXA is a better tool for the management of sarcopenic patients [27]. Osteosarcopenia can be diagnosed and the risk of fracture can be assessed combined BMD, the trabecular bone score (TBS) and the Bone Strain Index (BSI) in recent years [28]. DXA also has some limitations. (1) Although current new software provides the possibility to evaluate subcutaneous fat and visceral fat, DXA still cannot assess intramuscular fat, so qualitative analysis of skeletal muscle cannot be performed [4, 9]; (2) the values of relevant parameters measured by different devices are inconsistent, so standardized measurement protocols are required [3]; (3) DXA is susceptible to body thickness, hydration status, and diseases that can cause edema, such as DXA may overestimate muscle mass in patients with edema and ascites and underestimate muscle mass in obese people [5]. (4) There is no consensus on the assessment equation of muscle quantity such as ASM [29, 30]. Therefore, radiologists and radiographers should have standardized training for DXA examination acquisition, including patient positioning, demographics collection, and image analysis to improve the accuracy of outcomes [31]. And orientation of future researches should focus on the above limitations.

Table 2 Cutoff points for defining sarcopenia using ASMMI (cm^2/m^2) measured by DXA

	IWGS	AWGS	EWGSOP
Men	7.23	7.0	7.0
Women	5.67	5.4	5.5

ASMMI appendicular skeletal muscle mass index, *IWGS* International Working Group on Sarcopenia, *AWGS* Asian Working Group for Sarcopenia, *EWGSOP* European Working Group on Sarcopenia in Older People

CT and pQCT

CT

Characteristics, principles, levels, and muscles assessed in sarcopenia about CT

Computed tomography (CT), as the gold standard for evaluation of body composition, is currently a promising modality for quantitative and qualitative evaluation of muscles [32], which is widely used for tumor patients. The principle is to distinguish different tissue densities based on different X-ray attenuation values, so it can provide more detailed anatomical information. Muscle mass and muscle fat infiltration CT measured can be used in the diagnosis of sarcopenia and muscle fat infiltration that could reflect the quality of skeletal muscle. Park et al. have confirmed the accuracy of CT to be higher than that of MRI for the assessment of muscle mass [33]. At present, muscle mass and quality are mostly measured at the level of the L3 vertebra due to less motion artifacts [34]; and previous studies have confirmed that a more stable measurement level is the inferior endplate level of L3 [17]. Other levels that are used include the L4 level; the L1 level which has good consistency of measurement results with the L3 level and the measurement results are associated with prognosis [35, 36]; T4 and T12 levels [37, 38]; and the mid-thigh level [39]. The most commonly assessed cross-sectional area (CSA) of muscles are all muscles at the level of the L3 vertebra (Fig. 1A), including psoas major, paraspinal muscles, and abdominal muscles, which have the best correlation with total body muscle mass and fat

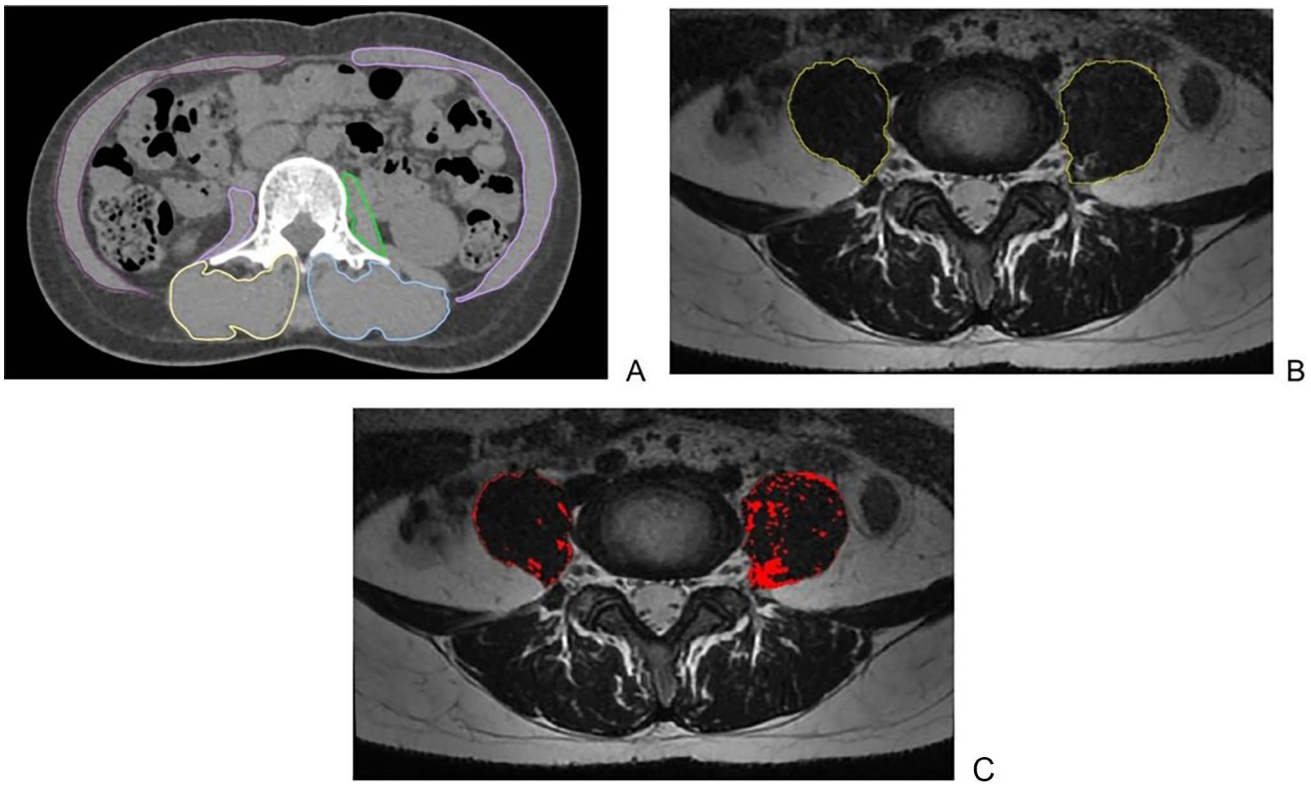

Fig. 1 Axial CT and MRI images assessing muscle mass and quality in sarcopenic patient. **A** 31-year-old woman. Axial CT image of the abdomen at the L3 level shows region of interest (ROI) delineation of all truncal muscles along muscle boundary to CSA evaluation. **B** A 67-year-old man. An axial MRI image of the abdomen at the L3 level is commonly used to measure the CSA of the psoas major muscle (yellow) by ROI delineation along the muscle fascia. **C** 67-year-old-man, Axial T2-weighted MRI image of the abdomen at the L3 level showing the segmentation of fatty tissue(red) of the psoas major muscle based on the grayscale signal by ImageJ software

infiltration [40]. Other involved muscles include the psoas muscle at the L3 and L4 levels; the latissimus dorsi muscle or all muscles based on the chest CT level [41]; the mid-thigh muscle group and the hip muscle group [42].

CT biomarkers in the assessment of muscle mass and quality in sarcopenia

Muscle volume, CSA, and skeletal muscle index (SMI) are commonly used in the assessment of muscle mass. SMI (TAMA/Height^2) at the L3 vertebral level is the most commonly used biomarker in most studies based on the following reasons: (1) total abdominal muscle area at this level can reflect muscle mass of the whole body [21]; (2) TAMA at this level is more reliable than total psoas muscle are [33]; (3) SMI can predict the mortality of patients with chronic liver diseases rather than psoas muscle index (PMI) [43]. The biomarkers commonly used for muscle quality assessment include muscle attenuation value, low-density lean muscle tissue, and intermuscular adipose tissue [44–46]. Kim et al. suggested that normal attenuation muscle is divided by total abdominal muscle area which can also be used for the assessment of muscle fat infiltration, and the cut-off point of diagnosis was obtained [45]. IMAT is a commonly used biomarker, because it can reflect changes in muscle strength, which is associated with poor patient prognosis [47]. The threshold method is commonly used for muscle segmentation and measurement of IMAT [48]. The muscle threshold is further divided into normal muscle thresholds of 30–150Hu and Low Muscle Threshold of −29 to 29Hu, and the fat threshold is −30 to 190 Hu. The cut-off point of diagnosing sarcopenia is also different in different age groups and scanning levels (Table 3) [49]. For the protocols of image acquisition, the enhanced images may affect the CT value of the muscle, and the KV peak value and the scanning slice thickness will also affect the measurement results [50, 51], therefore, extensive research is needed to standardize the scanning protocols in the future.

CT can provide more detailed anatomical information and distinguish subcutaneous fat and visceral fat and is more suitable for measuring muscle mass in the clinical environment. Moreover, in addition to accuracy and repeatability of measurement, SMI and IMAT measured by CT can also predict adverse outcomes [52]. However, due to the larger

Table 3 Use of CT-measured L3 levels to define cut-off points for relevant markers of sarcopenia

	SMI (cm^2/m^2)	PMI (cm^2/m^2)	SMA (cm^2)
Men	50	3.74	52.4
Women	39	2.29	38.5

SMI skeletal muscle index, *PMI* psoas muscle index, *SMA* skeletal muscle area

radiation dose, higher cost, complex post-processing and technical requirements, it is currently mainly used for the diagnosis of sarcopenia in patients with diseases that require CT examination, which is known as opportunistic examination. It is mainly aimed for tumor patients, patients undergoing major surgery, and trauma patients [53, 54].

Peripheral QCT (pQCT) and HR-pQCT

Application, strength, and limitation of pQCT in sarcopenia

Peripheral Quantitative Computed Tomography (pQCT) was primarily used to diagnose osteoporosis and to identify the risk of fracture through the measurement of BMD, bone content, and bone strength [55]. It is increasingly used for CSA measurement of appendicular muscles, muscle density, and IMAT with the application of software, which can distinguish different compositions based on different density thresholds. Compared with CT, it is portable and has a smaller radiation dose and lower cost [55]. CSA of muscles measured by pQCT has a strong correlation with measurements conducted by MRI [56], but the accuracy is not comparable to MRI. The most common acquisition sites are 2/3 (66%) of the full length of the tibia and 65% of the full length of the radius [57, 58]. Previous studies have demonstrated that low muscle mass can be determined when the CSA of the muscles is less than 83.3 cm^2 for males and less than 62.6 cm^2 for women of the tibia two-thirds along its length (starting from the tibiotarsal joint) [59]. Muscle CSA and muscle density obtained through pQCT measurement are related to adverse prognosis of sarcopenia such as mortality, and frailty [60], and studies also have demonstrated that muscle size is related to bone size and bone strength [58]. The pQCT evaluation of skeletal muscles still has certain limitations, (1) there are still no standard scanning conditions, and different scanning conditions and muscle segmentation methods may affect the accuracy of the measurement results [61]. (2) Although the tibia and radius are most common site, there are still no standard scanning sites and cut-off points. (3) pQCT has lower accuracy for the assessment of IMAT [35].

High-resolution peripheral quantitative computed tomography (HR-pQCT)

High-resolution peripheral quantitative computed tomography (HR-pQCT) is the main method used for quantifying in bone microstructure, and it is also used to measure parameters related to muscles and tendons [62]. Hildebrand et al. suggested that CSA of skeletal muscle and muscle density measured by pQCT and HR-pQCT had a significant positive correlation and higher accuracy [63], but for the specific application in sarcopenia, it still needs further research to confirm.

Magnetic resonance imaging (MRI)

Regular application of MRI in sarcopenia MRI can generate contrast between fat and non-fat tissue based on emission and adsorption of radiofrequency energy. It is also the gold standard for the study of body composition [64]. MRI has more advantages than CT, with no radiation, higher soft-tissue contrast, and the ability to detect changes in muscle microstructure, including edema, fibrosis, inflammation, and fatty infiltration [65]. Additionally, MRI is more advantageous in the assessment of muscle quality, because it can distinguish intramuscular and intermuscular adipose tissue and can detect early fatty infiltration and quantitative measurement through post-processing software (Fig. 1B, C). However, MRI has some limitations; longer acquisition time, the interference of metal or motion artifacts, and high cost and the lack of a standardized evaluation [55]. Sarcopenia is now routinely measured through cross-sectional imaging of the mid-thigh and the L4 and L5 vertebral body levels [66]; and most common biomarkers include muscle CSA, volume, and muscle thickness. The other levels include the superior mesenteric artery level [16], the L2 and L3 levels [67], and the C3 level [68]. The common biomarkers include TAMA, TPA, and CSA of the erector spine or the quadriceps [69–71]. Temporalis muscle thickness can be measured to assess sarcopenia in neurosurgical oncology, which has been shown to correlate with the CSA of the psoas major [72].

At present, with the application of MRI water-fat separation imaging (Dixon sequence) and proton spectroscopy imaging, the accuracy and sensitivity of muscle quality measurement have been improved. The most common site is the mid-thigh muscle, and the most common biomarker is the proton density fat fraction (PDFF) [73]. Studies have confirmed that PDFF measured by MRI has a significant correlation with muscle strength [74]. Other commonly used indicators include fat-free muscle area, intermuscular fat volume, intramuscular adipose tissue, T2 relaxation time, proton density water fraction, apparent diffusion coefficient (ADC), and diffusion coefficient [7, 75].

Common advanced MR technology for skeletal muscle measurement

Dixon and magnetic resonance spectroscopy (MRS) are chemical shift-based imaging methods separating water and fat (Dixon) based on the difference in proton resonance frequencies between water and fat. Grimm et al. confirmed muscle fat quantification using a 6-point Dixon has a significant correlation with MRS [76], which promotes their clinical application. The main method for the muscle lipid composition assessment is 1H-MRS, which can precisely measure the percentage of fat content. Chemical shift resonance frequency of water protons is at 4.7 ppm, extramyocellular lipids (EMCL) at 1.5 ppm and intramyocellular lipids (IMCL) at 1.3 ppm (Fig. 2B) [77]. EMCL is the main factor of muscle fat infiltration and decreased function [78]. Since the separation of (IMCL) and (EMCL) is orientation-dependent; we often select the spindle-shaped muscles in which the orientation of fibers is consistent with the long axis of the muscle, such as the vastus intermedius and the tibialis anterior muscle [79]. Even though MRS can distinguish between IMCL and EMCL, the inhomogeneous distribution of EMCL makes accurate quantification of EMCL challenging [80]. Surov et al. suggested that the accuracy of measurements can be increased through the selection of fat-selective imaging technique [53]. Further research on new sequences or algorithms is required to improve the precision of repositioning when repeatedly measured, because muscle fibers are easily deformed during measurement. Dixon magnetic resonance imaging can acquire two or more echoes at different echo times, obtaining images of water, lipid, in-phase, and out-phase images to measure PDFF (Fig. 2A) and PDWF. PDWF is varied due to the presence of muscle edema and fibrosis. Compared with the 2-point Dixon imaging, the multi-point Dixon can correct the inhomogeneity of the magnetic field, the attenuation of T2*, and increase the accuracy of the PDFF measurement [81]. Compared with MRS imaging, the Dixon sequence provides images of fat distribution and corrects for magnetic field inhomogeneity. Alexandra Grimm et al. confirm that the Dixon sequence has a higher repeatability to PDFF measurement [73], which supports its application in the future to predict mobility disorders and to evaluate the efficacy of therapeutic interventions for sarcopenia. However, it remains unclear for the most representative anatomical region and level for fat infiltration assessment of sarcopenia.

Rare advanced MR technology for skeletal muscle measurement

DTI

Advanced magnetic resonance techniques, such as diffusion tensor imaging (DTI), diffusion-weighted imaging (DWI), T1 mapping, T2 mapping, and strain rate tensor imaging, can also be used to evaluate muscle changes [32]. In addition to identifying early pathological changes in muscles that are difficult to detect on T1- and T2-weighted images, DTI could quantitatively evaluate myo-fibrosis, fat infiltration, and the anisotropy of muscle fiber orientation (Fig. 3A) [82]. These changes can be described through radial and axial diffusivity, mean diffusivity (MD), and fractional anisotropy (FA) (Fig. 3B). Scheel et al. have demonstrated that FA can predict the proportion of muscle fiber types, which Type I of fiber increased with FA value increased [83]. Current research about DTI focuses on muscle injury, muscle disease

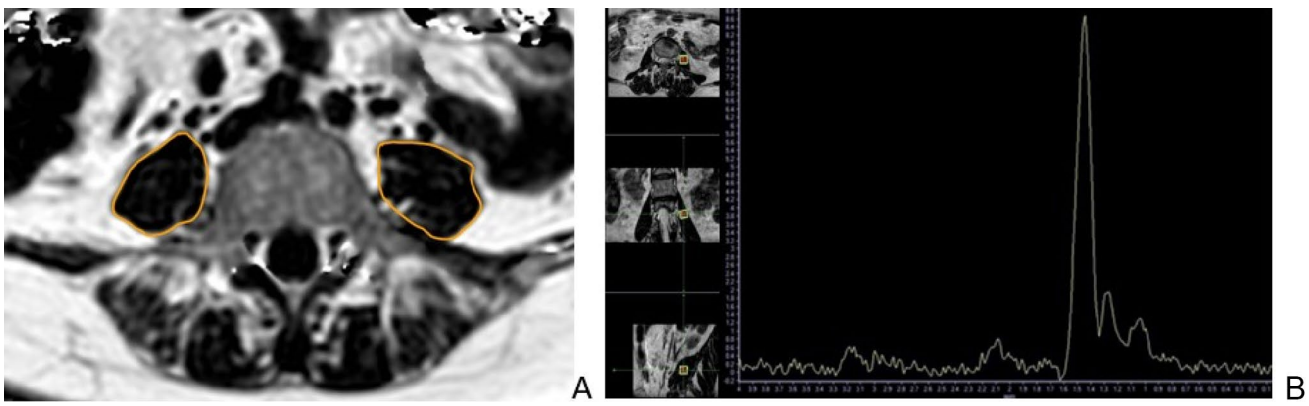

Fig. 2 Dixon and magnetic resonance spectroscopy images to evaluate PDFF, IMCL, and EMCL of psoas muscles. **A** Region of interest (ROI) delineation of psoas major muscle in the Dixon proton density fat fraction images of abdomen at the L3 level to evaluate the PDFF of psoas major muscle. **B** The volume of interest (VOI) for MR spectroscopy measurement was placed in the region of without macroscopic fatty infiltration of left psoas major muscle without macroscopic fatty infiltration on the sagittal, coronal, and axial orientation at the L3 level and obtained corresponding typical muscle spectrum with numbered peaks

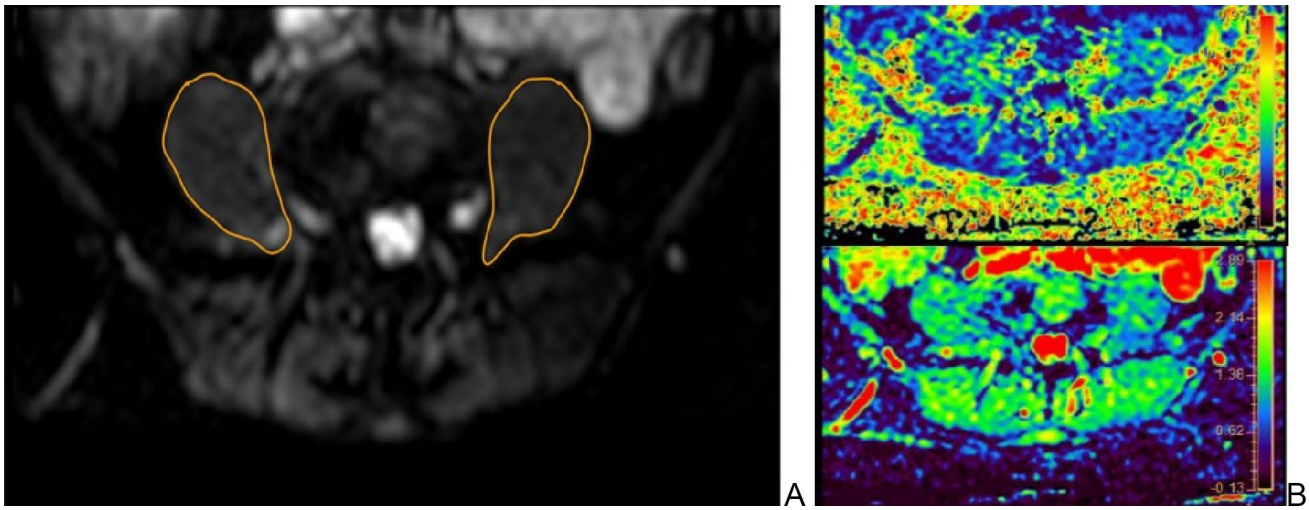

Fig. 3 ROI of psoas muscles axial images of DTI and measured values in a 65-year-old female patient. **A** A 65-year-old female. Axial diffusion tensor image abdomen images at the L3 level shows ROI delineation of psoas major muscles. **B** Corresponding calculated FA and MD maps from ROIs of psoas muscles

(Duchenne muscular dystrophy), and denervation changes, ischemia/reperfusion injury. DTI is expected to be used to evaluate the relation between muscle properties and external muscle strength in sarcopenia [84]

DWI, T1 mapping, and T2 mapping

Diffusion-weighted imaging (DWI) is an imaging technique based on the degree of motion of water molecules in tissues that are associated with their interaction with cell membrane macromolecules. Asides brain imaging, Apparent Diffusion Coefficient (ADC) value is helpful to evaluate the pathological changes of oncological tissues. Myositis and pathological muscle show increased ADC values compared to normal muscle, which suggests that ADC value can reflect the pathological status of muscle [85]. Surov et al. have confirmed that the ADC value has a significant association with end-stage liver disease in patients with cirrhosis [86]. The general skeletal muscle can also be measured using T1mapping and T2mapping. T1 mapping can measure muscle fat infiltration and is associated with the PDFF measured by Dixon [87]. T2 mapping can measure the increased T2 value (T2W) in sarcopenic patients with myo-fatty infiltration [88], which is sensitive to muscle changes and can assess acute and chronic muscle changes.

Strain rate tensor images, non-proton MRI, and MR elastography

Increased extracellular matrix is associated with decreased muscle strength and the magnitude of transient deformation. These changes can be detected through strain rate tensor images, which can provide information about the magnitude and direction of the deformation rate [32]. Besides this, the changes in muscle contractility and elasticity can also be observed in strain rate tensor imaging. The strain rate (SR) and the strain rate fiber angle (SR-fiber angle) are commonly used biomarkers [89]. Sinha et al. suggested that increased muscle stiffness with age may be related to the remodeling of the extracellular matrix [90]. In the future, strain rate tensor imaging may be used to assess the mechanical changes of muscles in sarcopenia, because it can reflect the mechanical properties of age-related muscles. Non-proton MRI techniques can achieve more microscopic assessment for the composition of muscle tissue through ^{23}Na MRI, having strongly correlation with the muscle tissue ion homeostasis and energy balance. The most commonly used biomarker is the tissue sodium concentration, which is a volume-weighted average of intra- and extracellular sodium concentrations. Gerhalter et al. demonstrated ^{23}Na MRI can detect elevated tissue sodium concentration in skeletal muscles of Duchenne muscular dystrophy [91], Besides ^{23}Na MRI, ^{35}Cl, and ^{39}K MRI of skeletal muscle tissue has been developed and conducted in some studies [92, 93]. Pathological changes of muscle, such as fat infiltration, fibrosis, and edema, can affect the muscle biomechanical properties. Magnetic resonance elastography (MRE) is based on the imaging of shear waves and enables quantitative evaluation of biomechanical tissue properties of skeletal muscle. MRE-derived biomechanical properties during skeletal muscle contraction and relaxation can reflect skeletal muscle function [94]. Recent studies demonstrated that MRE was a reliable technique to quantitatively detect muscle stiffness on thigh muscles and

paraspinal muscles [95, 96]. Current application of skeletal muscle mainly involves diseases related to neuromuscular dysfunction. Its application potential in sarcopenia is worthwhile to explore future. Although the new sequences mentioned above can reflect the changes in the microstructure and biomechanics of skeletal muscles, it is challenging to use these in clinical practice and some still are limited to the research field.

US

Compared with CT and MRI, ultrasonography provides the advantages of no radiation, simple and portable operation, low cost, good repeatability, and even the ability to measure muscle at the patient's bedside [97], making it a better choice for primary screening of sarcopenia. The lower extremity muscles are the most commonly measured muscle, because the loss of lower extremity muscles is higher than that of the upper extremities in sarcopenic patients [32]. The quadriceps femoris and gastrocnemius muscles are most often used in the research; and the commonly used indicators are muscle thickness (Fig. 4) and CSA for muscle mass and is echogenicity for muscle quality [98], which increases with the muscle fibrosis and fatty infiltration. Fukumoto et al. demonstrated that the echogenicity of the quadriceps was negatively correlated with muscle thickness and isometric knee extension force [99]. Other often used indicators include fascicle length, and pinnate angle [14]. At present, microvascular changes of muscles can also be assessed by measuring the microvascular blood volume, microvascular blood flow rate, and microvascular blood flow of the muscle through contrast-enhanced ultrasound [100]. The latest technologies include panoramic ultrasound and shear wave elastography. Jessica et al. confirmed that CSA of the quadriceps femoris measured by panoramic ultrasound was a significant correlation with the MRI-measured value [101]. Muscle stiffness can be quantitatively assessed by ultrasound shear wave elastography through measurement of shear wave velocity. However, due to the lack of standardized conditions, critical values, and poor accuracy, it has not been included in the diagnostic guidelines for sarcopenia so far.

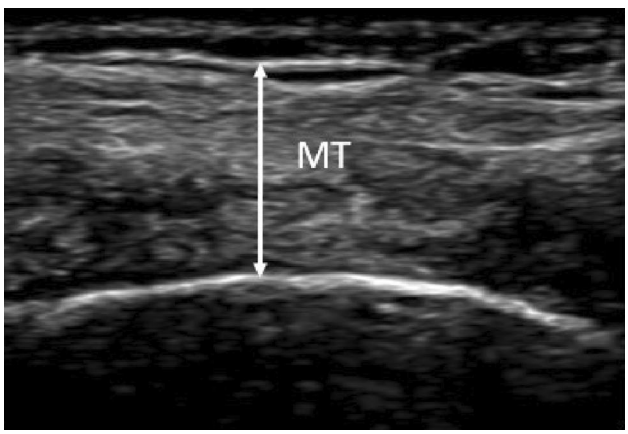

Fig. 4 Ultrasound measurement diagram of the muscular thickness (MT) of Vastus in the rectus femoris was shown

Application of artificial intelligence

The most important fields of artificial intelligence in radiology are machine learning and deep learning. In recent years, deep learning architectures is mainly used for image segmentation, reconstruction, recognition, and classification [102]. The machine learning method is mainly to extract lesion features from medical images to obtain valuable information [103]. The application of AI in sarcopenia can reduce time-consuming and increase accuracy. In sarcopenia, AI is mainly used for the automatic segmentation of body composition in images of CT, MRI, and ultrasonography; in addition, AI is helpful for evaluation and analysis of body composition parameters to collect information related to prognosis of sarcopenia or to recommend follow-up and potential treatment interventions [104]. Study of Gu et al. developed an AI segmentation model for a wider range of abdomen to predict sarcopenia and has been demonstrated high accuracy [105]. In the past two years, AI has achieved the transition from 2D to 3D in the automatic segmentation of CT body composition. And Mai et al. confirmed that the new segmental technique has higher feasibility and accuracy [106]. Cohort study of MBBS demonstrated that sarcopenia identified by a deep learning-based segmentation approach significantly affects overall survival in patients with cancer [107]. Although AI can reduce time consumption and decrease inter-evaluator variability, more rigorous guidelines and comparative studies are needed to assess the feasibility of AI segmentation models before into clinical practice.

Role of imaging techniques in sarcopenia

DXA be considered the mostly accept method for the assessment of body composition in clinical practice owing its safety, non-contraindications and clear diagnostic cut-off points. As cross-sectional imaging methods, CT and MRI have more advantages in measuring skeletal muscle fatty infiltration, especially MRI, which has higher accuracy in the assessment of skeletal muscle quality due to the rapid development and innovation of multi-functional and multi-parameter imaging sequences. In addition, CT and MRI also play an important role in treatment, follow-up and prognosis assessment of sarcopenic patients, mainly for patients with tumors and chronic diseases. The decrease in CT-measured PMI is also associated with risk for osteoporosis and vertebral fractures [108]. Recent study confirmed that measured SMI and psoas muscle thickness using routine MRI scans

can be used as imaging marker to predict the therapy efficacy and survival of patients with cancer in clinical practice [109, 110]. However, due to CT and MRI lack diagnostic criterion value, high costs and uneven distribution of medical resources, restricting their use on clinical settings. With technology development, ultrasound can also evaluate more microscopic changes in skeletal muscle, including skeletal muscle microvascular changes and muscle stiffness. However, due to the high compliance and low repeatability required by US, its clinical application is limited. AI are mostly focused on the improvement of segmentation efficiency to make easier to screen categories at risk of sarcopenia. The above indicates that various imaging parameters of sarcopenia play their respective advantages in malignant tumors and chronic diseases, but radiologists should choose the best imaging method according to the purpose of research and treatment.

Conclusion

Sarcopenia, as a silent disease, is rarely noticed in its early stages and people do not seek medical attention until symptoms appear. Imaging measurements of both muscle mass and quality are important diagnostic criteria for sarcopenia, suggesting that imaging techniques play a pivotal role in the evaluation of sarcopenia. Through comprehensive application of imaging methods and clinical assessment in diagnosing sarcopenia, patients can obtain early intervention through diet and exercise; thereby improving the prognosis, quality of life, and survival rates. However, there is a lack of standardization in scan site, diagnostic indicators, and criterion-based cut-off values. In addition, potential imaging biomarkers that can help to screen people at risk of developing sarcopenia at an early stage remain unknown, and there is no consensus about measurement indicators can predict adverse prognosis, restricting their application in the clinical environment. Therefore, future research is needed to solve the above problems.

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Data availability The authors declare data of the review is available.

Declarations

Conflict of interest The authors declare no conflict of interest.

Ethical approval This article is a review, so it does not require ethics approval with human participants or animals performed by any of the authors.

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