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3D quantitative CT study to assess rotator cuff muscle fatty infiltration

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Fatty infiltration is a degenerative condition of the tendon-muscle unit of rotator cuff muscles, characterized by fatty accumulation within and around the muscles. This study compares a 3D method to the Goutallier classification for evaluating fatty infiltration of the rotator cuff muscles. Employing a retrospective study design, four researchers performed 3D segmentation of the rotator cuff muscles on 65 CT scans of patients with rotator cuff arthropathy. The Goutallier classification was graded on screenshots of the Y view and two axial slices. Measurements, including HU, volume, cross-sectional area, and Goutallier grade, were performed on the 3D segmentations and the respective 2D slices. The inter- and intra-rater variability for 2D and 3D methods were calculated using the Intraclass Correlation Coefficient (ICC). The ICC for 2D and 3D methods was excellent (ICC: 0.90-0.95 and 0.81-0.99, respectively) and good for the Goutallier classification (ICC: 0.62-0.81). Overall, the relative 3D fatty infiltration was 0% for Goutallier grade 0 muscles, 7% for grade 1, 19% for grade 2, 33% for grade 3, and 37% for grade 4. The relative 2D fatty infiltration was 0%, 8%, 25%, 37%, and 43%, respectively. We conclude that 3D segmentation on CT scans is better reproducible and evaluates the muscle entirely. However, the time-intensive nature of the 3D method currently limits its clinical practicality. Quantitive 2D evaluation is excellently reproducible but may overestimate the actual fatty infiltration percentage of the whole muscle.

Keywords: Fatty infiltration, rotator cuff, 3D CT scan, Goutallier.

INTRODUCTION

Fatty infiltration is a degenerative condition of the tendon-muscle unit of rotator cuff muscles, characterized by fatty accumulation within and around the muscles[1–3]. Fatty infiltration is a common result of massive rotator cuff tears and is often found in patients with rotator cuff arthropathy (RCA). However, the pathophysiology behind fatty infiltration still needs to be fully understood[1,4]. Both mechanical unloading and muscle denervation are associated with fatty infiltration and atrophy[5]. The major difference between atrophy and fatty infiltration is that fatty infiltration is always irreversible, while atrophy can improve[4].

Goutallier et al.[1] proposed the first classification to assess fatty infiltration of the rotator cuff muscles after a tear. During this study, the rotator cuff muscles were visually rated on axial slices of computed tomography (CT) scans and divided into five stages. A different approach was used by Zanneti et al.[6], they assessed the amount of fatty infiltration on the Y-view using magnetic resonance imaging by comparing it to the signal intensity of the teres major (TMaj) muscle. Currently, the Goutallier classification is most commonly used and usually assessed on the Y-view; an example is shown in Figure 1.

In both the anatomical and functional outcome after a rotator cuff repair, a correct classification for fatty infiltration of the rotator cuff muscles is important[7,8]. A higher degree of pre-operative fatty infiltration is associated with worse postoperative outcomes and is a major predictor of tear recurrence. Intervention is proposed before Goutallier stage 2 is reached, when irreversible muscle changes have developed[7–9].

The current Goutallier classification has several limitations. Firstly, there have been numerous studies surrounding the inter-rater reliability, in which most conclude only a fair to moderate agreement (ICC: 0.43-0.72) in experienced observers[10–14]. Secondly, the Goutallier grade is usually assessed on only one two-dimensional (2D) slice. However, assessing fatty infiltration on a single slice is insufficient to correctly evaluate the fatty infiltration of the whole muscle[15–17]. Beeler et al.[18] showed that fatty infiltration of the rotator cuff muscles varies from proximal to distal,

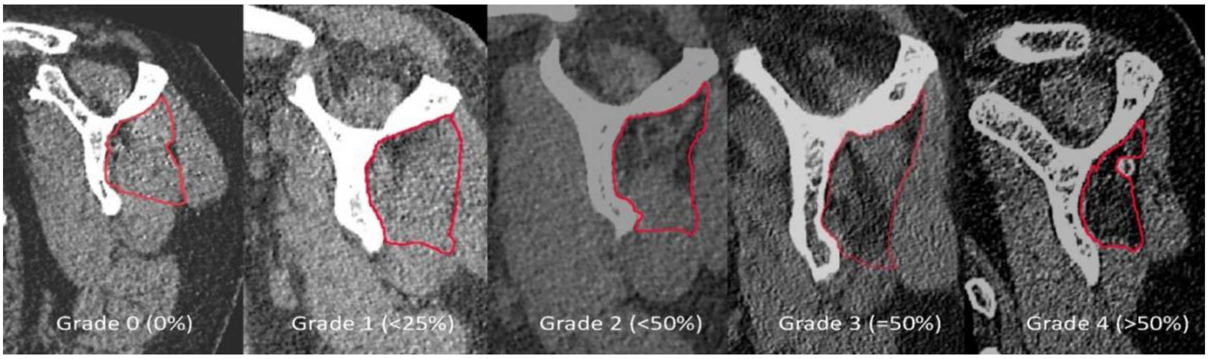

Fig. 1 — The Goutallier classification applied to the infraspinatus muscle, ranging from grade 0 to 4.

which can explain why a single slice is insufficient. Besides, the Goutallier classification is a qualitative method that does not quantify the exact amount of fatty infiltration.

This study aimed to create a reliable method to quantify the fatty infiltration of the muscle on CT scans (2D and 3D) and to compare this method to the current standard, the Goutallier classification.

PATIENTS AND METHODS

Data collection

This retrospective study utilized CT scans from Ghent University Hospital (UZ Ghent) taken between 2014 and 2021. The scans were acquired from rotator cuff arthropathy patients undergoing reverse shoulder arthroplasty. The inclusion criteria required the presence of a rotator cuff tear accompanied by fatty infiltration, and the whole scapula had to be visible on the CT scan. The exclusion criteria included shoulders previously operated on, traumatic tears, primary osteoarthritis, fractures, and CT scans of inferior quality. The included patients did not receive any additional radiation for this study. This study is approved by the ethical committee (BC- 08682).

The CT scans were acquired using a Somatom Volume Zoom – Siemens CT (Siemens, Erlangen, Germany) with a matrix set to 512 x 512, kV: 140; and 350 effective mA. Patients were positioned in the CT gantry using a standardized technique involving dorsal recumbency with a cushion on the abdomen and a strap around the body. This position ensured that the arm was adducted in the coronal plane and the forearm was flexed in the sagittal plane of the body.

This rigorous selection resulted in 65 CT scans from 59 patients with rotator cuff arthropathy. It comprised 44 female patients and 15 male patients. The mean age was 72.5 years (SD= 8.6), with females averaging 72.4 years (SD= 8.3) and males averaging 73.1 years (SD= 9.6).

Methodology and measurement

The rotator cuff muscles were manually outlined on the axial and sagittal views of the CT images. Contours were drawn every 3-5 slices using the 'Livewire' option on Mimics 23.0 (Materialise, Leuven, Belgium) (Figures 2 and 3). The software employed a sophisticated algorithm to generate a 3D representation of the muscle based on the outlined slices. The accuracy of the 3D model was verified visually on the axial and sagittal views. The Hounsfield units (HU) and volume of each model were recorded.

The segmentation process was performed by four researchers, who were medical students with extensive training in CT anatomy of the shoulder. Before the study, each researcher had a 2-hour session with an orthopedic surgeon to familiarize themselves with the anatomical landmarks and segmentation technique.

The teres major muscle and part of the subcutaneous fat of the anterior axilla were segmented to calculate the fatty infiltration percentage (FI%) according to the equation by Baillergeon et al.[19]. The subcutaneous fat mask encompassed a minimum volume of 1500 mm^3.

$$\text{Fatty infiltration percentage (FI\%)} = \frac{(\text{HU Teres major} - \text{HU muscle})}{(\text{HU Teres Major} - \text{HU Subcutaneous fat})} \times 100\%$$

Two-dimensional measurements were conducted on reformatted images perpendicular to the scapular plane, the scapular plane was created according to Jaxcsens et al.[20]. Screenshots were taken at the Y-view level (the most lateral slice where the scapular spine is in contact with the rest of the scapula) (Slice Y), the superior glenoid rim (Slice A), and the inferior glenoid rim (Slice B). These screenshots were uploaded to Google Forms (Google, Mountain view, CA, USA) for the randomized assessment of the Goutallier grade by the four raters. The raters evaluated and assigned the Goutallier grade based on the screenshots.

Additionally, to quantitatively evaluate 2D fatty infiltration, the rotator cuff muscles and teres major muscle were marked on the Y-view. This allowed for the assessment of HU and subsequent calculation of FI% using the equation proposed by Baillergeon et al.[19].

Statistical analysis

All statistical calculations were conducted in SPSS version 28 (IBM Corp, Armonk, NY, USA). The significance level for all tests was set at $p < 0.05$. The inter- and intra-rater reliability was calculated between the four researchers using the intraclass correlation coefficient (ICC) for 3D and 2D measurements, including HU, volume, cross-sectional area, and Goutallier grade. The mean Goutallier grade was calculated as the average sum of the four raters Y-view and the axial slice grades. The relative mean fatty infiltration percentage (2D and 3D) was calculated for each Goutallier grade and each rotator cuff muscle. The Pearson correlation coefficient (r) was used to determine the correlation between 2D FI% and 3D FI%, as well as between 3D FI% and the mean Goutallier grade.

RESULTS

Inter-rater reliability for 3D FI% assessment showed excellent agreement, with an ICC ranging from 0.81 to 0.99. The intra-rater reliability for 3D FI% was excellent (0.94-0.99). A more detailed overview is presented in Table I.

The inter-rater reliability for the cross-sectional area (2D) of the rotator cuff muscles on the Y-view ranged from 0.77 to 0.85. The intra-rater reliability was excellent (0.88-0.93) for all rotator cuff muscles, except the teres minor muscle, which was fair (0.41). A more detailed overview is presented in Table II.

Inter-rater reliability for the Goutallier classification, assessed on both the Y-view and axial slices, showed good agreement with ICC values ranging from 0.63 to 0.74 (Table III). The inter-rater reliability for 2D FI% was excellent, with ICC values ranging from 0.90 to 0.95.

The mean relative fatty infiltration, for 2D and 3D was calculated for every rotator cuff muscle and compared to the Goutallier classification, as presented in Table IV.

Table I. — 3D inter-rater reliability and intra-rater reliability for mean HU, volume and fatty infiltration of the rotator cuff muscles and teres major muscle.

	SS	IS	TMin	SSc	TMaj
Inter-rater reliability					
ICC mean HU	0,96 (0.82-0.99)	0.99 (0.95-1.0)	0.88 (0.73-0.96)	0.92 (0.73-0.98)	0.95 (0.88-0.99)
ICC Volume	0.94 (0.83-0.98)	0.98 (0.95-0.99)	0.80 (0.58-0.94)	0.98 (0.94-0.99)	0.76 (0.45-0.93)
ICC Fatty infiltration	0.95 (0.77-0.98)	0.98 (0.93-0.99)	0.81 (0.61-0.94)	0.81 (0.56-0.94)	N/A
Intra-rater reliability					
ICC mean HU	0.99 (0.98-1.00)	1.00 (0.98-1.00)	0.96 (0.83-0.99)	0.95 (0.75-0.99)	0.99 (0.96-1.00)
ICC Volume	0.96 (0.84-0.99)	0.95 (0.62-0.99)	0.70 (0.20-0.91)	0.98 (0.93-1.0)	N/A
ICC Fatty infiltration	0.99 (0.97-1.00)	0.99 (0.97-1.00)	0.95 (0.81-0.98)	0.94 (0.73-0.98)	N/A

Supraspinatus muscle (SS), Infraspinatus muscle (IS), Teres minor muscle (TMin), Subscapularis muscle (SSc), Teres major muscle (TMaj); Intraclass Correlation Coefficient (ICC).

Table II. — 2D inter-rater reliability and intra-rater reliability for the cross-sectional area of all slices of the rotator cuff muscles.

	SS	IS	TMin	SSc
Inter-rater reliability				
Slice A	0.54 (0.22-0.83)	N/A	N/A	N/A
Slice B	N/A	0.79 (0.56-0.93)	0.72 (0.45-91)	0.82 (0.61-0.95)
Slice Y	0.78 (0.55-0.93)	0.77 (0.53-0.93)	0.77 (0.51-0.93)	0.85 (0.66-0.95)
Intra-rater reliability				
Slice A	0.68 (0.17-0.91)	N/A	N/A	N/A
Slice B	N/A	0.97 (0.85-0.99)	0.89 (0.63-0.97)	0.66 (0.07-0.91)
Slice Y	0.93 (0.62-0.99)	0.88 (0.62-0.97)	0.41 (-0.32-0.82)	0.94 (0.78-0.98)

Supraspinatus muscle (SS), Infraspinatus muscle (IS), Teres minor muscle (TMin), Subscapularis muscle (SSc); Slice A: upper glenoid rim; Slice B: lower glenoid rim; Slice Y: Y-view; Intraclass Correlation Coefficient (ICC).

Table III. — Inter-rater reliability (ICC) Goutallier grades.

	SS	IS	TMin	SSc
Slice A	0.79 (0.71-0.86)	N/A	N/A	N/A
Slice B	N/A	0.81 (0.73-0.88)	0.62 (0.49-73)	0.67 (0.57-0.77)
Slice Y	0.63 (0.52-0.73)	0.64 (0.53-0.74)	0.74 (0.65-0.82)	0.70 (0.60-0.79)

Supraspinatus muscle (SS), Infraspinatus muscle (IS), Teres minor muscle (TMin), Subscapularis muscle (SSc); Slice A: upper glenoid rim; Slice B: lower glenoid rime; Slice Y: Y-view.

There was a strong correlation between the 3D fatty infiltration and the mean Goutallier classification (average value of slice Y + axial slice). The 2D and 3D fatty infiltration percentages correlate strongly (Table V).

DISCUSSION

Fatty infiltration is known to be a significant prognostic factor for rotator cuff repair, with higher pre-operative infiltration associated with increased retear recurrence and poorer functional outcomes[1,4,8]. The main issue with the current standard to assess fatty infiltration, the Goutallier classification, is that the inter-rater reliability is fair to moderate[10–14]. Another problem is that a 2D slice does not completely capture the rotator cuff muscle, resulting in different grades depending on the slice because the fat distribution differs within the muscle[15–17]. This study used 3D segmentation of the rotator cuff muscles and quantitive 2D measurements to compare fatty infiltration percentages to the Goutallier classification.

Our study demonstrated that 3D quantitative fatty infiltration can be determined from CT scans with a high reproducibility. The intra-rater and interrater variability was excellent for the 3D measurements and good to excellent for the 2D measurements. This is the first study evaluating the inter-rater reliability of 3D segmentation of the rotator cuff muscles on

Table IV. — The relative mean fatty infiltration of each rotator cuff muscle compared to the Goutallier classification.

Muscle	Goutallier	0	1	2	3	4
Supraspinatus	**Number of cases**	11	27	16	7	0
	Relative 3D fatty infiltration	0% (SD = 7)	11% (SD = 9)	17% (SD = 8)	22% (SD = 12)	N/A
	Relative 2D fatty infiltration	0% (SD = 8)	12% (SD = 10)	27% (SD = 14)	32 % (SD = 17)	N/A
Infraspinatus	**Number of cases**	10	19	14	11	5
	Relative 3D fatty infiltration	0% (SD = 5)	6% (SD = 9)	22% (SD = 15)	34% (SD = 12)	37% (SD = 5)
	Relative 2D fatty infiltration	0% (SD = 6)	12% (SD = 11)	26% (SD = 8)	35% (SD = 12)	42% (SD = 7)
Teres Minor	**Number of cases**	40	8	4	2	0
	Relative 3D fatty infiltration	0% (SD = 7)	9% (SD = 13)	24% (SD = 12)	61% (SD = 13)	N/A
	Relative 2D fatty infiltration	0% (SD = 8)	4% (SD = 11)	37% (SD = 24)	73 % (SD = 9)	N/A
Subscapularis	**Number of cases**	27	23	7	0	1
	Relative 3D fatty infiltration	0% (SD = 6)	3% (SD = 6)	10% (SD = 7)	N/A	36% (SD = 0)
	Relative 2D fatty infiltration	0% (SD = 8)	5% (SD = 7)	18% (SD = 10)	N/A	48% (SD = 0)
All muscles total	**Number of cases**	88	77	41	20	6
	Relative 3D mean fatty infiltration	**0% (SD = 6)**	**7% (SD = 8)**	**19% (SD = 10)**	**33% (SD = 12)**	**37% (SD = 4)**
	Relative 2D mean fatty infiltration	**0% (SD = 8)**	**8% (SD = 8)**	**25% (SD = 12)**	**37% (SD = 13)**	**43% (SD = 6)**

SD = Standard deviation.

Table V. — Pearson correlation coefficient (r) for 3D FI% and the mean Goutallier classification (average value of slice Y + axial slice), and 2D FI%.

2D evaluation	3D FI% SS	3D FI% IS	3D FI% TMin	3D FI% SSc
Goutallier classification	r = 0.619	r = 0.772	r = 0.796	r = 0.598
2D FI%	r = 0.584	r = 0.820	r = 0.867	r = 0.882

Three-dimensional (3D), Two-dimensional (2D), Fatty infiltration percentage (FI%), Supraspinatus muscle (SS), Infraspinatus muscle (IS), Teres minor muscle (TMin), Subscapularis muscle (SSc); $p < 0.001$ for all tests.

CT scans. On MRI scans, excellent reliability for 3D measurements has already been established[21,22,27,28]. It is worth noting that the teres minor (TMin) muscle had a slightly lower intra- and interobserver variability than the other rotator cuff muscles. This could be explained by the difficulty of correctly differentiating the TMin from the infraspinatus (IS) muscle on CT scans[6].

The inter-rater reliability (ICC) of the Goutallier classification for the Y-view and axial slices was good. The ICC for the Y-view ranged from 0.63 to 0.74, which is higher than other studies that have reported[11,12,14,24]. One distinguishing factor in our study was the evaluation of slices using screenshots instead of the scans, ensuring the exact view for all researchers. Additionally, our study focused exclusively on patients with rotator cuff arthropathy, which may have influenced the ICC. Both factors could account for the observed higher ICC values.

Furthermore, this study showed a strong correlation between fatty infiltration, calculated using 3D measurements, and the mean Goutallier grade and 2D FI%.

The 3D fatty infiltration percentage was compared to the mean Goutallier grade. The overall percentage was lower than expected per Goutallier category: 0% for Goutallier grade 0 muscles, 7% for Goutallier grade 1 muscles, 19% for Goutallier grade 2 muscles, 33% for Goutallier grade 3 muscles and 37% for Goutallier grade 4 muscles. The quantitive 2D percentages are similar for grade 0 and grade 1. The relative FI percentages for grades 2 to 4 are 4 to 6% higher than 3D. These percentages align with previously performed research on 3D representations of the rotator cuff muscles[23,24,29]. They are, however, lower than you would expect when evaluating the muscles according to the Goutallier classification.

Several factors likely contribute to these lower percentages. Firstly, we calculated fatty infiltration with the TMaj muscle as a reference for 100% muscle, however, Baillargeon et al.[19] demonstrated a mean percentage of 2.9 % fat (SD= 4.0) in a population of patients with shoulder pathologies. Secondly, when outlining the muscle for 3D segmentation, there is always a possibility for some voxels of the scapula to be included in the muscle. This is the case for muscles that lie directly on the scapula (i.e., Supraspinatus (SS), Subscapularis (SSc), IS), but this does not apply to the TMaj muscle. Lastly, the fat distribution within the muscle and the fact that a 2D slice does not represent the whole muscle also needs to be considered 15. Consequently, when viewing a muscle on a 2D slice, 50% of fat on 2D is an overestimation compared to when the whole muscle is considered. The overestimation is more apparent when evaluated with the Goutallier classification, but it is still present, albeit to a lesser extent, using a 2D quantitative method.

3D evaluation of fatty infiltration of the rotator cuff muscles is more commonly studied on MRI imaging[21–23]. While MRI imaging provides excellent soft tissue contrast for evaluating fatty infiltration of the rotator cuff muscles, it has disadvantages such as cost, limited availability, and potential patient tolerance issues. Only one other study has used CT scans to evaluate 3D fatty infiltration[24]. While CT scans are readily available, cost-effective, and commonly utilized preoperatively for reverse shoulder arthroplasty. However the downside is the use of ionizing radiation.

Another limitation of this study is that only the bone algorithm data of the CT scans were available because they were made in a pre-operatively context of a reverse shoulder arthroplasty. Consequently, evaluating the soft tissue, such as the rotator cuff muscles, becomes more difficult because of the lower spatial resolution. This low resolution caused the software to regard some muscle pixels as bone pixels incorrectly. Hence, differentiating fat from muscle using pre-existing HU thresholds was impossible because of the lower quality of the CT scans[24–26]. To address this issue, we employed a method with the TMaj muscle as a reference for 100% muscle. A disadvantage of using this method is the difficulty in differentiating the TMaj muscle from the latissimus dorsi muscle during segmentation, and as previously mentioned, the TMaj muscle is not entirely composed of 100% muscle. Nevertheless, this method offers the advantage of not necessitating high-quality CT scans.

One of the biggest disadvantages of manual segmentation is its time-consuming aspect[24,27]. Another limitation of this study is that only pre-operative CT scans showing the complete scapula were included, which diverges from the current standard practice.

Lastly, we could not compare muscle volumes as we did not standardize volume per patient, like Werthel et al.[24], who used scapula volume as a reference. We observed variability in scapular volume measurements among different researchers during the preparation phase of our study. Due to time constraints, we decided not to include this parameter in our study.

Objective assessment of fatty infiltration is important in determining the appropriateness and effectiveness of surgical intervention of rotator cuff tears. Among the evaluated methods, the 3D method is the most complete and reproducible tool to assess the rotator cuff muscles. We anticipate that ongoing innovation and improvement of the segmentation software will make the method less time-consuming. Because 3D segmentation considers the whole muscle, we believe this approach should be employed in further research to enhance treatment selection (surgical or conservative) and improve outcome prediction. Additionally, exploring whether a quantitative method could enhance patient selection for rotator cuff repair compared to the traditional Goutallier classification is worthwhile. Further research in this direction is warranted.

CONCLUSION

To conclude our study, a quantitative 3D method applied to CT scans provides more complete and reproducible results for evaluating fatty infiltration than the Goutallier classification. Nonetheless, its current time requirements limit its clinical efficiency. On the other hand, the quantitative 2D method demonstrates excellent reproducibility, although it may overestimate fatty infiltration of the whole muscle.

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