Body composition analysis by radiological imaging – methods, applications, and prospects

Radiologische Bestimmung der Gewebezusammensetzung im menschlichen Körper (*Body Composition*) – Methoden, Anwendungen und Aussichten

Authors

Nicolas Linder[1, 2], Timm Denecke[1], Harald Busse[1]

Affiliations

1 Department of Diagnostic and Interventional Radiology, University of Leipzig Medical Center, Leipzig, Germany

2 Division of Radiology and Nuclear Medicine, Kantonsspital St. Gallen, Sankt Gallen, Switzerland

Keywords

CT, MR-imaging, physiological studies, treatment effects, CT-quantitative, metabolic Disorders

received 24.6.2023
accepted after revision 24.12.2023
published online 2024

Bibliography

Fortschr Röntgenstr
DOI 10.1055/a-2263-1501
ISSN 1438-9029

Georg Thieme Verlag KG, Rüdigerstraße 14, 70469 Stuttgart, Germany

Correspondence

Dr. Nicolas Linder
Division of Radiology and Nuclear Medicine, Kantonsspital St. Gallen, Sankt Gallen, Switzerland
Tel.: +41/71 494 9089
nicolas.linder@kssg.ch

ABSTRACT

Background This review discusses the quantitative assessment of tissue composition in the human body (body composition, BC) using radiological methods. Such analyses are gaining importance, in particular, for oncological and metabolic problems. The aim is to present the different methods and definitions in this field to a radiological readership in order to facilitate application and dissemination of BC methods. The main focus is on radiological cross-sectional imaging.

Methods The review is based on a recent literature search in the US National Library of Medicine catalog (pubmed.gov) using appropriate search terms (body composition, obesity, sarcopenia, osteopenia in conjunction with imaging and radiology, respectively), as well as our own work and experience, particularly with MRI- and CT-based analyses of abdominal fat compartments and muscle groups.

Results and Conclusion Key post-processing methods such as segmentation of tomographic datasets are now well established and used in numerous clinical disciplines, including bariatric surgery. Validated reference values are required for a reliable assessment of radiological measures, such as fatty liver or muscle. Artificial intelligence approaches (deep learning) already enable the automated segmentation of different tissues and compartments so that the extensive datasets can be processed in a time-efficient manner – in the case of so-called opportunistic screening, even retrospectively from diagnostic examinations. The availability of analysis tools and suitable datasets for AI training is considered a limitation.

Key Points

- Radiological imaging methods are increasingly used to determine body composition (BC).
- BC parameters are usually quantitative and well reproducible.
- CT image data from routine clinical examinations can be used retrospectively for BC analysis.
- Prospectively, MRI examinations can be used to determine organ-specific BC parameters.
- Automated and in-depth analysis methods (deep learning or radiomics) appear to become important in the future.

Citation Format

- Linder N, Denecke T, Busse H. Body composition analysis by radiological imaging – methods, applications, and prospects. Fortschr Röntgenstr 2024; DOI 10.1055/a-2263-1501

ZUSAMMENFASSUNG

Hintergrund Die vorliegende Arbeit stellt die quantitative Erfassung der Gewebezusammensetzung im menschlichen Körper (Body Composition) mit den Mitteln der Radiologie vor. Derartige Analysen gewinnen vor allem bei onkologischen und metabolischen Fragestellungen an Bedeutung. Zielsetzung ist es, einer Leserschaft die unterschiedlichen Methoden und Definitionen auf diesem Gebiet vorzustellen, um deren Anwendung und Verbreitung zu erleichtern. Das

Hauptaugenmerk gilt dabei der radiologischen Schnittbildgebung.

Methoden Die Übersicht stützt sich auf eine aktuelle Literaturrecherche im Katalog der US-amerikanischen National Library of Medicine (pubmed.gov) mit entsprechenden Suchbegriffen (body composition, obesity, sarcopenia, osteopenia in Verbindung mit imaging bzw. radiology), sowie auf eigene Arbeiten und Erfahrungen, insbesondere mit der MRT- und CT-gestützten Analyse von abdominellen Fettkompartimenten und Muskelgruppen.

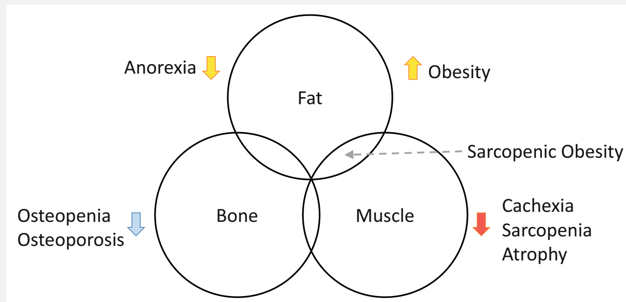
Ergebnisse und Schlussfolgerung Zentrale Nachverarbeitungsmethoden wie die Segmentierung von tomografischen Datensätzen sind inzwischen gut etabliert und finden in zahlreichen klinischen Studien Anwendung, u. a. in der Adipositas-Chirurgie. Für die verlässliche Beurteilung der radiologischen Messgrößen, z. B. einer Verfettung von Leber oder Muskulatur, sind validierte Referenzwerte erforderlich. Ansätze der Künstlichen Intelligenz (Deep Learning) ermöglichen bereits heute die automatisierte Segmentierung unterschiedlicher Gewebe und Kompartimente, damit die umfänglichen Datensätze zeiteffizient bearbeitet werden können – beim sogenannten opportunistischen Screening sogar retrospektiv aus diagnostischen Untersuchungen. Als Limitation gilt die Verfügbarkeit von Analyse-Werkzeugen sowie geeigneter Datensätze für das KI-Training.

Background and method

The body composition (BC) of different tissues, particularly, fat, muscle, and bone, can be quantified with radiological methods. Such analyses are particularly important for diseases like overweight and obesity, cachexia (pathological muscle loss), sarcopenia (age-related muscle loss), osteopenia (reduced bone density), and osteoporosis (bone loss with risk of fracture). ▶ **Fig. 1** provides a graphical overview of the main BC terms. Computed tomography (CT) and magnetic resonance imaging (MRI), in particular, provide good and nearly anatomical visualization of tissues and accurate information about their spatial distribution. Phenotypes that are associated with a specific disease, e. g., sarcopenic obesity, can be identified with the help of tissue parameters. So far, BC parameters have rarely been considered in daily clinical routine. Radiological findings like "visceral obesity" or "lipomatous changes in the dorsal musculature" are rather uncommon.

This review provides an overview of the current methods and features of a BC analysis. It will present some research highlights and focus on the translation of results into clinical practice. For this purpose, a literature search over the last five years was performed in the American *National Library of Medicine* (pubmed.gov) for the terms *body composition*, *obesity*, *sarcopenia*, *osteopenia* in connection with the key words *imaging* and *radiology* to identify relevant studies.

The primary aim of this study is to provide a better understanding of the current applications. The focus is on tomographic methods, which are required for a correct spatial visualization of tissues such as visceral adipose tissue (VAT). In principle, BC parameters can also be assessed with simpler methods like DEXA (*Dual Energy X-ray Absorptiometry*). In practice, however, this will have limitations like the underestimation of *visceral adipose tissue* (VAT) [1]. A further advantage of tomography is the large selection of available biomarkers. For the musculature, for example, it is possible to determine both the volume as well as the fat infiltration of individual muscles [2]. While conventional BC analysis methods have advantages with respect to availability and feasibility, CT and MRI are more versatile and more reliable. The reader is referred to the literature for further details on the techniques and applications of DEXA and ultrasound imaging [3–9].



▶ **Fig. 1** Overview of body composition terms.

Body composition parameters

Overweight and obesity are defined by the World Health Organization (WHO) as the ratio of body weight to the square of the body size (body mass index) with cutoff values at 25 and 30 kg/m^2, respectively [10]. The prevalence of obesity has seen a global increase over the last years. One third of the world's population is currently suffering from overweight or obesity. The term pandemic has been used to describe the situation [11]. Due to its simplicity and feasibility, BMI is still the most widely used measure of BC in spite of the known limitations [12]. Intraindividual changes in BMI during treatment are considered particularly meaningful [13]. Studies on overweight and obesity also rely on radiological methods for BC assessment when anthropometry is not sufficient [14–16], e. g., to differentiate fat from muscle mass [17]. The limited use of anthropometric parameters has recently been highlighted in a longitudinal study with over 3000 participants. Whereas BMI, body weight, or WHR (*waist-to-hip-ratio*) of the participants remained practically unchanged over the course of two years, significant changes were seen in the visceral and intermuscular fat tissue with MRI [18]. A complete segmentation of all cross-sectional images in the context of a volumetric BC assessment is rather rare. Due to time constraints, the analysis is often restricted to the segmentation of a representative slice, e. g., at the level of the lumbar spine for abdominal fat quantification [1, 19–22]. Using refined methods, for example, in longitudinal studies, MRI is also able to detect subtle changes in BC, sometimes even much earlier than conventional methods [18].

In BC analysis of the muscles, both the size and quality can be evaluated, particularly the degree of fatty degeneration. Patients with an oncological primary disease often have a special type of cachexia (cancer cachexia). A loss of skeletal muscle is often accompanied by a functional impairment that may often be partially compensated for, for example, by a special diet [23]. From early on, in an attempt to facilitate the analysis, studies have explored to which degree the loss of muscle mass, e. g., due to sarcopenia, can be detected on a well-defined single slice, often an axial CT scan at the level of the lumbar spine [24]. Similarly, volume and quality of the skeletal muscles can also be quantified by MRI [25].

The BC analysis of bone is traditionally based on the X-ray attenuation measured by DEXA or CT imaging. For peripheral bones, imaging provides its own biomarkers like the diameter, curvature, volume or three-dimensional geometry [26]. For bone tissue, MRI features special techniques to characterize the trabecular bone structure QSM, *quantitative susceptibility mapping*) and the cortical bone (UTE imaging, *ultrashort echo time TE*). For the differentiation between osteoporotic and pathological fractures, MRI offers several methods to evaluate the bone marrow fat, especially MR spectroscopy or imaging techniques sensitive to the chemical shift between fat and water signals [27].

The liver is a further target organ for BC analysis, particularly in the context of *metabolic dysfunction-associated steatotic liver disease* (MASLD). MRI may also be used in that case to determine the fat and water content from the ratio of the respective signals of the hydrogen atoms (PDFF, *proton density fat fraction*). For that purpose, MRI signals are recorded at more than two points in time (often six) and analyzed by a dedicated software application. MR elastography (MRE) is another functional technique that uses an external, periodic excitation (noninvasive) to generate shear waves in the body, which propagate in a tissue-specific manner. Information about the microscopic tissue displacement during wave propagation is encoded in a series of MR phase images. This data is then processed by a mathematical inversion algorithm to compute an elastogram, which represents the distribution of tissue stiffness. For many years, MRE has been used for the noninvasive evaluation of liver fibrosis, but the technique can also be used in other target regions, e. g., to determine the mechanical and elastic properties of muscular structures [28–30]. Ultrasound-based elastography should also be mentioned here as a BC method that is broadly used for the liver [31] although it is not a tomographic technique. Compared to elastographic methods, MRI diffusion imaging has so far only been used sporadically for BC analysis in spite of its clinical value for many diagnostic questions. There are still some applications, e. g., for the characterization of bone tissue [32, 33].

In an aging society, the phenotypes of metabolic primary diseases (obesity, osteoporosis, and cachexia) are often observed in combination and will then affect BC. In these cases, bone mineralization and muscle mass will often be reduced, whereas body fat content will be higher [34]. For a standardized BC analysis, age as well as sex and ethnicity must be taken into consideration [35]. Correlating BC parameters with cardiometabolic risk factors, for example, men revealed a pronounced association with intramuscular fat, whereas women showed a (weaker) association for visceral fat instead [36]. Comparing subjects with the same BMI, people of Asian descent often have a higher body fat content, greater abdominal obesity, and a higher intramyocellular lipid and liver fat content than Caucasians [37].

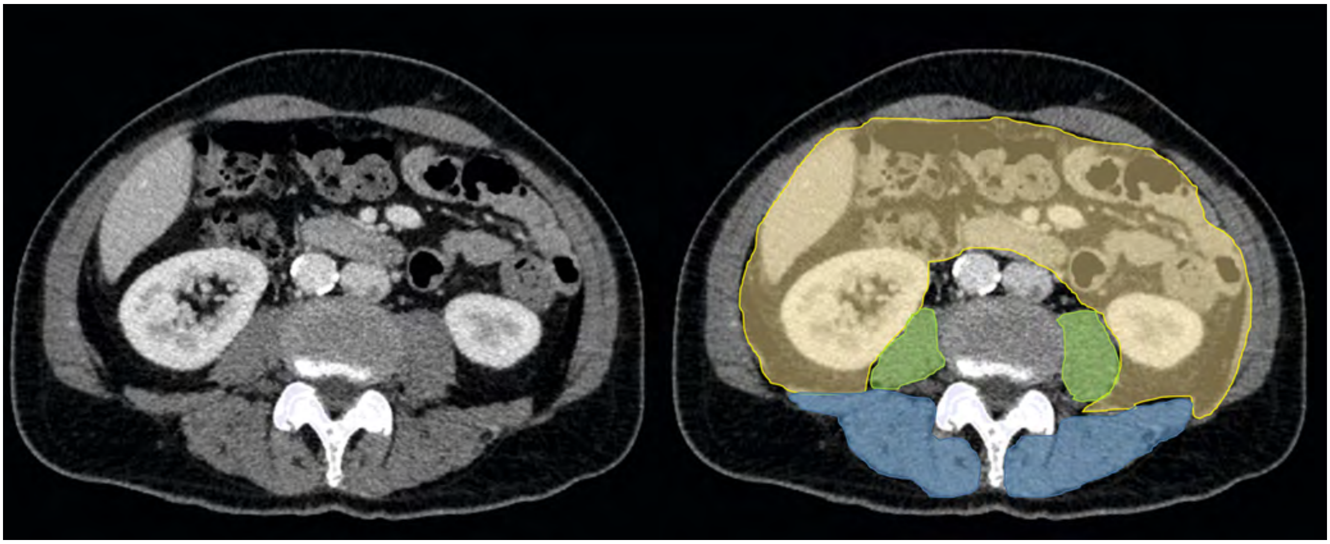
The most promising BC parameters are those that may serve as target variables or biomarkers for novel therapeutic strategies. The physical fitness is often assessed in patients with oncological diseases to evaluate the risks of morbidity and mortality. The disease-related and often unknowing weight loss in cachexia [38] cannot always be differentiated from the age-related physiological loss of muscle mass in sarcopenia [39–42].

Collaboration between radiology and other diagnostic disciplines including human genetics could help to characterize phenotypes even better [43]. This novel approach to diagnostics is sometimes referred to as integrated diagnostics [44].

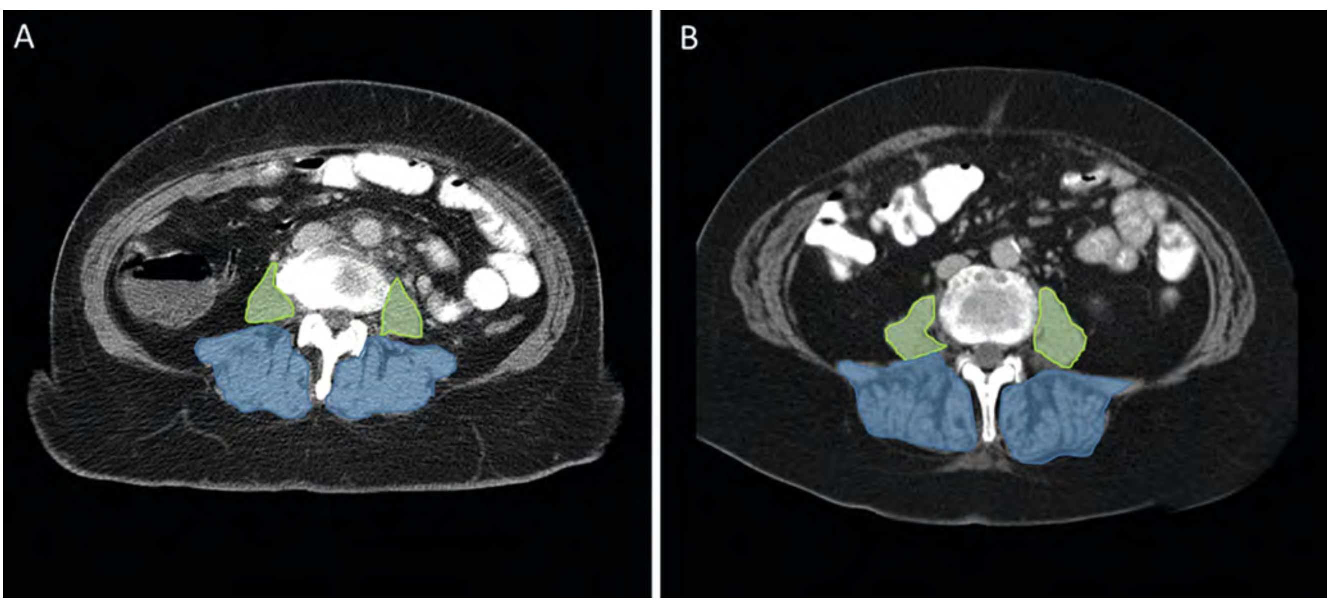
Imaging and evaluation methods

Cross-sectional imaging has been used since the 1990s to quantify fat compartments. To date, radiological BC analyses have usually been retrospective and have used, e. g., oncological CT staging data. The usually first task is to segment the corresponding tissue, i. e., to digitally define its margins or contours. ► **Fig. 2** shows an example of a segmentation of typical fat and muscle groups on a defined axial CT slice. Manual, semiautomatic, and fully automatic analysis tools are available and can be embedded in to the radiology workflow [16]. Some software used for research projects is self-developed and provided for other purposes as well, sometimes as open source code [45]. This allows for a flexible adjustment and extension of functionality, also for third parties, and is usually associated with lower costs. Commercial applications are usually less open but can be used more readily, depending on the degree of certification (e. g., as a medical product), and often have interfaces to the radiological information systems [46–48]. Deep learning methods are used increasingly to automate and accelerate the analysis. Such methods are of particular use for the analysis of large cohorts or on a national level. One prominent example is the management of data collected during the COVID-19 pandemic [49–51].

CT plays a special role in the context of gathering image data for BC analysis. CT imaging is relatively fast and uncomplicated, often part of a routine radiological examination, and also performed repeatedly during follow-up. ► **Fig. 3** shows a sample case for the evaluation of a patient with a combination of sarcopenia and obesity. One advantage of CT over MRI is the standardized scale for measurements (Hounsfield units). In the future, quantitative CT could also play a greater role in the characterization of MASLD [52]. There is, for example, a deep learning analysis of the skeletal muscles, which is based on routine CT scans of the abdomen [53]. Moreover, DL algorithms can also be used for quality control of the imaging itself [54].



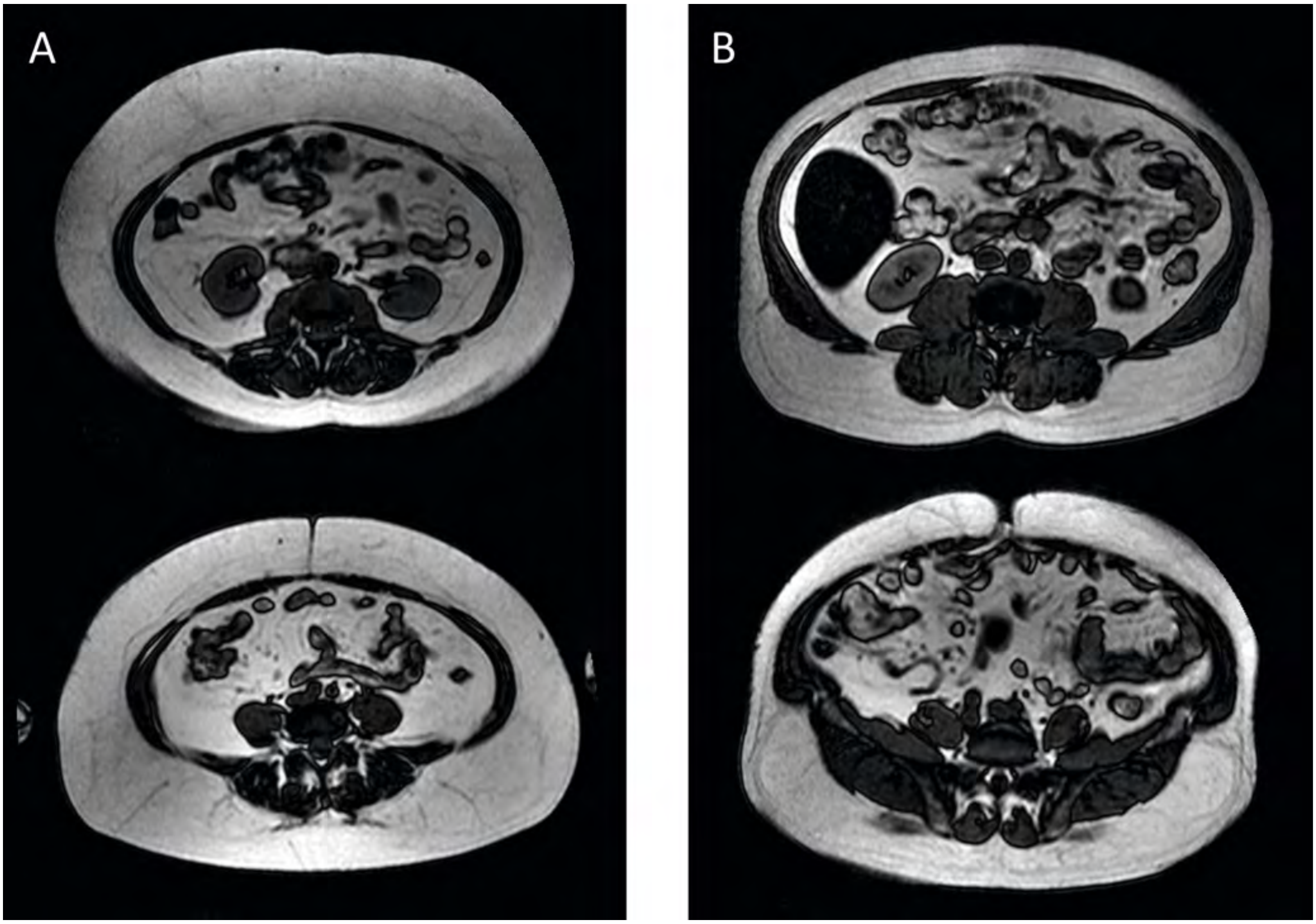
► **Fig. 2** Single CT slice at the level of L3 / L4 to evaluate body composition in a 60-year-old patient with no known primary metabolic disease (BMI 20.8 kg/m²). Compartments of subcutaneous fat tissue (not labeled here, area 89.3 cm²) and visceral fat tissue (yellow, 43.5 cm²), psoas muscle (green, 12.6 cm²) and paravertebral muscles (blue, 50.1 cm²). Mean muscle attenuation is 40.4 Hounsfield units (HU).



► **Fig. 3** Mean muscle (radiation) attenuation (MA) for evaluating sarcopenic obesity. Axial CT images of two female patients with a similar BMI (**A**: 32.3 kg/m², **B**: 33.5 kg/m²) but different MA (**A**: 47.2 HU, **B**: 11.3 HU).

In recent years, MRI-based BC analyses have improved the characterization of important metabolic diseases, including the metabolic syndrome and type 2 diabetes. The focus has been on the association with insulin resistance, visceral fat tissue, and treatment success after obesity surgery. ► **Fig. 5** shows an example of a longitudinal MRI examination of relative fat content before and after obesity surgery. MRI has also been increasingly used for pharmacological studies. PDFF measurements, for example, have demonstrated, at least preliminarily, a positive effect of semaglutide on MASLD; in 2023, the drug has also been publicly referred to as "weight loss medication" [55, 56]. Averaged PDFF values in the liver were also found to decrease after bariatric (obesity) surgery (► **Fig. 6**).

The MRI sequences needed for fat quantification (T1-weighted or Dixon technique) are available on nearly every system. So far, however, the method is not part of the routine examination protocol [57]. Interactive segmentation of fat and muscle tissue takes time and training, but many manufacturers are already providing advanced application modules to automatically evaluate and visualize the results. There are actually reports about corresponding requests to clinical radiologists. In addition, there are some commercial providers that offer such a non-clinical service.



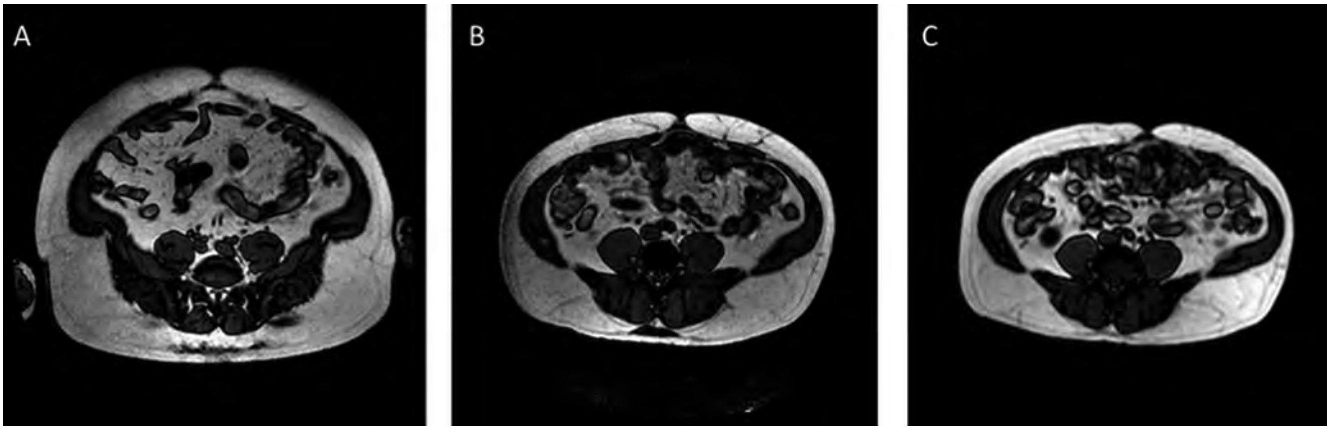
▶ **Fig. 4** MRI examination of patients with obesity: Comparison of two patients with a similar age and BMI (**A**: female, 50 years old, BMI 40.9 kg/m^2, **B**: male, 48 years old, BMI 39.2 kg/m^2). Initial cross-sectional imaging (**A**: at the level of the middle lumbar spine, L3 / L4, **B**: at the level of the lumbosacral joint L5 / S1) shows the differences between gluteofemoral (**A**) and visceral (**B**) fat distribution.

The training of deep learning models is substantially more difficult in the case of MRI images due to the multitude and variability of image weighting with sequences being selected as a function of anatomical region and clinical question. Conventional T1-weighted images may also be used for quantification even though segmentation is slightly more demanding. The advantages of using thicker slices, i. e., less efforts for acquisition and segmentation of the images and a higher signal-to-noise ratio, usually outweigh the disadvantage of a lower spatial resolution. For practical reasons and due to time constraints, many MRI studies, like their CT counterparts, restrict their analysis to single (representative) slices. An individual comparison with the total abdominal volumes showed, for example, a relatively good linear correlation for various fat compartments [19–22]. The MRI sequences on most systems have become so time-efficient that even whole-body imaging takes only a couple of minutes. ▶ **Fig. 4** illustrates the use of MRI for the evaluation of patients with obesity.

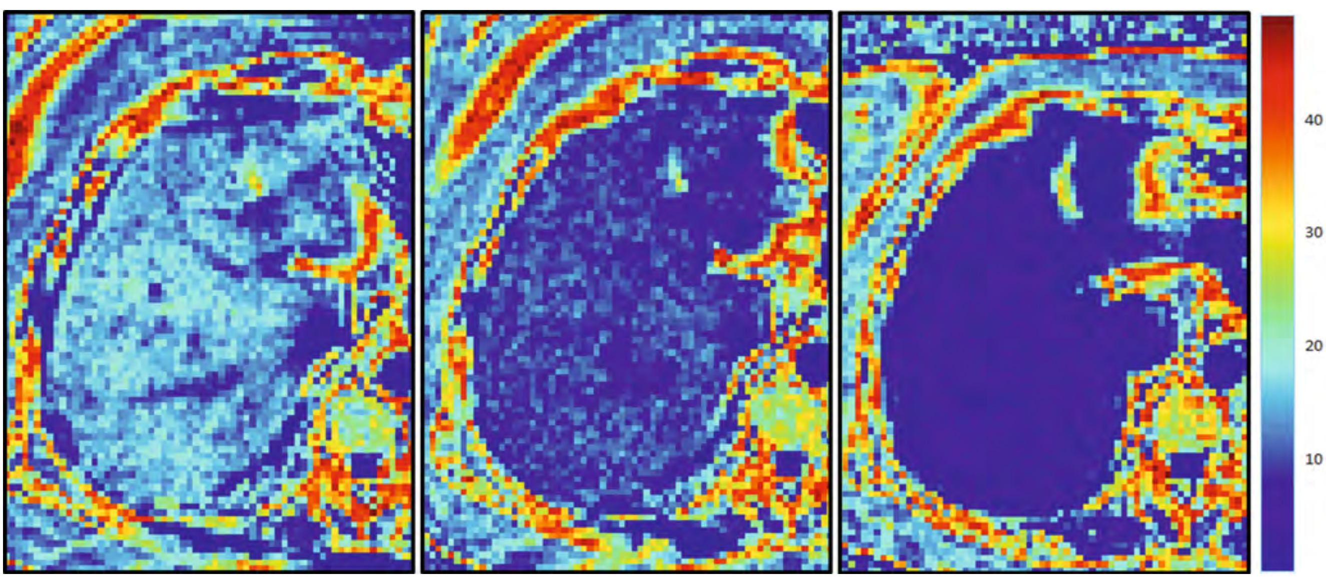
In PET-MRI whole-body imaging, Dixon sequences are routinely used for attenuation correction so that corresponding fat and water images are already available. Such datasets can now be segmented fully automatically to analyze compartments like fat, muscle, bone, and organs, also in pediatric patients [58]. New PET detectors allow multiphase PET/CT examinations during continuous table movement with robust data transfer (better than the conventional step-and-shoot technique) and are used, for example, in oncological imaging. Such technological progress should gradually provide deeper insights into specific metabolic processes. Time-resolved methods, e. g., dynamic whole-body PET/CT, are currently not widely available [59].

A tomographic assessment of the body composition is closely related to the clinical question, which is why serial examinations are rare. In one example, a mobile MRI system was used to determine body composition over the course of an ultramarathon (4500 km). The athletes showed a significant decrease in muscle and fat mass (VAT and SAT) [60].

The results of user-dependent BC analyses should be interpreted with some caution [61]. With respect to accuracy and reproducibility, some deep-learning approaches now outperform conventional segmentation of selected slices [62]. However, there are no standards with which the available evidence can be transferred to the clinical routine. This includes clear requirements, particularly in the case of therapeutic questions, e. g., for defining a controlled physical activity during sport or activity interventions. Another critical issue are the specific hardware components used. For



▶ **Fig. 5** Abdominal fat distribution of a 54-year-old man at the level of the navel before as well as 6 and 12 months after bariatric surgery (Roux-Y bypass). The visceral fat volume determined after segmentation of all axial MR slices (between diaphragm and symphysis) was significantly reduced – 8.3 L > 4.9 L > 4.2 L.



▶ **Fig. 6** Proton density fat fraction (PDFF) maps of the liver prior to obesity surgery, Roux-Y gastric bypass (average over shown region of interest 14 %) and in the follow-up examinations after 1 and 7 months (8.5 % and 4.6 %, respectively).

example, what is the potential impact of a particular imaging system or imaging protocol? One of the few methodological studies on 18 subjects showed, for example, that the inaccuracy of BC analyses by MRI (including PDFF in the liver, fat, and muscle volume) was largely determined by the repeatability of the measurement on the same system [63].

Current developments and outlook

In recent years, radiological methods have been increasingly used for BC analyses, particularly in sarcopenia [64, 65]. Disregarding a few exceptions, low muscle mass is now widely considered a risk factor for an unfavorable course of chemotherapy. The basis for this finding is a meta-analysis from the year 2023, which included 35 studies and over 3800 patients [66]. In 2022, the results of an automatic BC analysis were published with over 9200 asymptomatic adults undergoing colon cancer screening by CT over a median time period of 9 years. The X-ray attenuation of the skeletal muscles and the calcium content of the abdominal aorta had a prognostically significant effect on the 10-year survival rate. The AUC (area under the curve) was 0.72 (men) and 0.76 (women) [67].

Some fundamental limitations remain. For example, a standard for collecting and processing BC data is often lacking. The analyses are performed anyway, sometimes simply because many parameters are relatively easy to measure. Radiological BC parameters are often measured in clinical departments whose patients undergo radiological imaging. Subsequent correlations with clinical outcome variables are common and range from degenerative orthopedic diseases like lumbar disc herniation [68] to various malignancies (e. g., renal cell carcinoma [69] or non-metastasized colorectal carcinoma [70]), inflammatory diseases (chronic inflammatory bowel diseases) [71], and hospitalization in SARS-CoV2 infection [72]. BC analyses are usually aimed at a specific question and population and in-depth assessments are often secondary [4]. BC parameters can also be derived from the non-diagnostic CT information of a planning CT scan [73]. At the other end, controlled analyses from large cohorts like the *UK Biobank* [74] or National Cohort (Germany) [49] are needed for a reliable translation into the clinical routine but remain rare.

Considering the lack of standards and reference values, there is a demand for more evidence for radiological BC analyses. Already in 2007, the *Quantitative Imaging Biomarkers Alliance* (QIBA) of the Radiological Society of North America (RSNA) was founded with the goal of achieving the highest possible validity and reproducibility in radiological image data analysis. One prominent result is the multicenter evaluation of multi-echo MRI sequences (Dixon technique), the basis for determining liver fat content (PDFF) [75]. It was shown that field strength, MRI manufacturer, and reconstruction method barely had an influence on reproducibility. The clear methodological specifications were a pivotal element of this study. The increasing demand for scientific publication in combination with easily available image data may potentially provide some room for less stringent evaluations. In radiology, there is a growing demand to ensure that the evidence of such analyses has a solid basis.

Essentially, radiological imaging is meant to answer specific questions from the referring physicians (after justification of the indication) to ultimately provide optimal care to the patient. Reviewing the indication for a CT examination is particularly strict because patients will be exposed to ionizing radiation. Modern multidetector CT scanners generate high-resolution 3D data sets with complete body coverage, e. g., in routine staging examinations. Regardless of the original indication, the image data can be used for "opportunistic screening", i. e., a search for further diagnostic findings not yet reported [76]. It is then possible to derive quantitative metabolic or BC information from these data sets that may ideally serve as a biomarker. Important imaging features include the mineral salt content in osteopenia, visceral fat volume in overweight and obesity, vascular calcifications in arteriosclerosis, intrahepatic fat in MASLD, and skeletal muscle mass and quality in sarcopenia. From a radiological standpoint, there is a clear medical advantage for patients. Outside the context of a clinical or scientific study, however, the reimbursement of these additional services needs to be clarified [77].

An individual risk profile can be defined from the wealth of features. BC measurements are also of interest from an ethical point of view. If, for example, the screening examination does not show the wanted imaging feature, a quantitative BC analysis may provide additional information. The question that arises here is whether potentially relevant BC information that is rather easy to assess can actually be withheld from the patient? The extra efforts would already be acceptable today but in the future, such evaluations will likely become automated. Some experts already consider BC information as a contribution to a radiology, where the value of information is more important than its volume [53].

The number of examinations and data volume in radiology will likely increase. Traditional, risk-stratified, step-by-step diagnosis could be replaced by a higher prioritization of imaging, particularly when disadvantages like radiation exposure are further reduced by technology, and referring physicians, e. g., in the emergency department, demand a higher efficiency. A relative lack of medical expertise and insufficient training structures could reinforce the trend to verify clinical decisions with a broader indication for imaging. So far, urgent, i. e., early imaging has been reserved for emergencies, e. g., of the cardiovascular system. The indication for imaging over other diagnostic tests is already discussed in the literature: what is the effect of a CT examination on the clinical course in older people with a suspicion of acute appendicitis [78–80]? If cross-sectional imaging would be performed at the beginning of the diagnostic chain, a BC analysis with metabolic risk profile could be useful for more individualized patient care. This would require well-trained personnel, modern and available imaging systems with a corresponding IT infrastructure, and regulated allocation of costs.

It can be concluded that the value of radiology for the evaluation of body composition has increased in recent years. The application spectrum will probably grow as a result of the fundamental challenges faced by the health care system, particularly the demographic change and the increase in obesity-related diseases. For the field of radiology, it is therefore important to keep an eye on the overall picture and the relevant trends and interactions between the players involved.

Conflict of Interest

The authors declare that they have no conflict of interest.

References

[1] Borga M, West J, Bell JD et al. Advanced body composition assessment: from body mass index to body composition profiling. Journal of Investigative Medicine 2018; 66: 1–9

[2] Borga M. MRI adipose tissue and muscle composition analysis-a review of automation techniques. Br J Radiol 2018; 91: 20180252. doi:10.1259/bjr.20180252

[3] Guglielmi G, Ponti F, Agostini M et al. The role of DXA in sarcopenia. Aging Clin Exp Res 2016; 28: 1047–1060

[4] Tosato M, Marzetti E, Cesari M et al. Measurement of muscle mass in sarcopenia: from imaging to biochemical markers. Aging Clin Exp Res 2017; 29: 19–27

[5] Albano D, Messina C, Vitale J et al. Imaging of sarcopenia: old evidence and new insights. Eur Radiol 2020; 30: 2199–2208

[6] Ponti F, De Cinque A, Fazio N et al. Ultrasound imaging, a stethoscope for body composition assessment. Quant Imaging Med Surg 2020; 10: 1699–1722

[7] Hemke R, Buckless C, Torriani M. Quantitative Imaging of Body Composition. Semin Musculoskelet Radiol 2020; 24: 375–385

[8] Messina C, Albano D, Gitto S et al. Body composition with dual energy X-ray absorptiometry: from basics to new tools. Quant Imaging Med Surg 2020; 10: 1687–1698

[9] Chianca V, Albano D, Messina C et al. Sarcopenia: imaging assessment and clinical application. Abdom Radiol (NY) 2021. doi:10.1007/s00261-021-03294-3

[10] Ng M, Fleming T, Robinson M et al. Global, regional, and national prevalence of overweight and obesity in children and adults during 1980-2013: a systematic analysis for the Global Burden of Disease Study 2013. Lancet 2014; 384: 766–781

[11] Chooi YC, Ding C, Magkos F. The epidemiology of obesity. Metabolism 2019; 92: 6–10

[12] Thomas EL, Saeed N, Hajnal JV et al. Magnetic resonance imaging of total body fat. Journal of Applied Physiology 1998; 85: 1778–1785

[13] Wu Z, Gao Z, Qiao Y et al. Long-Term Results of Bariatric Surgery in Adolescents with at Least 5 Years of Follow-up: a Systematic Review and Meta-Analysis. Obes Surg 2023; 33: 1730–1745

[14] Heymsfield SB. Development of imaging methods to assess adiposity and metabolism. Int J Obes (Lond) 2008; 32 (Suppl. 7): S76–S82

[15] Heymsfield SB, Hu HH, Shen W et al. Emerging Technologies and their Applications in Lipid Compartment Measurement. Trends Endocrinol Metab 2015; 26: 688–698

[16] Hu HH, Chen J, Shen W. Segmentation and quantification of adipose tissue by magnetic resonance imaging. MAGMA 2016; 29: 259–276

[17] Bray GA. Beyond BMI. Nutrients 2023; 15: 2254. doi:10.3390/nu15102254

[18] Whitcher B, Thanaj M, Cule M et al. Precision MRI phenotyping enables detection of small changes in body composition for longitudinal cohorts. Sci Rep 2022; 12: 3748. doi:10.1038/s41598-022-07556-y

[19] Schwenzer NF, Machann J, Schraml C et al. Quantitative analysis of adipose tissue in single transverse slices for estimation of volumes of relevant fat tissue compartments: a study in a large cohort of subjects at risk for type 2 diabetes by MRI with comparison to anthropometric data. Investigative radiology 2010; 45: 788–794

[20] Springer F, Ehehalt S, Sommer J et al. Predicting volumes of metabolically important whole-body adipose tissue compartments in overweight and obese adolescents by different MRI approaches and anthropometry. European Journal of Radiology 2012; 81: 1488–1494

[21] Schaudinn A, Linder N, Garnov N et al. Predictive accuracy of single- and multi-slice MRI for the estimation of total visceral adipose tissue in overweight to severely obese patients: MRI prediction of visceral fat volumes. NMR in Biomedicine 2015; 28: 583–590

[22] Linder N, Schaudinn A, Garnov N et al. Age and gender specific estimation of visceral adipose tissue amounts from radiological images in morbidly obese patients. Scientific Reports 2016; 6: 22261. doi:10.1038/srep22261

[23] Fearon K, Strasser F, Anker SD et al. Definition and classification of cancer cachexia: an international consensus. Lancet Oncol 2011; 12: 489–495

[24] Zopfs D, Theurich S, Große HokampN et al. Single-slice CT measurements allow for accurate assessment of sarcopenia and body composition. Eur Radiol 2020; 30: 1701–1708

[25] Sizoo D, de Heide LJM, Emous M et al. Measuring Muscle Mass and Strength in Obesity: a Review of Various Methods. Obes Surg 2021; 31: 384–393

[26] Lacoste JeansonA, Santos F, Villa C et al. Architecture of the femoral and tibial diaphyses in relation to body mass and composition: Research from whole-body CT scans of adult humans. Am J Phys Anthropol 2018; 167: 813–826

[27] Sollmann N, Löffler MT, Kronthaler S et al. MRI-Based Quantitative Osteoporosis Imaging at the Spine and Femur. J Magn Reson Imaging 2021; 54: 12–35

[28] Low G, Ferguson C, Locas S et al. Multiparametric MR assessment of liver fat, iron, and fibrosis: a concise overview of the liver “Triple Screen”. Abdom Radiol (NY) 2023; 48: 2060–2073

[29] Hayashi D, Roemer FW, Tol JL et al. Emerging Quantitative Imaging Techniques in Sports Medicine. Radiology 2023; 308: e221531. doi:10.1148/radiol.221531

[30] Yin M, Ehman RL. MR Elastography: Practical Questions, From the Am J Roentgenol Special Series on Imaging of Fibrosis. Am J Roentgenol 2023. doi:10.2214/Am J Roentgenol.23.29437

[31] Barr RG, Wilson SR, Rubens D et al. Update to the Society of Radiologists in Ultrasound Liver Elastography Consensus Statement. Radiology 2020; 296: 263–274

[32] Herrmann J, Krstin N, Schoennagel BP et al. Age-related distribution of vertebral bone-marrow diffusivity. Eur J Radiol 2012; 81: 4046–4049

[33] Raya JG, Duarte A, Wang N et al. Applications of Diffusion-Weighted MRI to the Musculoskeletal System. J Magn Reson Imaging 2023. doi:10.1002/jmri.2887034

[34] JafariNasabian P, Inglis JE, Reilly W et al. Aging human body: changes in bone, muscle and body fat with consequent changes in nutrient intake. Journal of Endocrinology 2017; 234: R37–R51

[35] Magudia K, Bridge CP, Bay CP et al. Population-Scale CT-based Body Composition Analysis of a Large Outpatient Population Using Deep Learning to Derive Age-, Sex-, and Race-specific Reference Curves. Radiology 2021; 298: 319–329

[36] Schorr M, Dichtel LE, Gerweck AV et al. Sex differences in body composition and association with cardiometabolic risk. Biol Sex Differ 2018; 9: 28

[37] Wulan SN, Westerterp KR, Plasqui G. Ethnic differences in body composition and the associated metabolic profile: a comparative study between Asians and Caucasians. Maturitas 2010; 65: 315–319

[38] Nixon DW. Cancer, cancer cachexia, and diet: lessons from clinical research. Nutrition 1996; 12: S52–S56

[39] Evans WJ, Campbell WW. Sarcopenia and age-related changes in body composition and functional capacity. J Nutr 1993; 123: 465–468

[40] Han J, Harrison L, Patzelt L et al. Imaging modalities for diagnosis and monitoring of cancer cachexia. EJNMMI Res 2021; 11: 94

[41] Tolonen A, Pakarinen T, Sassi A et al. Methodology, clinical applications, and future directions of body composition analysis using computed tomography (CT) images: A review. Eur J Radiol 2021; 145: 109943

[42] Vogele D, Otto S, Sollmann N et al. Sarcopenia – Definition, Radiological Diagnosis, Clinical Significance. Zeitschrift Fortschr Röntgenstr 2023; 195: 393–405. doi:10.1055/a-1990-0201

[43] Mahajan A, Spracklen CN, Zhang W et al. Multi-ancestry genetic study of type 2 diabetes highlights the power of diverse populations for discovery and translation. Nat Genet 2022; 54: 560–572

[44] Haselmann V, Schoenberg SO, Neumaier M et al. Integrated diagnostics. Radiologie (Heidelb) 2022; 62: 11–16

[45] Stange R, Linder N, Schaudinn A et al. Dicomflex: A novel framework for efficient deployment of image analysis tools in radiological research. PLoS ONE 2018; 13: e0202974

[46] Karlsson A, Rosander J, Romu T et al. Automatic and quantitative assessment of regional muscle volume by multi-atlas segmentation using whole-body water-fat MRI. J Magn Reson Imaging 2015; 41: 1558–1569

[47] Borga M, Thomas EL, Romu T et al. Validation of a fast method for quantification of intra-abdominal and subcutaneous adipose tissue for large-scale human studies: Quantification of IAAT and ASAT. NMR in Biomedicine 2015; 28: 1747–1753

[48] West J, Dahlqvist LeinhardO, Romu T et al. Feasibility of MR-Based Body Composition Analysis in Large Scale Population Studies. PLoS One 2016; 11: e0163332

[49] Schlett CL, Hendel T, Weckbach S et al. Population-Based Imaging and Radiomics: Rationale and Perspective of the German National Cohort MRI Study. Zeitschrift Fortschr Röntgenstr 2016; 188: 652–661

[50] Scherer J, Nolden M, Kleesiek J et al. Joint Imaging Platform for Federated Clinical Data Analytics. JCO Clin Cancer Inform 2020; 4: 1027–1038

[51] Salg GA, Ganten MK, Bucher AM et al. A reporting and analysis framework for structured evaluation of COVID-19 clinical and imaging data. NPJ Digit Med 2021; 4: 69

[52] Starekova J, Hernando D, Pickhardt PJ et al. Quantification of Liver Fat Content with CT and MRI: State of the Art. Radiology 2021; 301: 250–262

[53] Pickhardt PJ, Graffy PM, Perez AA et al. Opportunistic Screening at Abdominal CT: Use of Automated Body Composition Biomarkers for Added Cardiometabolic Value. Radiographics 2021; 41: 524–542

[54] Nowak S, Theis M, Wichtmann BD et al. End-to-end automated body composition analyses with integrated quality control for opportunistic assessment of sarcopenia in CT. Eur Radiol 2022; 32: 3142–3151

[55] Flint A, Andersen G, Hockings P et al. Randomised clinical trial: semaglutide versus placebo reduced liver steatosis but not liver stiffness in subjects with non-alcoholic fatty liver disease assessed by magnetic resonance imaging. Aliment Pharmacol Ther 2021; 54: 1150–1161

[56] Alkhouri N, Herring R, Kabler H et al. Safety and efficacy of combination therapy with semaglutide, cilofexor and firsocostat in patients with non-alcoholic steatohepatitis: A randomised, open-label phase II trial. Journal of Hepatology 2022; 77: 607–618

[57] Baum T, Cordes C, Dieckmeyer M et al. MR-based assessment of body fat distribution and characteristics. European Journal of Radiology 2016; 85: 1512–1518

[58] Lee SB, Cho YJ, Yoon SH et al. Automated segmentation of whole-body CT images for body composition analysis in pediatric patients using a deep neural network. Eur Radiol 2022; 32: 8463–8472. doi:10.1007/s00330-022-08829-w

[59] Tamaki N, Kotani T, Nishimura M et al. Dynamic whole-body FDG-PET imaging for oncology studies. Clin Transl Imaging 2022; 10: 249–258

[60] Schütz UHW, Billich C, König K et al. Characteristics, changes and influence of body composition during a 4486 km transcontinental ultramarathon: results from the TransEurope FootRace mobile whole body MRI-project. BMC Med 2013; 11: 122

[61] Barbalho ER, Rocha IMG da, Medeiros GOC de et al. Agreement between software programmes of body composition analyses on abdominal computed tomography scans of obese adults. Arch Endocrinol Metab 2020; 64: 24–29

[62] Borrelli P, Kaboteh R, Enqvist O et al. Artificial intelligence-aided CT segmentation for body composition analysis: a validation study. Eur Radiol Exp 2021; 5: 11

[63] Borga M, Ahlgren A, Romu T et al. Reproducibility and repeatability of MRI-based body composition analysis. Magn Reson Med 2020; 84: 3146–3156

[64] Lee K, Shin Y, Huh J et al. Recent Issues on Body Composition Imaging for Sarcopenia Evaluation. Korean J Radiol 2019; 20: 205–217

[65] Tagliafico AS, Bignotti B, Torri L et al. Sarcopenia: how to measure, when and why. Radiol Med 2022; 127: 228–237

[66] Surov A, Strobel A, Borggrefe J et al. Low skeletal muscle mass predicts treatment response in oncology: a meta-analysis. Eur Radiol 2023; 33: 6426–6437

[67] Lee MH, Zea R, Garrett JW et al. Abdominal CT Body Composition Thresholds Using Automated AI Tools for Predicting 10-year Adverse Outcomes. Radiology 2023; 306: e220574

[68] Mateos-Valenzuela AG, González-Macías ME, Ahumada-Valdez S et al. Risk factors and association of body composition components for lumbar disc herniation in Northwest, Mexico. Sci Rep 2020; 10: 18479

[69] Higgins MI, Martini DJ, Patil DH et al. Quantification of body composition in renal cell carcinoma patients: Comparing computed tomography and magnetic resonance imaging measurements. Eur J Radiol 2020; 132: 109307

[70] Ying P, Jin W, Wu X et al. Association between CT-Quantified Body Composition and Recurrence, Survival in Nonmetastasis Colorectal Cancer Patients Underwent Regular Chemotherapy after Surgery. Biomed Res Int 2021; 2021: 6657566

[71] Bamba S, Inatomi O, Takahashi K et al. Assessment of Body Composition From CT Images at the Level of the Third Lumbar Vertebra in Inflammatory Bowel Disease. Inflamm Bowel Dis 2021; 27: 1435–1442

[72] Chandarana H, Pisuchpen N, Krieger R et al. Association of body composition parameters measured on CT with risk of hospitalization in patients with Covid-19. Eur J Radiol 2021; 145: 110031

[73] Muresan BT, Sánchez JuanC, Artero A et al. Measurement of body composition in cancer patients using CT planning scan at the third lumbar vertebra. Nutr Hosp 2019; 36: 1307–1314

[74] Dodds RM, Granic A, Robinson SM et al. Sarcopenia, long-term conditions, and multimorbidity: findings from UK Biobank participants. J Cachexia Sarcopenia Muscle 2020; 11: 62–68

[75] Yokoo T, Serai SD, Pirasteh A et al. Linearity, Bias, and Precision of Hepatic Proton Density Fat Fraction Measurements by Using MR Imaging: A Meta-Analysis. Radiology 2018; 286: 486–498

[76] Pickhardt PJ. Value-added Opportunistic CT Screening: State of the Art. Radiology 2022; 303: 241–254

[77] Pickhardt PJ, Summers RM, Garrett JW et al. Opportunistic Screening: Radiology Scientific Expert Panel. Radiology 2023; 307: e222044

[78] Stoker J, van Randen A, Laméris W et al. Imaging patients with acute abdominal pain. Radiology 2009; 253: 31–46

[79] van Randen A, Laméris W, van Es HW et al. A comparison of the accuracy of ultrasound and computed tomography in common diagnoses causing acute abdominal pain. Eur Radiol 2011; 21: 1535–1545

[80] Lau HT, Liu W, Lam V et al. Early routine (erCT) versus selective computed tomography (sCT) for acute abdominal pain: A systematic review and meta-analysis of randomised trials. Int J Surg 2022; 101: 106622