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Original article

Comparing bedside and CT-derived muscle mass assessment methodologies at intensive care unit admission: A critical step towards bedside detection of reduced muscle mass[☆]

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SUMMARY

Background and Aims: Reduced skeletal muscle mass at Intensive Care Unit (ICU) admission is associated with increased mortality. Bedside techniques, including bioelectrical impedance analysis (BIA), ultrasonography (US), and calf circumference (CC), may help to estimate skeletal muscle mass in critically ill patients. This study aimed to investigate the accuracy of these bedside methods in assessing muscle mass compared to lumbar 3 (L3) CT-derived skeletal muscle index (CT-SMI) and determine cut-offs for reduced muscle mass upon ICU admission.
Methods: A prospective, single-centre, cohort study conducted between May 2023 and April 2025. Patients (≥18 years) with an expected ICU stay ≥3 days were included. Bedside parameters (<48 h of ICU admission) included multifrequency BIA-derived skeletal muscle mass (BIA-SMM) and fat-free mass (BIA-FFM)), US-derived *rectus femoris* cross-sectional area (US-RFCSA) and *quadriceps* muscle layer thickness (US-QMLT), and CC (adjusted for BMI). These were compared to L3 CT-SMI and CT-derived skeletal muscle area (CT-SMA) retrieved 7 days before to 24 h after ICU admission. Correlations between CT and bedside methods were assessed. Reduced muscle mass was defined using CT-based SMI cut-offs (females <38 cm^2/m^2; males <50 cm^2/m^2) to determine cut-off values of bedside parameters using ROC analyses.
Results: Fifty-six ICU patients (70 % male) were included, showing 64 % having reduced skeletal muscle mass. Correlations of CT-SMI with BIA and US parameters were weak to moderate ($r = 0.36$–0.45, all $p < 0.05$), while CT-SMA correlated moderately with BIA-FFM ($r = 0.57$) and BIA-SMM ($r = 0.62$, both $p < 0.001$) but not with US-RFCSA, US-QMLT, and CC ($p > 0.05$). Cut-offs for reduced skeletal muscle mass were BIA-FFMI: 23.8 kg/m^2 and 20.0 kg/m^2; BIA-SMMI: 13.4 kg/m^2 and 10.7 kg/m^2; adjusted CC: 36.8 cm and 33.8 cm, in males and females, respectively, and US-RFCSA: 4.3 cm^2 and US-QMLT: 2.3 cm (both sexes).
Conclusion: At ICU admission, correlations between bedside methods and L3 CT-derived muscle mass were low to moderate. Cut-off values were derived to detect reduced skeletal muscle upon ICU admission. However, further validation is required before clinical implementation.

Abbreviations: AI, Artificial Intelligence; APACHE, Acute Physiology and Chronic Health Evaluation; ASIS, Anterior Superior Iliac Spine; AUC, Area Under the Curve; BIA, Bioelectrical Impedance Analysis; BIA-FFM, BIA Fat-Free Mass; BIA-FFMI, BIA Fat-Free Mass Index; BIA-SMM, BIA Skeletal Muscle Mass; BIA-SMMI, BIA Skeletal Muscle Mass Index; BMI, Body Mass Index; CC, Calf Circumference; COPD, Chronic Obstructive Pulmonary Disease; CRP, C-Reactive Protein; CT, Computed Tomography; CT-SMA, CT-Derived Skeletal Muscle Area; CT-SMI, CT-Derived Skeletal Muscle Index; DICOM, Digital Imaging and Communications in Medicine; eGFR, Estimated Glomerular Filtration Rate; ESPEN, European Society of Clinical Nutrition and Metabolism; EWGSOP, European Working Group on Sarcopenia in Older People; GLIM, Global Leadership Initiative on Malnutrition; HU, Hounsfield Units; ICU, Intensive Care Unit; L3, Lumbar Vertebra 3; MRI, Magnetic Resonance Imaging; NUTRIC, Nutrition Risk in the Critically Ill; PACS, Picture Archiving and Communication System; ROC, Receiver Operating Characteristic; SOFA, Sequential Organ Failure Assessment; US, Ultrasonography; US-QMLT, Ultrasound Quadriceps Muscle Layer Thickness; US-RFCSA, Ultrasound Rectus Femoris Cross-Sectional Area.

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1. Introduction

Skeletal muscle mass is a critical indicator of overall health, reflecting nutritional status and functional capacity in patient populations [1,2]. In critically ill patients admitted to an intensive care unit (ICU), reduced skeletal muscle mass at admission is a common finding [3]. It is significantly associated with increased length of stay and both short-term and long-term mortality [3,4]. Assessing muscle mass is essential for diagnostic frameworks such as malnutrition (e.g. Global Leadership Initiative on Malnutrition (GLIM criteria) and sarcopenia (e.g. European Working Group on Sarcopenia in Older People (EWGSOP)) [5,6]. Moreover, the assessment of skeletal muscle mass is crucial in guiding nutritional support and physical therapy to prevent further deterioration and promote recovery [7].

Computed tomography (CT) imaging and magnetic resonance imaging (MRI) at the level of the third lumbar vertebra (L3) are regarded as the most direct methods for assessing skeletal muscle mass [4,8]. However, these are not always feasible in ICU settings due to logistical concerns, and their use is generally limited to when imaging is already indicated for other clinical purposes. This challenge warrants validated, non-invasive, bedside methods to estimate skeletal muscle mass in ICU patients. At present, several practical tools for bedside assessment of muscle mass are proposed by GLIM and EWGSOP, including bioelectrical impedance analysis (BIA), muscle size assessed by ultrasonography (US), and anthropometric measurements (such as upper-arm or calf circumference) [5,6].

Among these, muscle US, particularly of the *quadriceps* muscle, has been increasingly used to assess skeletal muscle mass in clinical ICU studies [9,10]. However, clear cut-off values for defining reduced muscle mass or sarcopenia are lacking, even among healthy populations [11,12]. Additionally, muscle US captures only appendicular muscle mass, which may not reflect whole-body skeletal muscle mass (SMM). On the other hand, BIA-derived SMM and fat-free mass (BIA-FFM), as well as anthropometric measures such as calf circumference (CC), may be affected by fluid shifts and altered body composition commonly present in critically ill patients. Existing cut-offs for these measurements are often derived from healthy populations [6,13], limiting their applicability to ICU patients. While definitive interventional evidence is still limited, the current European guidelines recognise lean body mass as an important parameter in guiding protein delivery during critical illness [14]. Establishing ICU-specific bedside cut-offs to identify reduced muscle mass may help operationalise this guidance and reduce the risk of inadequate feeding, particularly in patients with altered body composition such as sarcopenia or obesity [14].

This study aimed to evaluate, at ICU admission, the accuracy of three bedside methods, BIA, US, and CC, for assessing skeletal muscle mass, as compared to the gold standard L3 CT-derived skeletal muscle index and area (CT-SMI and CT-SMA). We quantified their correlations with CT, and derived sex-specific cut-offs to detect reduced muscle mass, as a step towards bedside, guideline-concordant identification of patients at risk of malnutrition.

2. Methods

2.1. Study design

This prospective, single-cohort study with retrospective L3 CT-scan imaging analysis among patients admitted to the ICU of hospital Gelderse Vallei (Ede, the Netherlands) was conducted between May 1, 2023, and April 30, 2025. All patients who were prospectively included for bedside muscle mass measurements were retrospectively assessed, and those with available CT imaging at the L3 level within seven days prior to ICU admission, and up to 24 h after ICU admission were included. Patients without an eligible CT-scan and concurrent bedside muscle mass measurement were excluded from this study. As the study was exploratory in nature, no formal a priori sample size calculation was performed. The study population comprised all consecutive eligible patients admitted during the predefined study period.

Eligibility criteria for the collection of bedside measurements included all ICU patients aged 18 years or older with an expected ICU length of stay of 3 days or longer. Exclusion criteria included the inability to perform BIA measurements (e.g., pregnancy, limb amputation, pacemaker, or an Implantable Cardioverter Defibrillator *in situ*), as well as factors such as moribund status, previous ICU admission within same hospitalisation period, and expected transfer to another medical facility during the ICU stay. During the initial phase of the study (May–December 2023), patients who did not meet specific criteria were excluded, as laboratory data were collected in parallel with the muscle mass measurements as part of another prospective cohort study (Reg. No.: 2023–16269). These additional criteria included: preexisting Diabetes Mellitus (type I or II), preexisting kidney insufficiency (eGFR <20 mL/min/1.73 m^2), history of hyperparathyroidism, and liver cirrhosis (Child-Pugh class C). From January 2024 to April 2025, these exclusion criteria were no longer applied, allowing for a more representative general ICU cohort. CC measurements were only collected in patients included from September 2024 to April 2025.

2.2. Study procedures

After obtaining informed consent, BIA, muscle US, and CC measurements were collected at the earliest possible opportunity following ICU admission (within 48 h after ICU admission). An overview of all methods and their parameters is presented in Fig. 1.

2.2.1. CT-derived skeletal muscle measurements at the third lumbar vertebral level

A retrospective search was conducted in the patient's electronic medical record (NEXUS Nederland, Vianen, Netherlands) to identify available abdominal CT scans that included the L3 level. L3 was selected as a standard reference point to represent whole-body skeletal muscle mass [15,16]. If multiple CT scans were available within the timeframe, the one closest to the time of ICU admission was selected, in line with recent recommendations [17]. An experienced radiologist (MV) reviewed each selected scan to identify the axial slice at the L3 vertebral level, characterised by the transverse processes being most clearly visible. Ideally, slices were taken from the portal-venous contrast phase. If unavailable, a slice from another contrast phase was selected. All relevant CT-slices were extracted from the Picture Archiving and Communication System (PACS) in native DICOM format and anonymised for further processing. Only original axial DICOM slices, with a resolution of 512 $\times$ 512 pixels and slice thickness of 1–3 mm (mean 1.8 $\pm$ 0.4 mm) were used.

The anonymised images were then analysed using artificial intelligence (AI)-assisted automatic analysis software (SarcoMeas AI, version 1.0, UMCG, Groningen), to outline the abdominal wall muscle. An experienced radiologist (AV) supervised the process and manually corrected the segmentation results if necessary. Within these delineations, muscle area was defined as the sum of all voxels with a radiodensity ranging from −29 to 150 Hounsfield Units (HU). From each selected CT-slice, the software calculated the CT-SMA (cm^2) and the CT-SMI, by dividing the muscle SMA by the squared patient height (cm^2/m^2).

2.2.2. Bio-electrical impedance analysis

ICU nurses routinely performed BIA upon admission as part of standard care. If not available, the measurement was performed for study purposes as soon as possible after enrolment. A multi-frequency BIA was conducted using the InBody S10 device® (*InBody* Co., Ltd., Seoul, Korea), with patients in a semi-supine position (30°), ensuring that the limbs did not touch each other or the torso. Patient height, age, sex, and total body mass (measured using an integrated ICU bed scale) were entered into the device, and BIA-FFM and BIA-SMM were extracted.

2.2.3. Quadriceps muscle ultrasonography

All *quadriceps* muscle US were performed by a trained researcher for study purposes using a Philips Sparq® ultrasound system (Philips AG Health Systems, Horgen, Switzerland). Researchers were trained and supervised during their initial assessments by an experienced physician-researcher (see Supplementary Information 1). US assessments were performed on the quadriceps muscle of the right leg, with patients positioned in a standardised semi-supine position (30°). Before the measurement, the distance between the anterior superior iliac spine (ASIS) and the superior border of the patella was measured (ASIS–patella length). A mark was drawn using a waterproof marker at two-thirds of this distance from the ASIS to assure consistency of the measurement location. All measurements were performed with a curved-array transducer (to ensure complete horizontal visualisation of the muscle) at this anatomical landmark using fixed US settings. Three transverse cross-sectional images were acquired at the marked landmark, with the probe positioned perpendicularly (90°) to the long axis of the quadriceps muscle applying minimal pressure.

All US images were analysed using ImageJ.JS (National Institutes of Health, Bethesda, MD, USA). Distance measurements were calibrated based on the scale. To obtain the US-RFCSA, the muscle border, excluding the fascia, was outlined using the polygon function in ImageJ. The US-QMLT was measured as the vertical distance from the upper border of the *M. rectus femoris* to the lower border of the *M. vastus intermedius*. The average of the three analysed images (triplicate measurements) per measurement was used for US-RFCSA and US-QMLT.

2.2.4. Calf circumference

CC was measured for study purposes by a trained researcher directly after study inclusion. Measurements were taken on the right leg, with the patient in a supine position and the knees semi-flexed at approximately 90°. Using a flexible measuring tape, the point of maximum calf circumference was identified and marked. At this marked point, CC was measured in millimetres, taking care to apply minimal pressure to avoid compression of subcutaneous tissue. CC was adjusted for BMI by reducing CC by 3 cm for those with a BMI of 25–29.9 kg/m^2, 7 cm for a BMI of 30–39.9 kg/m^2, and 12 cm for a BMI of over 40 kg/m^2, as described in previous work [18].

2.3. Clinical characteristics

Clinical data were collected from the patient data monitoring system (MetaVision, iMDsoft, Tel Aviv, Israel). These included demographic characteristics (sex, age, weight, height, and body mass index [BMI]), ICU admission diagnosis, medical history, clinical scores and relevant laboratory values at ICU admission. Additionally, data on 28-day mortality were retrieved from the electronic medical records (NEXUS Nederland, Vianen, the Netherlands), which is connected to the Dutch population register.

2.4. Study outcomes

The primary outcome was the correlation between CT derived SMI and SMA, and the corresponding absolute values and indices from bedside methods: BIA (BIA-FFM, BIA-SMM), muscle ultrasound (US-RFCSA, US-QMLT), and CC. Secondary outcomes included optimal cut-off values for each bedside tool to diagnose reduced muscle mass. Reduced muscle mass was defined as CT-SMI <38 cm^2/m^2 for females and <50 cm^2/m^2 for males, based on a recent review examining the relationship between CT-derived muscle mass and mortality in critically ill patients [4]. Diagnostic accuracy of existing ESPEN guidelines was assessed using the recommended cut-offs, including BIA-FFMI thresholds of <15 kg/m^2 for females and <17 kg/m^2 for males, and BMI-adjusted CC thresholds (<33 cm for males and <32 cm for females) [13,19]. Additionally, cohort-specific optimal cut-off values were explored.

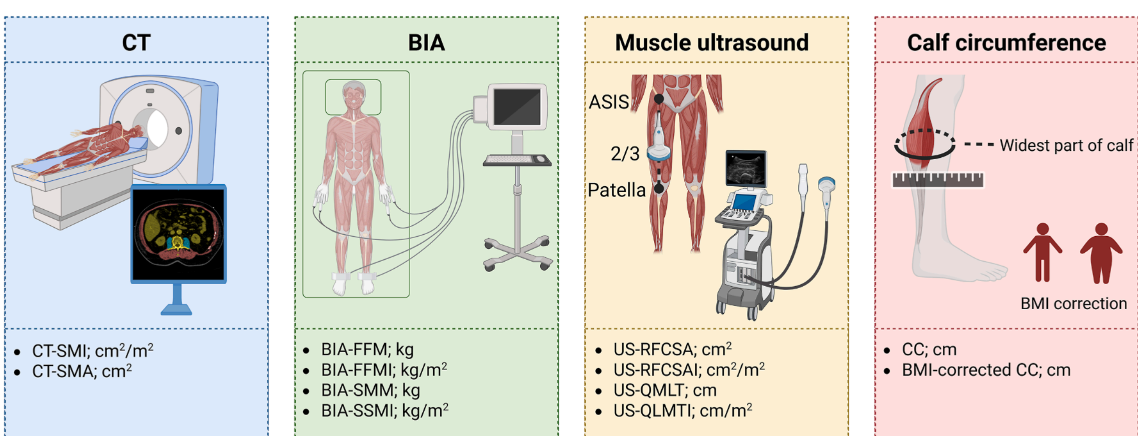

Fig. 1. Overview of methods used in this study to assess muscle mass in critically ill patients.
CT-derived skeletal muscle measurements at the third lumbar vertebral level (L3) included the total skeletal muscle area (CT-SMA, cm^2) and the Skeletal Muscle Index (CT-SMI), which is the SMA adjusted for patient height (cm^2/m^2). CT image analysis was performed using AI-assisted automatic segmentation software (SarcoMeas AI, version 1.0, University Medical Centre Groningen). A multifrequency bioelectrical impedance analysis (BIA) was performed to assess fat-free mass (BIA-FFM) and skeletal muscle mass (BIA-SMM). Muscle ultrasonography was conducted on the right leg at two-thirds of the distance from the anterior superior iliac spine (ASIS) to the patella, using minimal pressure, to determine the cross-sectional area of M. rectus femoris (US-RFCSA) and quadriceps muscle layer thickness (US-QMLT). Calf circumference (CC) was measured using minimal pressure at the point of maximum circumference of the right calf and was corrected for BMI. *Figure created with Biorender.com.*

Tertiary outcomes were the number of identified patients with sarcopenic obesity, defined as reduced muscle mass (based on CT-SMI) combined with a BMI ≥30.0 kg/m^2, and 28-day mortality among patients with and without reduced muscle mass.

2.5. Statistical analysis

Categorical variables were summarised as counts and percentages per category. Continuous variables were tested for normality using the Shapiro–Wilk test: if normally distributed, the mean and standard deviation (SD) were reported; if not, the median and interquartile range (median [IQR]) were presented. The number of completed values was reported for each variable.

Correlations between CT-derived measures and the bedside method's parameters were determined using Pearson's or Spearman's correlation coefficient for parametric and non-parametric data, respectively. Correlations were also calculated for indexed BIA (BIA-FFMI, and BIA-SMMI) and US (US-RFCSAI and US-QMLTI) parameters. These were derived by dividing the absolute values by the patient's height in meters squared (m^2). Correlations were calculated for the total study population, as well as for the subgroups stratified by sex (male and female). Correlation coefficients were interpreted as follows: 0.90 to 1.00 (or −0.90 to −1.00) indicated a very high positive (or negative) correlation; 0.70 to 0.90 (−0.70 to −0.90) a high correlation; 0.50 to 0.70 (−0.50 to −0.70) moderate; 0.30 to 0.50 (−0.30 to −0.50) low; and 0.00 to 0.30 (0.00 to −0.30) negligible correlation [20].

For the secondary outcome, diagnostic accuracy of existing ESPEN proposed cut-off values to detect reduced muscle mass was assessed. Subsequently, receiver operating characteristic (ROC) analyses were conducted using CT-SMI thresholds as the reference standard. Youden's Index was applied to determine the optimal cut-off values for each bedside-derived absolute and indexed parameter, analysed separately for males and females. Area under the curve (AUC) values were interpreted as follows: an AUC of 0.9 or higher was considered excellent; values between 0.8 and 0.9 were considered considerable; between 0.7 and 0.8 were considered fair; between 0.6 and 0.7 were considered poor; and values between 0.5 and 0.6 were interpreted as a fail [21]. For the tertiary outcomes, sarcopenic obesity (based on CT-SMI) was reported as absolute and relative frequencies, and differences in 28-day mortality between patients with reduced versus normal muscle mass at ICU admission were analysed using Fisher's exact test. For all tests, p-values <0.05 were considered statistically significant. All statistical analyses and figures were generated using R version 4.1.1 (RStudio, PBC, Boston, MA, USA).

3. Results

Between May 1, 2023, and April 30, 2025, a total of 1118 patients were admitted to the ICU. Of the 160 patients included for bedside muscle measurements, 56 patients (35 %) had a CT-scan available and were included in the study (Fig. 2). Most CT-scans were performed within 24 h of ICU admission (n = 50); the remaining six patients underwent CT-scanning within one week prior to ICU admission. Baseline characteristics of the study population are presented in Table 1. Among the included patients, n = 39 (69.6 %) were male, with a mean BMI of 28.0 (SD 5.3). All included patients (n = 56), had both a L3 CT-scan and a BIA measurement available. Of the BIA measurements, 46 were performed on the day of ICU admission and 10 on the following day. Additionally, *quadriceps* muscle US was performed in 51 patients (91.1 %), with 36 procedures performed on the day of admission and 15 on the following day. In 18 patients (32.1 %), CC measurements were available, of which 12 patients were measured on the day of ICU admission, and six patients were measured the following day.

Among the study population, CT-SMI averaged 45.0 (SD 7.2) kg/m^2 in males and 40.4 (SD 7.0) kg/m^2 in females. The average values of CT-derived values and the beside methods are summarised in Supplementary Table 1. In total, 36 patients (64.3 %) met the definition of reduced muscle mass based on CT-SMI.

3.1. Correlation between CT and bedside methods

The correlation between CT-SMI and BIA-FFMI, and CT-SMI and BIA-SMMI was low (Pearson's r = 0.36, p = 0.006 and r = 0.45, both p < 0.001, respectively) (Fig. 3). Regarding muscle US, CT-SMI also showed a low correlation with the US-RFCSAI (r = 0.38, p = 0.007) and US-QMLTI (r = 0.42, p = 0.002). CT-SMA showed a moderate correlation with BIA-FFM (Pearson's r = 0.57, p < 0.001) and BIA-SMM (r = 0.62, p < 0.001) (Supplementary Fig. 1). In contrast, correlations between CT-SMA and US-derived muscle mass parameters (US-RFCSA: r = 0.232, p = 0.101; US-QMLT: r = 0.260, p = 0.061) as well as corrected CC (r = 0.227, p = 0.366) were negligible.

3.2. Cut-off values for reduced muscle mass

Using ESPEN-recommended BIA-FFMI cut-off values, sensitivity for detecting CT-defined reduced muscle mass was 6 % in males and 0 % in females; specificity was 100 % for both sexes. For ESPEN corrected CC cut-offs, sensitivity was 38 % in males and 0 % in females, with specificities of 67 % and 75 %, respectively.

Optimal cut-off values for all indexed and non-indexed bedside muscle mass assessment methods are summarised in Table 2. Overall, indices of BIA-derived parameters demonstrated the highest diagnostic performance, with moderate-to-good discrimination for CT-defined reduced muscle mass, particularly in males. Ultrasound-based measures showed lower and more variable performance, with lower AUC values, especially in females. Corrected CC demonstrated moderate diagnostic accuracy, with high specificity but variable sensitivity across sexes. The non-stratified cut-off values are presented in Supplementary Table 2.

3.3. Tertiary outcomes

Among the 17 patients with obesity, reduced muscle mass was detected in 9 patients (52.9 %). The 28-day mortality rate was 50 % among patients reduced muscle mass (n = 18 patients) compared to 25 % among patients without reduced muscle mass (n = 5 patients) (p = 0.092).

4. Discussion

In this prospective cohort of 56 ICU patients, we compared skeletal muscle assessment methods bedside BIA, US, and CC against L3 CT-derived muscle mass indices. Low skeletal muscle mass upon ICU admission based upon L3 CT-SMI was common (64 %). Both BIA and US showed low to moderate correlations with L3 CT metrics. Unindexed BIA values showed moderate correlations with CT-derived SMA, whereas unindexed US and CC parameters correlated negligibly. Sex-specific ICU cut-offs outperformed current thresholds for healthy populations [5].

4.1. Reduced muscle mass

Low skeletal muscle mass at ICU admission is frequently encountered and prognostically relevant [22,23]. Using CT-SMI cut-offs associated with short-term mortality (<38 cm^2/m^2 women,

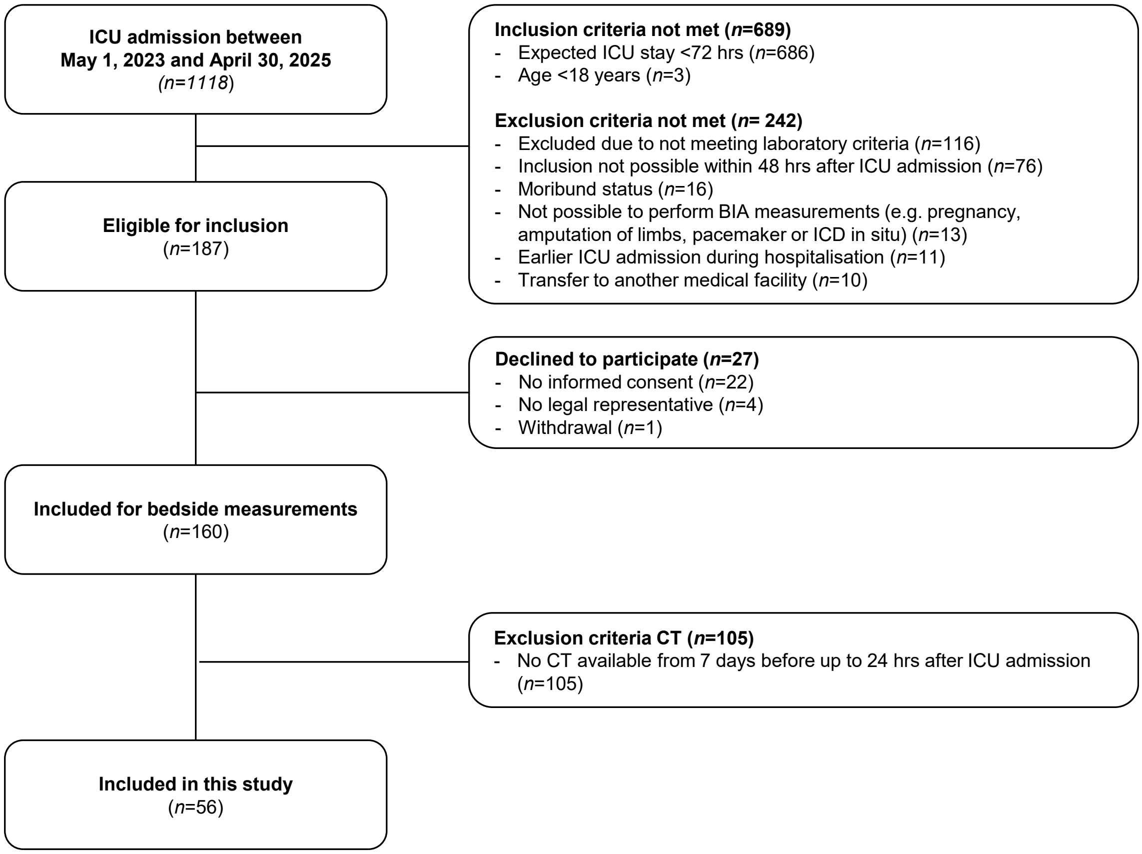

Fig. 2. Flow chart of study inclusion.
Study inclusion of eligible ICU patients. For the primary outcome analysis, 56 patients had a CT-scan at the L3 level available, with at least one bedside muscle mass measurement, e.g., bioelectrical impedance analysis (BIA), muscle ultrasound (quadriceps muscle), or calf circumference. The exclusion criterion 'Excluded due to not meeting laboratory criteria' refers to patients included during the initial phase of the study (May–December 2023, n = 316) who did not meet one or more predefined criteria: preexisting diabetes mellitus (type I or II), preexisting kidney insufficiency (eGFR <20 mL/min/1.73 m^2), a history of hyperparathyroidism, and liver cirrhosis (Child-Pugh class C).

<50 cm^2/m^2 men) (4), 64 % of our patient cohort were classified as having a reduced muscle mass. This prevalence is higher than a previous reported pooled 44 % in mechanically ventilated patients [22], likely reflecting heterogeneity in CT-SMI thresholds and patient populations across studies [3,4,22,24–26]. Consistent with prior work [4], 28-day mortality was numerically higher with low CT-SMI, although our study was not powered for these outcomes.

Importantly, BMI or body mass may mask low muscle mass, particularly in patients with obesity (i.e., sarcopenic obesity). Prior ICU studies reported sarcopenia in 41–56 % and sarcopenic obesity in 22–24 % of patients [3,27,28]. In our cohort, sarcopenic obesity was present in 16 %, likely reflecting the lower proportion of patients with obesity (30 %) compared with the aforementioned studies (47 % and 34 %, respectively) [27,28]. Notably, despite the lower overall obesity rate, half of the obese patients still met criteria for reduced muscle mass, underscoring the high burden of sarcopenia within our subgroup. These estimates are influenced by the definitions and cut-off values applied; Ji et al. used lower CT-SMI thresholds (40.8 cm^2/m^2 for males; 34.9 cm^2/m^2 for females) and observed similar findings with nearly 50 % of obese patients being classified as sarcopenic [26]. This has clear clinical implications. Failure to identify these patients may limit opportunities for targeted nutritional and rehabilitative intervention strategies [29,30]. In accordance with the current guidelines, protein delivery in obese ICU patients should preferably be guided by lean body mass, assessed by CT or other bedside tools, to minimise the risk of inadequate feeding (under- or overfeeding) [14,31]. Finally, recognising sarcopenic obesity is important because it has been associated with increased 30-day mortality in critically ill patients with intra-abdominal sepsis [28].

4.2. Relation to bedside-derived parameters

In our study, BIA showed low to moderate correlations with CT-derived muscle parameters. The correlation we observed between CT-derived SMA and BIA-SMM ($r = 0.617$, $p < 0.001$) is comparable to findings reported by Kim et al. ($r = 0.651$ for males and $r = 0.584$ for females, both $p < 0.001$) and Looijaard et al. ($r = 0.635$, $p < 0.001$) in critically ill patients. Remarkably, the latter study observed a stronger correlation with total muscle compartment estimates (Talluri equation, which incorporates FFM, total body water, and phase angle) instead of BIA-SMM [32]. In contrast, we found a weaker correlation between BIA-FFM and CT-SMA ($r = 0.570$, $p < 0.001$), possibly due to the inclusion of water compartments and organ mass in BIA-FFM, which may be affected by the fluid overload commonly seen in critically ill patients [33]. The correlation we observed between *quadriceps* US parameters and CT-derived SMI was negligible upon ICU admission, while previous studies reported strong correlations between QMLT and CT-based SMA ($r = 0.90$ and $r = 0.70$, both $p < 0.001$) [34,35]. Several factors may explain this discrepancy. First, *quadriceps* muscle size represents a single appendicular muscle group, whereas CT-derived SMI reflects the combined cross-sectional area of multiple axial trunk muscles. Second, measurements at ICU admission captures patients at varying stages of systemic inflammation and immobilization [9,12], and extremity muscles

Table 1
Baseline characteristics at ICU admission.

Characteristics		Study population ($n = 56$)
Age, years	Median [IQR]	73 [65–76]
	Mean (SD)[†]	70 (11)
Sex, male	N (%)	39 (69.6)
Actual body weight, kg	Mean (SD)	87.9 (17.2)
Height, m	Mean (SD)	1.77 (0.08)
BMI, kg/m^2	Mean (SD)	28.0 (5.3)
Obesity (BMI>30 kg/m^2)	N (%)	17 (30.4)
Sarcopenic obesity[a]	N (%)	9 (16.1)
Type of ICU admission	**N (%)**	
Medical		38 (67.9)
Emergency surgery		18 (32.1)
Comorbidities	**N (%)**	
Active malignancy		7 (12.7)
Chronic heart failure		6 (10.7)
Diabetes mellitus		8 (14.3)
COPD		11 (19.6)
Chronic renal insufficiency		11 (19.6)
Admission scores		
APACHE II	Mean (SD)	24 (7)
APACHE IV	Mean (SD)	89 (23)
SOFA	Mean (SD)	8 (3)
mNUTRIC	Median [IQR]	6 [4–7]
Barthel index ($n = 54$)	Median [IQR]	20 [20-20]
Clinical frailty scale ($n = 52$)	Median [IQR]	3 [2–5]
Laboratory values		
Creatinine, μmol/L	Median [IQR]	121 [81–165]
CRP, mg/L	Median [IQR]	147 [68–247]
UCR, μmol/L:μmol/L	Median [IQR]	90 [67–113]
IMV	N (%)	
IMV <24 h after ICU admission		24 (42.9)

Baseline characteristics of the 56 patients with available CT-scans at the L3 level and corresponding measurements (muscle ultrasound, bioelectrical impedance analysis, or calf circumference) are shown.

[a] Sarcopenic obesity was defined as a BMI >30 kg/m^2 in combination with low muscle mass, indicated by a Skeletal Muscle Index (CT-SMI) of <38 cm^2/m^2 for females and <50 cm^2/m^2 for males.

[†] In addition to the median, the mean age is also reported for comparison with other studies. Abbreviations: Acute Physiologic Assessment and Chronic Health Evaluation (APACHE), Body Mass Index (BMI), Chronic Obstructive Pulmonary Disease (COPD), C-Reactive Protein (CRP), modified Nutrition Risk in the Critically Ill score (mNUTRIC score), Sequential Organ Failure Assessment (SOFA), Urea-to-Creatinine Ratio (UCR), Invasive Mechanical Ventilation (IMV). ICU admission diagnoses and comorbidities were determined according to the guidelines of the National Institute for Health and Care Excellence (NICE).

are more at-risk of atrophy during immobilization than trunk muscles [36]. Additionally, we observed higher US-RFCSA values than the pooled estimates reported by Venco et al. (4.7 (SD 1.9) cm^2 in males and 4.4 (SD 1.7) cm^2 in females vs. pooled 2.83 cm^2 [2.29–3.37]), while US-QLMT was comparable [10]. However, there was considerable heterogeneity across studies, which may be attributed to methodological and population-specific factors including age, BMI, measurement landmark, and the use of probe compression [10].

In this study, both BIA and CC, using the cut-offs recommended by ESPEN [13,19], showed limited diagnostic accuracy with low sensitivity for CT-defined reduced muscle mass. Notably, these ESPEN cut-offs for BIA-FFMi and CC were developed for healthy adults [5,18,37], which restricts direct applicability in ICU settings and risks under-diagnosis when early detection is critical. In our cohort, ROC-derived ICU cut-offs based on L3 CT-SMI improved sensitivity while maintaining acceptable specificity. AUC and sensitivity values were consistently higher in males than females when applying the sex-specific thresholds proposed by Bertoni Maluf et al. [4]. Specifically, 31 out of 39 males (79.5 %) met the CT-based definition of reduced muscle mass, versus only 5 out of 17 females (29.4 %). The smaller number of female participants may partly explain the higher US-RFCSA and US-RFCSAI cut-offs (US-RFCSA: 5.5 cm^2 in females vs 4.3 cm^2 in males; US-RFCSAI: 1.9 cm^2/m^2 in females vs 1.3 cm^2/m^2 in males). Nevertheless, Nakanishi et al. also reported slightly higher indexed US-RFCSAI values in females than in males in a Japanese ICU population (2.0 vs. 1.9 cm^2/m^2) [12]. Moreover, sex stratification is not invariably required, in another study, absolute US-RFCSA (optimal cut-off 2.39 cm^2) was a better predictor of ICU mortality than indexed or sex-adjusted values [38] and in our data, US-RFCSA AUCs were similar with and without sex stratification. This supports the notion that sex-specific indexing may be less critical for US-area measures, which directly visualise muscle size, than for CC or BIA, which are influenced by additional body compartments. Prior ICU work further showed US-RFCSA (≤5.9 cm^2/m^2) to be a better independent predictor of 28-day mortality than BIA-SMM (<19.2 kg/m^2) [39]. Furthermore, ultrasound may still be valuable for longitudinal within-patient monitoring rather than cross-sectional comparison with CT. Finally, lower CC, especially analysed as a continuous variable, has been associated with ICU readmission, whereas associations with ICU or in-hospital mortality and length of stay were not observed [40].

4.3. Strengths and limitations

A key strength of this study is the parallel, head-to-head evaluation of several bedside muscle measures against L3 CT-derived metrics in the same patients. Nevertheless, the single-centre design and inclusion of CT-scans obtained as part of routine care may have introduced selection bias and thereby limit generalisability to broader ICU populations. In addition, our proposed cut-offs were derived from their reported mortality associations rather than from ICU-specific reference standards or guideline-endorsed thresholds. While clinically relevant, they may not represent the optimal values for all ICU patients. Furthermore, both imaging-based and bedside muscle mass parameters should be interpreted with caution, considering factors inherent to the critically ill population, including fluid shifts, alterations in tissue density, and changes in cell membrane integrity, all of which can affect measurement accuracy. Lastly, the cut-off values were derived in a single derivation cohort without internal validation, which may limit their robustness. This underscores the need for external validation in larger, independent ICU populations.

4.4. Future recommendations

Our approach of CT-SMI cut-off values for reduced muscle mass facilitated comparison with prior research and ensured relevance to patient prognosis, but emphasises the need for standardized, population-specific reference values in critically ill adults. Combining biochemical markers of catabolism, such as the urea-to-creatinine ratio, with muscle mass assessment may provide a more comprehensive understanding of the metabolic state and nutritional status during critical illness. Future studies should explore clinically oriented threshold values optimised for screening and confirmation of reduced muscle mass, such as cut-offs prioritising high sensitivity or specificity. In addition to ICU admission, longitudinal muscle mass measurements may aid in evaluating effectiveness of study interventions to mitigate muscle wasting during critical illness. However, further research is needed to determine how these tools can be best applied longitudinally, including their validity and the frequency of measurements. Given that reduced muscle mass is a core phenotypic criterion in the diagnosis of malnutrition and sarcopenia, bedside muscle mass assessment methods remain to be a cornerstone of nutritional assessment during critical illness, which might thereby be used to guide nutritional and physiotherapy treatment throughout ICU stay.

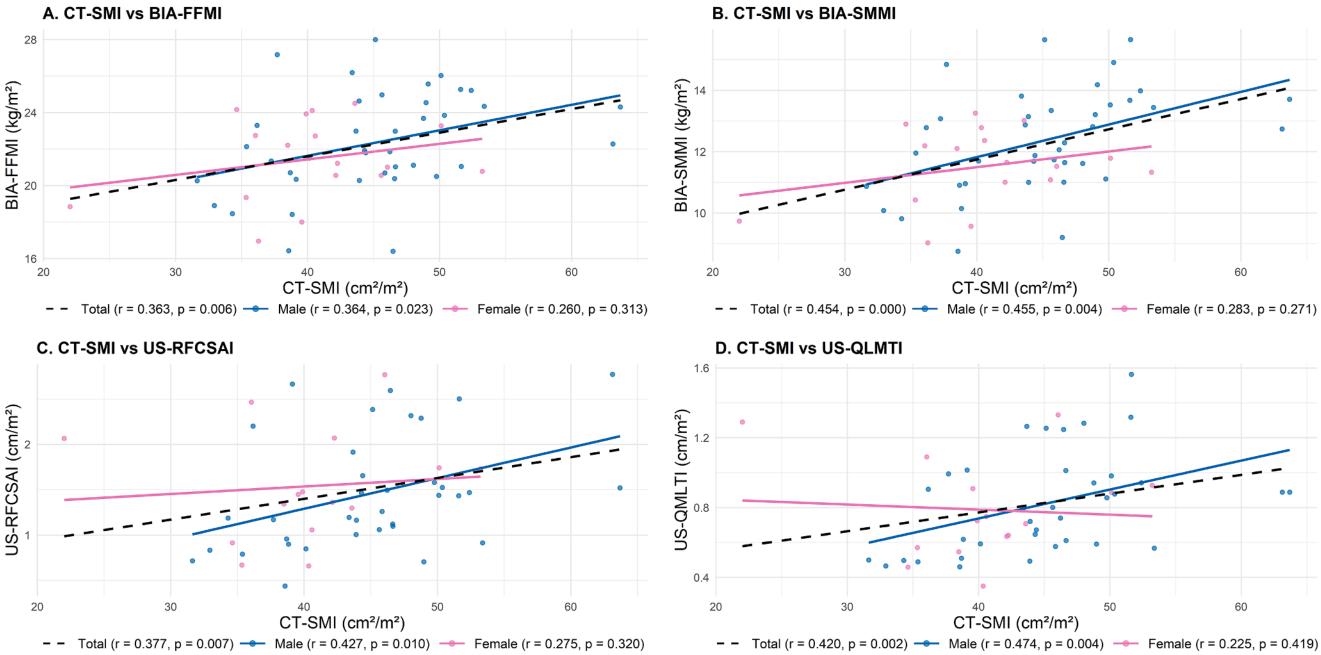

Fig. 3. Correlations between skeletal muscle index from CT with Bioelectrical Impedance Analysis and Quadriceps Ultrasound-Derived Muscle Indices. Correlations between skeletal muscle index (CT-SMI) measured by CT-scan at the L3 level with muscle indices derived from bioelectrical impedance analysis (BIA, **panel A** and **B,** $n = 56$) and quadriceps muscle ultrasound (US, **panel C** and **D,** $n = 51$) in 56 ICU patients. The US- and BIA-derived muscle indices are displayed for the total group (black dashed line), as well as separately for males (blue) and females (pink). Abbreviations: Fat-Free Mass Index (BIA-FFMI), Quadriceps Muscle Thickness index (US-QMLTI), Rectus Femoris Cross-Sectional Area index (US-RFCSAI), and Skeletal Muscle Mass Index (BIA-SMMI).

Table 2
Optimal cut-off values and their diagnostic accuracy for bedside parameters in the study cohort.

	Sex	Cut-off	AUC [95 % CI]	Sensitivity (%)	Specificity (%)
BIA-FFMI, kg/m^2	Male	23.8	0.75 [0.59–0.92]	77.4	75.0
	Female	20.0	0.65 [0.27–1.00]	60.0	91.7
BIA-FFM, kg	Male	73.5	0.71 [0.50–0.91]	58.1	87.5
	Female	58.7	0.65 [0.30–1.00]	60.0	83.3
BIA-SMMI, kg/m^2	Male	13.4	0.88 [0.76–0.99]	87.1	87.5
	Female	10.7	0.67 [0.31–1.00]	60.0	91.7
BIA-SMM, kg	Male	41.2	0.84 [0.71–0.96]	74.2	100.0
	Female	31.5	0.68 [0.34–1.00]	60.0	83.3
US-RFCSAI, cm^2/m^2	Male	1.3	0.67 [0.47–0.88]	60.7	87.5
	Female	1.9	0.48 [0.02–0.94]	50.0	81.8
US-RFCSA, cm^2	Male	4.3	0.67 [0.47–0.86]	57.1	87.5
	Female	5.5	0.48 [0.00–0.98]	50.0	90.9
US-QMLTI, cm/m^2	Male	0.9	0.72 [0.53–0.92]	67.9	87.5
	Female	1.0	0.52 [0.06–0.98]	50.0	90.9
US-QMLT, cm	Male	2.6	0.74 [0.54–0.93]	64.3	87.5
	Female	2.9	0.55 [0.10–0.99]	50.0	90.9
Corrected CC, cm	Male	36.8	0.69 [0.37–1.00]	62.5	100.0
	Female	33.8	0.71 [0.26–1.00]	100.0	50.0
Uncorrected CC, cm	Male	38.5	0.46 [0.03–0.89]	62.5	66.7
	Female	40.3	0.54 [0.01–1.00]	100.0	50.0

Optimal cut-off values based on muscle mass measurements in 56 ICU patients, using reduced skeletal muscle mass measured by CT-scan at the L3 level as the reference standard. Reduced muscle mass was defined as CT-derived Skeletal Muscle Index (SMI) of <38 cm^2/m^2 for females and <50 cm^2/m^2 for males. The table shows the area under the curve (AUC) with 95 % confidence intervals in brackets, along with sensitivity (%) and specificity (%). Cut-off values were rounded to one decimal point. Abbreviations: Fat-Free Mass (FFM), Fat-Free Mass Index (FFMI), Quadriceps Muscle Layer Thickness (QMLT), Quadriceps Muscle Layer Thickness index (QMLTI), Rectus Femoris Cross-Sectional Area (US-RFCSA), Rectus Femoris Cross-Sectional Area index (US-RFCSAI), Skeletal Muscle Mass (BIA-SMM), and Skeletal Muscle Mass Index (BIA-SMMI). Corrected calf circumference (CC) was adjusted for BMI by reducing CC by 3 cm for those with a BMI of 25–29.9 kg/m^2, 7 cm for a BMI of 30–39.9 kg/m^2, and 12 cm for a BMI of over 40 kg/m^2.

5. Conclusion

In our cohort of 56 critically ill patients, low skeletal muscle mass based upon L3 CT-scans was present in nearly two-thirds at ICU admission. Correlations of *quadriceps* US and CC with L3 CT-SMA at ICU admission were weak, whereas BIA showed a moderate association with CT-SMA. We determined ICU-derived, sex-specific cut-offs that performed better than existing thresholds that were derived from healthy populations. Multicentre validation and outcome-oriented studies are now needed to confirm prognostic value, refine integration with biomarkers, and define longitudinal use during ICU stay.

Ethics approval and consent to participate

All eligible patients were asked to provide prospective, written informed consent. In cases where the patient was deemed incompetent, consent was obtained from a legal representative, next of kin, or proxy. If a representative provided initial consent, the patient was concomitantly asked for informed consent at the earliest possible opportunity. The study was approved by the ethical review committee of the Gelderse Vallei Hospital (Reg no: 2312-051) and received an obligatory non-WMO statement (i.e. meaning that the study did not fall under the Medical-Scientific Act for Human Research) from the Medical Ethics Review Committee East Netherlands (Reg no: 2023–16980). Participants' data were collected in accordance with the Personal Data Protection Act and were used anonymously for all data analysis.

Availability of data

The datasets used are available from the corresponding author on reasonable request.

Author contributions

MCP: Conceptualisation, Methodology, Formal analysis, Writing – original draft/review. MM: Conceptualisation, Methodology, Formal analysis, Writing – original draft/review. IWKK: Conceptualisation, Methodology, Writing – review. MV: Formal analysis, writing - review. ARV: Conceptualisation, Methodology, Formal Analysis, writing - review. ARHvZ: Conceptualisation, Methodology, Writing – review. All authors read and approved the final manuscript. No one eligible for authorship has been excluded from the list of authors.

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Conflict of interest

Prof. dr Van Zanten reported receiving honoraria for advisory board meetings, lectures, research, and travel expenses from Abbott, AOP Pharma, Baxter, Cardinal Health, Danone-Nutricia, Fresenius Kabi, GE Healthcare, InBody, and Rousselot. The other authors have no declarations to make.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clnu.2026.106574.

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