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Three-dimensional muscle loss assessment: a novel computed tomography–based quantitative method to evaluate rotator cuff muscle fatty infiltration

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Background: Rotator cuff fatty infiltration (FI) is one of the most important parameters to predict the outcome of certain shoulder conditions. The primary objective of this study was to define a new computed tomography (CT)–based quantitative 3-dimensional (3D) measure of muscle loss (3DML) based on the rationale of the 2-dimensional (2D) qualitative Goutallier score. The secondary objective of this study was to compare this new measurement method to traditional 2D qualitative assessment of FI according to Goutallier et al and to a 3D quantitative measurement of fatty infiltration (3DFI).
Materials and methods: 102 CT scans from healthy shoulders (46) and shoulders with cuff tear arthropathy (21), irreparable rotator cuff tears (18), and primary osteoarthritis (17) were analyzed by 3 experienced shoulder surgeons for subjective grading of fatty infiltration according to Goutallier, and their rotator cuff muscles were manually segmented. Quantitative 3D measurements of fatty infiltration (3DFI) were completed. The volume of muscle fibers without intramuscular fat was then calculated for each rotator cuff muscle and normalized to the patient's scapular volume to account for the effect of body size (NV_{fibers}). 3D muscle mass (3DMM) was calculated by dividing the NV_{fibers} value of a given muscle by the mean expected volume in healthy shoulders. 3D muscle loss (3DML) was defined as 1 – (3DMM). The correlation between Goutallier grading, 3DFI, and 3DML was compared using a Spearman rank correlation.
Results: Interobserver reliability for the traditional 2D Goutallier grading was moderate for the infraspinatus (ISP, 0.42) and fair for the supraspinatus (SSP, 0.38), subscapularis (SSC, 0.27) and teres minor (TM, 0.27). 2D Goutallier grading was found to be significantly and highly correlated with 3DFI (SSP, 0.79; ISP, 0.83; SSC, 0.69; TM, 0.45) and 3DML (SSP, 0.87; ISP, 0.85; SSC, 0.69; TM, 0.46) for all 4 rotator cuff muscles ($P < .0001$). This correlation was significantly higher for 3DML than for the 3DFI for SSP only ($P = .01$). The mean

This study was approved by the Institutional Review Board of the Ethical Committee of Hôpital Privé Jean Mermoz, Lyon, France (COS-RGDS-2020-05-001-WALCH-G).

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values of 3DFI and 3DML were 0.9% and 5.3% for Goutallier 0, 2.9% and 25.6% for Goutallier 1, 11.4% and 49.5% for Goutallier 2, 20.7% and 59.7% for Goutallier 3, and 29.3% and 70.2% for Goutallier 4, respectively.
Conclusion: The Goutallier score has been helping surgeons by using 2D CT scan slices. However, this grading is associated with suboptimal interobserver agreement. The new measures we propose provide a more consistent assessment that correlates well with Goutallier's principles. As 3DML measurements incorporate atrophy and fatty infiltration, they could become a very reliable index for assessing shoulder muscle function. Future algorithms capable of automatically calculating the 3DML of the cuff could help in the decision process for cuff repair and the choice of anatomic or reverse shoulder arthroplasty.
Level of evidence: Anatomy Study; Imaging

Keywords: Goutallier; 3D Goutallier; Muscle volume; 3D CT scan; Atrophy; Volumetric analysis

Rotator cuff fatty infiltration (FI) is recognized as one of the most important parameters to predict the outcome the outcome of certain shoulder procedures,[5,8,9,11,23,33] and it is considered crucial for clinical decision making prior to rotator cuff repair and shoulder arthroplasty.[14,20,43] Goutallier et al[9] first reported a method to subjectively and qualitatively stage intramuscular FI into 5 grades using computed tomography (CT) on axial views. This method was then adapted by Fuchs et al for its application on magnetic resonance imaging (MRI) on T1-weighted sequences.[5] These 2 qualitative 2-dimensional (2D) classifications are known to have poor intra- and interobserver reliability between 0.26 and 0.81 for intraobserver reliability and between 0.36 and 0.6 for interobserver reliability,[30,35,41] and several recent studies have shown how modern imaging sequences and techniques have the potential to provide a better estimate of FI by allowing accurate quantitative calculation of the intramuscular fat fraction after manual segmentation of rotator cuff muscle boundaries either on 2D sagittal Y-views[17,22,28,29,31] or in 3-dimensional (3D) images.[16,26,28,41] A number of imaging techniques (single-voxel MR spectroscopy,[31] spectroscopic gradient echo imaging,[17] 2-point Dixon imaging,[16,26,29] or chemical shift–based water-fat separation techniques[22,28]) have been reported to correlate with Goutallier scores. However, the objective quantitative percentage of intramuscular fat calculated with these methods was much lower than the expected fat ratio as determined qualitatively according to Goutallier.[28,41] This is probably due to 2 reasons: first, distribution of intramuscular fat is not uniform inside the muscle body[15,2,18,27,28] and as such 2D assessments cannot capture 3D FI measurements[19,41]; and second, the subjective qualitative assessment of the Goutallier score may sometimes be difficult to apply, because the precise distinction between atrophy and FI is often unclear in the literature as it is often difficult to distinguish the boundaries between intra- and extramuscular fat in cases of severe muscle atrophy and FI (Fig. 1).

We therefore hypothesized that the qualitative Goutallier score would be better translated quantitatively by calculating the percentage of remaining muscle tissue (independent of intra- or extramuscular fat) rather than by calculating the percentage of fat within the muscle. The primary objective of this study was to define a new quantitative 3D measure of muscular loss (ie, 3DML) based on a rationale of the 2D qualitative Goutallier score. The secondary objective of this study was to compare this new measurement method to the traditional 2D qualitative assessment of FI according to Goutallier et al and to a 3D quantitative measurement of FI.

Materials and methods

Study cohort

We retrospectively reviewed shoulder CT scans performed between 2015 and 2020 and obtained from a database incorporating 4 institutions (Lyon, Nice, and Paris [France], and Belo Horizonte, MG [Brazil]). The CT scan examinations had been performed using one of 2 CT scan systems (Revolution CT [GE Healthcare, Chicago, IL, USA] or Siemens Somatom CT Scanner [Siemens Healthcare, Erlangen, Germany]) with the patient positioned supine on the CT table. CT scan examinations of healthy shoulders and shoulders with primary osteoarthritis (OA), cuff tear arthropathy (CTA), and irreparable rotator cuff tears (IRCTs) were included provided they had been obtained using the following acquisition parameters: slice thickness <1.2 mm, number of slices >200, field of view: whole scapula, X-Y resolution <0.5 mm, matrix size: 512 × 512, 140 kV, >300 mA, and both bone and soft tissue algorithms.

Our final study sample included a total of 102 CT scans (healthy shoulders 46, CTA 21, ICRT 18, and OA 17 shoulders). The CT of healthy shoulders had been obtained from patients aged older than 18 years without shoulder pathology or injury in the setting of (1) polytrauma, (2) traumatic head injury, or (3) unilateral shoulder trauma with a contralateral normal shoulder. The CT scan images of patients with CTA, IRCT, or OA were preoperative CT scans performed prior to shoulder arthroplasty. Shoulders with full-thickness rotator cuff tears were classified as CTA if they were grade 4 or higher in the Hamada classification[10] and as IRCT if they had at least 2 irreparable rotator cuff tendons but no glenohumeral arthritis (Hamada grade < 4). Patient's demographics are detailed in Table I.

Qualitative 2D analysis of FI: traditional Goutallier score using 2D CT images

Axial and sagittal CT slices were analyzed according to the principles underlying the Goutallier et al[9] and Fuchs et al[5]

Figure 1 Sagittal view of a right shoulder in a massive rotator cuff tear (MRCT) patient with severe fatty infiltration of the supraspinatus and infraspinatus. Intra- and extramuscular fat can be seen. This example shows the difficulty to define precisely the difference between intra- and extramuscular fat.

protocols for the presence of FI, which was classified according to the 5-grade qualitative scale described by Goutallier et al[9]: grade 0, normal; grade 1, some fatty streaks; grade 2, more muscle than fat; grade 3, equal amounts of fat and muscle; and grade 4, more fat than muscle. All the CT scans were examined independently by 3 different fellowship-trained shoulder surgeons (J.D.W, P.M., P.G.) in order to assess the inter-rater reliability of this subjective quantitative method. The final grading of each muscle used for analysis was based on consensus agreement where 2 of 3 or 3 of 3 surgeons had classified the same grade. A difference of more than 1 grade required that all surgeons review the examination together again in order to reach consensus.

Three-dimensional muscle reconstruction

The soft tissue DICOM (Digital Imaging and Communications in Medicine) images for each CT scan were manually segmented using the Slicer version 4.10.0 software (Slicer Community Boston, MA, USA; http://slicer.org). Muscle boundaries were manually identified and marked to segment the 4 rotator cuff muscles: supraspinatus, subscapularis, infraspinatus, and teres minor. To create a robust process, muscle boundaries were identified on each image slice in all 3 planes (coronal, axial, and sagittal). The segmentations were performed either by a shoulder fellowship-trained orthopedic surgeon or by trained technicians; segmentation performed by technicians was verified and corrected when needed by the same orthopedic surgeon who had completed manual segmentation of a proportion of the CT. Published threshold values were used to identify muscle and fat tissue.[1] Extramuscular fat was not assessed. The volume of muscle fibers without intramuscular fat (V_{fibers}) and the volume of intramuscular fat (V_{imfat}) were calculated in cubic centimeters for each muscle.

Quantitative 3D analysis of FI, muscle mass, and muscle loss

Quantitative 3D analysis of FI (3DFI) was possible once the muscle fiber volume (V_{fibers}) and the intramuscular fat volume (V_{imfat}) have been calculated. The following formula was applied to each rotator cuff muscle:

$$3DFI = \frac{V_{imfat}}{V_{fibers} + V_{imfat}}$$

The bone DICOM series were then automatically segmented using a validated 3D-software (BluePrint, version 2.1.6; Tornier SAS, Montbonnot, France), which provides a 3D model of the scapula and allows automatic calculation of its volume in cubic centimeters. Each measurement of muscle fiber volume was then normalized to the patient's scapular volume to account for the effect of body size on muscle volume.[24] This allowed us to calculate the normalized volume of muscle fibers (NV_{fibers}) for each rotator cuff muscle. Mean NV_{fibers} were calculated for each muscle in the 4 different groups of patients (Healthy Controls, IRCT, CTA, OA). In order to establish a frame of reference for normal muscle volume, the NV_{fibers} value for each muscle was divided by the theoretical volume that this muscle would have if it were healthy. This theoretical volume was determined by calculating the mean NV_{fibers} of the healthy shoulders, which were used to obtain a reference value for males and females for each of the rotator cuff muscles (Ref NV_{fibers}). Table II summarizes mean NV_{fibers} for each muscle and each group. Quantitative calculation of 3D muscle mass (3DMM) was completed by dividing the NV_{fibers} value for a given muscle by the $RefNV_{fibers}$ of that muscle.

$$3DMM = \frac{NV_{fibers}}{Ref\,NV_{fibers}}$$

Table I Patient demographics

	Healthy controls (46)	CTA (21)	IRCT (18)	OA (17)	All
Age, mean ± SD					
Total sample	36 ± 16	77 ± 8	71 ± 8	69 ± 8	56 ± 22
Females	46 ± 19	78 ± 8	73 ± 7	69 ± 8	67 ± 17
Males	33 ± 14	73 ± 8	68 ± 8	70 ± 8	46 ± 22
Left/right	25/21	9/12	4/14	9/8	47/55
Females/males, n	12/34	16/5	11/7	10/7	49/53

SD, standard deviation; *CTA*, cuff tear arthropathy; *IRCT*, irreparable rotator cuff tear; *OA*, osteoarthritis.

Table II Normalized muscles fiber volume (NV_{fibers}) for each condition

	Healthy controls			CTA			IRCT			OA		
	Total sample	Male	Female	Total sample	Male	Female	Total sample	Male	Female	Total sample	Male	Female
Supraspinatus	0.65 ± 0.1	0.67 ± 0.1	0.59 ± 0.1	0.24 ± 0.1	0.32 ± 0.1	0.21 ± 0.1	0.27 ± 0.1	0.31 ± 0.1	0.24 ± 0.1	0.37 ± 0.1	0.34 ± 0.1	0.39 ± 0.1
Subscapularis	1.89 ± 0.3	1.98 ± 0.3	1.63 ± 0.2	1.06 ± 0.3	1.04 ± 0.4	1.07 ± 0.3	1.03 ± 0 .2	1.05 ± 0.2	1.02 ± 0.3	1.04 ± 0.2	0.97 ± 0.2	1.09 ± 0.3
Infraspinatus	1.37 ± 0.2	1.40 ± 0.2	1.29 ± 0.2	0.65 ± 0.3	0.73 ± 0.3	0.62 ± 0.3	0.74 ± 0.2	0.88 ± 0.1	0.66 ± 0.2	0.92 ± 0.2	0.90 ± 0.2	0.93 ± 0.2
Teres minor	0.30 ± 0.1	0.32 ± 0.1	0.26 ± 0.1	0.21 ± 0.1	0.25 ± 0.1	0.20 ± 0.1	0.21 ± 0.1	0.20 ± 0.1	0.21 ± 0.1	0.19 ± 0.1	0.20 ± 0.1	0.19 ± 0.1

CTA, cuff tear arthropathy; *IRCT*, irreparable rotator cuff tear; *OA*, osteoarthritis.

3D muscle loss (3DML) is then determined by subtracting 3DMM from 100.

$$3DML = 100 - 3DMM.$$

For example, the average $RefNV_{fibers}$ value of the infraspinatus for males is 1.4 (Table I). If the NV_{fibers} infraspinatus measurement of a given shoulder of a male patient is 0.88, the infraspinatus 3DMM for such shoulder would be 0.88/1.40 = 63%, which means that 63% of the expected muscle mass is still present and the remaining 37% of the expected muscle mass has been replaced by infiltrated fat (3DML = 1 – 0.88/1.4 = 37%). Two examples can be seen in Figures 2 and 3.

Statistical analysis

Reliability of agreement between the 3 raters of the Goutallier grade was assessed using a Fleiss kappa (κ). Fleiss kappa value and 95% confidence intervals were computed for each muscle, for the whole cohort but also for each diagnostic group (Healthy Controls, CTA, IRCT, OA). Concordance was evaluated using the table of Landis et al.[21]

One-way analysis of variance was used to test the difference between the means of several diagnostic subgroups (Healthy Controls, CTA, irreparable rotator cuff tear [IRCT], OA) of a continuous variable (3DFI or 3DML). Levene test was used to check the equality of variances. The hypothesis that the means of at least 2 of the subgroups differ significantly is accepted if the P value of the F statistic is less than .05. The pairwise comparison of the subgroups was then calculated using the Tukey-Kramer test. If the Levene test is positive ($P < .05$), then the variances in the different groups are different and we used a nonparametric statistic. In that case, the Kruskal-Wallis test (H test) was used. For the whole cohort, but also each diagnostic group (Healthy Controls, CTA, IRCT, OA), the correlation between the consensus Goutallier score and the quantitative 3D analysis of FI (3DFI) and 3DML was computed using a Spearman rank correlation. The coefficient of rank correlation, rho, was assessed using a Steiger test.

For all tests, the level of statistical significance was set at $P < .05$. Statistical analyses were performed using R (version 3.6.1, R Foundation, Vienna, Austria) or MedCal (version 19.4.0; MedCalc Software Ltd., Ostend, Belgium) depending on the test.

Results

Goutallier interobserver reliability

Analysis of the interobserver reliability showed fair interobserver reliability for supraspinatus, subscapularis, and teres minor FI, with κ values of 0.38 (range 0.31, 0.44), 0.27 (range 0.22, 0.33), and 0.27 (range 0.19, 0.36), respectively. Interobserver reliability was moderate for infraspinatus FI, with a κ value of 0.42 (range 0.35, 0.48). Interobserver reliability is detailed in Table III.

3DFI and 3DML

The mean 3DFI and 3DML are detailed for each rotator cuff muscle and for each patient group (Healthy Controls, CTA, IRCT, OA) in Tables IV and V.

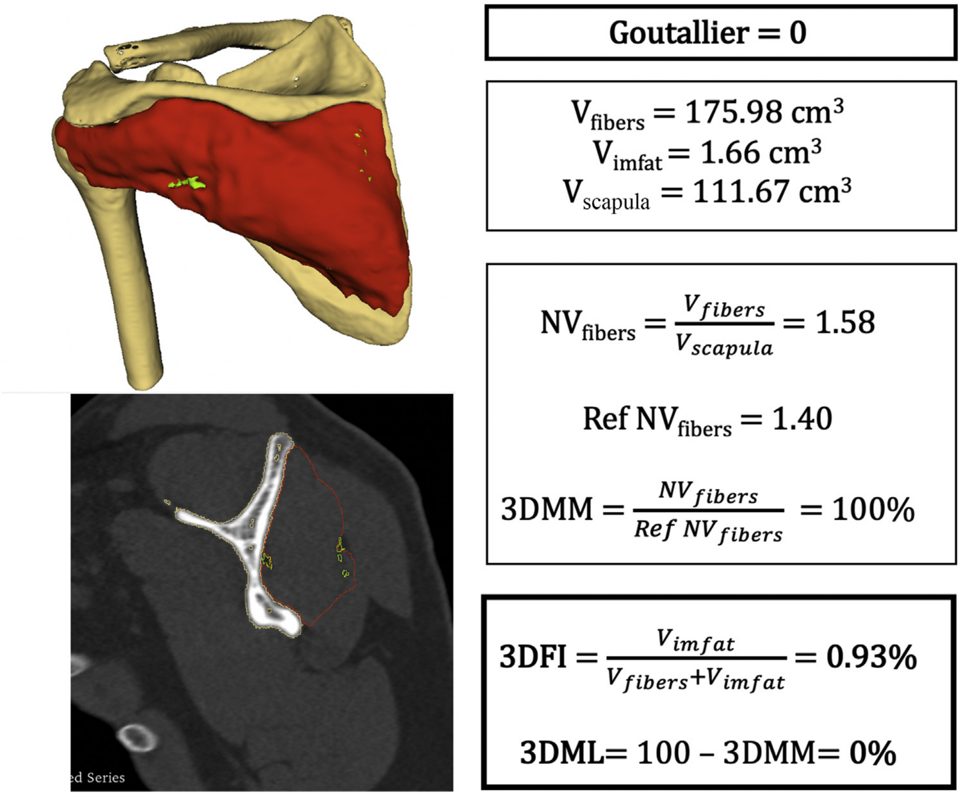

Figure 2 Example of a 42-year-old man from the healthy cohort. Three-dimensional reconstruction and sagittal view of the left infraspinatus (*red*) and intramuscular fat (*yellow*). V_{fibers}, muscle fiber volume; V_{imfat}, intramuscular fat volume; $V_{scapula}$, scapular volume; NV_{fibers}, normalized volume of muscle fibers; *Ref* NV_{fibers}, reference value for *males* for the infraspinatus; *3DMM*, 3-dimensional muscle mass; *3DFI*, 3-dimensional quantitative calculation of fatty infiltration; *3DML*, 3-dimensional muscle loss.

The mean 3DFI was significantly greater for all 4 rotator cuff muscles in pathologic groups than in the healthy control group ($P < .0001$). Among the pathologic groups, the mean FI was significantly higher for the supraspinatus of CTA and MRCT patients than for OA patients ($P < .02$) and for the infraspinatus of CTA patients than for OA patients ($P < .001$).

The mean 3DML was significantly greater for all 4 rotator cuff muscles in pathologic groups than in the healthy control group ($P < .0001$). Among the pathologic groups, the mean 3DML was significantly higher for the supraspinatus of CTA and MRCT patients than for OA patients ($P < .001$) and for the infraspinatus of CTA patients than for OA patients ($P < .005$).

The correlation between the consensus 2D Goutallier score and the quantitative 3D analysis of FI and ML is detailed in Table VI. For all rotator cuff muscles, mean values of 3DFI were 0.9% ± 1.5% for Goutallier 0 muscles, 2.9% ± 4.6% for Goutallier 1 muscles, 11.4% ± 9.9% for Goutallier 2 muscles, 20.7% ± 17.5% for Goutallier 3 muscles, and 29.3% ± 23.4% for Goutallier 4 muscles. Mean values of 3DML for all 4 rotator cuff muscles were 5.3% ± 17.4% for Goutallier 0 muscles, 25.6% ± 22.3% for Goutallier 1 muscles, 49.5% ± 16.3% for Goutallier 2 muscles, 59.7% ± 13.9% for Goutallier 3 muscles, and 70.2% ± 16.3% for Goutallier 4 muscles. Results for each rotator cuff muscle are detailed in Table VI. The 2D Goutallier score was significantly and highly correlated to the volume measurement of 3DFI and 3DML for all 4 rotator cuff muscles ($P < .0001$). This correlation was significantly higher for the 3DML than for the measure of 3DFI for supraspinatus ($P = .01$).

Discussion

Rotator cuff FI is extremely important in the decision-making process prior to rotator cuff repair or shoulder arthroplasty. Despite advances in preoperative planning for shoulder arthroplasty using dedicated software with 3D assessments, currently most surgeons grade rotator cuff FI subjectively on 2D CT or MRI. The results of our study seem to indicate that the interobserver reliability of the Goutallier classification for FI on CT is only fair to moderate, in accordance with prior studies.[30,34,41] In addition, our study seems to indicate that quantitative measurements of muscle mass and muscle loss may be of value when assessing rotator cuff degeneration in shoulders with OA, CTA, and IRCT.

Several authors have proposed to improve the assessment of FI by using 2D quantitative methods.[28,37] These

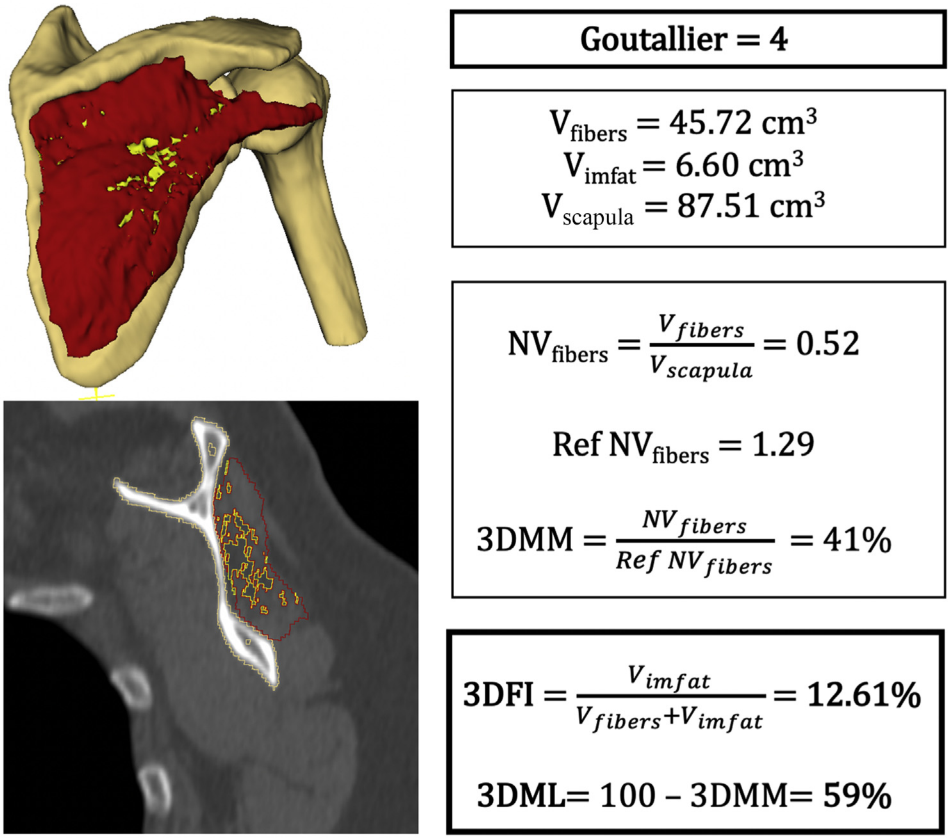

Figure 3 Example of a 72-year-old woman from the irreparable rotator cuff tear (IRCT) cohort. Three-dimensional reconstruction and sagittal view of the left infraspinatus (*red*) and intramuscular fat (*yellow*). V_{fibers}, muscle fiber volume; V_{imfat}, intramuscular fat volume; $V_{scapula}$, scapular volume; NV_{fibers}, normalized volume of muscle fibers; $Ref\ NV_{fibers}$, reference value for *females* for the infraspinatus; *3DMM*, 3-dimensional muscle mass; *3DFI*, 3-dimensional quantitative calculation of fatty infiltration; *3DML*, 3-dimensional muscle loss.

methods were reported to be significantly correlated with Goutallier grades. However, we believe that analyzing a 3D structure on a single 2D slice is incorrect and subject to significant bias, particularly considering that fat is not homogeneously distributed inside rotator cuff muscles.[27,42] Vidt et al[41] have recently demonstrated that single-image assessments are not able to capture 3D measures of FI, and that the use of a 3D quantitative method allows better discrimination between the various Goutallier grades.

In our study, when we calculated 3DFI values, we found a very different percentage of fat-to-muscle ratio than expected according to Goutallier criteria. Indeed, Goutallier grades 3 and 4 are traditionally considered to correspond to a muscle replacement by fat of 50% or more, but our mean 3DFI values were 20.7% and 29.3%, respectively. This finding is in agreement with previous studies[28,41] which have also found much lower quantitative values than expected after qualitative assessment. In other words, it only takes loss of 30% of fatty infiltration to translate into a 2D visual estimate of >50% FI replacement.

Table III Interobserver agreement for Goutallier classification (Fleiss kappa)

	Overall	
	Fleiss kappa	95% CI
Supraspinatus	0.38	0.31, 0.44
Subscapularis	0.27	0.22, 0.33
Infraspinatus	0.42	0.35, 0.48
Teres minor	0.27	0.19, 0.36

CI, confidence interval.

Muscle atrophy and FI have been recognized as independent predictive parameters of outcome for a number of surgical procedures.[5,8,9,11,23,33] However, as independent as these parameters may be, all the methods that we currently use to assess them inevitably make them dependent on each other. Indeed, measures of muscle volume and muscle atrophy (tangent sign,[44] occupation ratio[38]) typically include intramuscular fat,[6-8,25,39] and the measures of FI depend on muscle volume as they are expressed as the ratio of intramuscular fat volume to muscle volume.[5,9] Therefore, a decrease in muscle volume, with no change in the volume of intramuscular fat, automatically leads to an increase in the FI ratio. It has been shown that increased percentages of fat observed in cases of severe FI are more related to

Table IV Quantitative 3-dimensional fatty infiltration (3DFI)

	Healthy controls		CTA		IRCT		OA		Kruskal-Wallis test
	2D Goutallier	3DFI, %	2D Goutallier	3DFI, %	2D Goutallier	3DFI, %	2D Goutallier	3DFI, %	
Supraspinatus	0.2 ± 0.5	0.8 ± 1.1	2.3 ± 0.9	15.9* ± 19 OA	2 ± 0.7	11.7* ± 11 OA	1.4 ± 0.7	4.6* ± 4 CTA/MRCT	$P < .02$
Subscapularis	0 ± 0	0.7 ± 1.0	1.2 ± 0.6	8.9 ± 10	1.1 ± 1.1	7.5 ± 10	0.4 ± 0.5	3.9 ± 3	
Infraspinatus	0.2 ± 0.4	0.6 ± 0.9	2.9 ± 1.2	21* ± 19 OA	2.2 ± 1.3	9.9 ± 13	1.2 ± 0.8	3.3* ± 3 CTA	$P < .001$
Teres minor	0 ± 0.1	0.7 ± 2.0	1.4 ± 1.4	9 ± 22	0.9 ± 1.1	4.4 ± 10	0.5 ± 1	2.4 ± 4	

CTA, cuff tear arthropathy; *IRCT*, irreparable rotator cuff tear; *OA*, osteoarthritis.
* Significantly different.

Table V Three-dimensional muscle loss (3DML)

	Healthy controls		CTA		IRCT		OA		ANOVA
	2D Goutallier	3DML, %	2D Goutallier	3DML, %	2D Goutallier	3DML, %	2D Goutallier	3DML, %	
Supraspinatus	0.2 ± 0.5	0	2.3 ± 0.9	61* ± 13 OA	2 ± 0.7	56* ± 16 OA	1.4 ± 0.7	39* ± 14 CTA/MRCT	$P < .001$
Subscapularis	0 ± 0	0	1.2 ± 0.6	37 ± 21	1.1 ± 1.1	41 ± 14	0.4 ± 0.5	40 ± 17	
Infraspinatus	0.2 ± 0.4	0	2.9 ± 1.2	51* ± 22 OA	2.2 ± 1.3	44 ± 16	1.2 ± 0.8	30* ± 15 CTA	$P < .005$
Teres minor	0 ± 0.1	0	1.4 ± 1.4	22 ± 36	0.9 ± 1.1	25 ± 33	0.5 ± 1	30 ± 44	

CTA, cuff tear arthropathy; *IRCT*, irreparable rotator cuff tear; *OA*, osteoarthritis; *ANOVA*, analysis of variance.
* Significantly different.

Table VI Correlation between the consensus Goutallier score and the quantitative 3D analysis of fatty infiltration (3DFI) and muscle loss (3DML)

Goutallier	0	1	2	3	4	Rho	*P* value
Supraspinatus							
n	38	24	30	7	3		
3DFI, %	0.7 ± 1.2	2.2 ± 2.7	11.2 ± 10.2	25.3 ± 27	24.2 ± 13.9	0.79	<.0001
3DML, %	0.7 ± 0.5	25.6 ± 22.8	53.1 ± 15.2	72.7 ± 10.4	74.8 ± 4.0	0.87	<.0001
Subscapularis							
n	65	25	9	3	0		—
3DFI, %	1.2 ± 1.6	6.3 ± 7.3	13.7 ± 8.7	22.2 ± 14.1	N/A	0.69	<.0001
3DML, %	10 ± 16.9	37.6 ± 18.5	50.2 ± 17.5	58.4 ± 12.2	N/A	0.69	<.0001
Infraspinatus							
n	43	26	9	12	12		—
3DFI, %	0.6 ± 1.0	1.9 ± 2.2	7.5 ± 7.0	18.0 ± 14.1	29.7 ± 20.0	0.83	<.0001
3DML, %	2.3 ± 7.0	20.3 ± 18.6	36.5 ± 11.4	55.9 ± 10.5	62.6 ± 12.5	0.85	<.0001
Teres minor							
n	71	20	4	2	5		—
3DFI, %	0.8 ± 1.8	1.0 ± 1.3	17.4 ± 15.3	21.0 ± 10.1	31.7 ± 36.8	0.45	<.0001
3DML, %	5.3 ± 24.3	17.6 ± 25.3	50 ± 21.3	31 ± 21.2	84.2 ± 19.5	0.46	<.0001
All muscles							
n	217	95	52	24	20		
3DFI, %	0.9 ± 1.5	2.9 ± 4.6	11.4 ± 9.9	20.7 ± 17.6	29.3 ± 23.4	0.71	<.0001
3DML, %	5.3 ± 17.4	25.6 ± 22.3	49.5 ± 16.3	59.7 ± 13.9	70.2 ± 16.3	0.74	<.0001

muscle atrophy than to increased fat volume.[41] Furthermore, it is not clear from the Goutallier score whether FI includes only intramuscular fat or both intra- and extramuscular fat, especially in cases of severe FI and muscle atrophy.

For these reasons, we reasoned that assessment of rotator cuff muscle degeneration could be much improved by developing quantitative 3D assessments of remaining muscle mass and muscle loss. The method presented in our study is complex and tedious, because it requires manual segmentation and 2 normalization steps. However, they provided the basis and ground truth for training algorithms that in the near future will incorporate automatic muscle segmentation using statistical models and deep learning techniques.[3,32] Furthermore, a major benefit of the proposed 3DML measurement is that it integrates both atrophy and FI into a single value, which will hopefully best correlate with remaining strength as well as predicted outcomes after surgery.[12,13,40]

Interestingly, although the Goutallier score was found to be relatively unreliable when evaluated by a single shoulder-specialized surgeon, this was no longer the case when a consensus Goutallier score was determined among 3 surgeons. Indeed, the consensus values were strongly and significantly correlated with both 3DFI and 3DML measurements, with superior correlation with the 3DML measurements for the supraspinatus muscle (Table VI). In addition, 3DML values were found to be much closer to the expected Goutallier fat ratio than 3DFI values. Indeed, the mean 3DML values were found to be 5.3% for Goutallier 0 muscles, 25.6% for Goutallier 1, 49.5% for Goutallier 2, 59.7% for Goutallier 3, and 70.2% for Goutallier 4, suggesting that 3DML values correspond better to the traditional Goutallier grading currently used in practice. We suspect that calculation of 3DML values will be the most useful FI parameter to consider when assessment of muscle atrophy and FI is fully automated.

Our study has several limitations. First, the size of the cohort of pathologic shoulders was relatively small; this was due to difficulties obtaining CT scans with both bone and soft tissue algorithms and the entire scapula, which was unfortunately often truncated at its medial or distal tip. With the recent trend to use high-quality CT protocols in preoperative planning software, it is likely that future CT scans will routinely include the entire scapula. Second, we did not perform inter- and intraobserver reliability analysis for manual segmentation because of the high number of cases and the extensive amount of time needed to segment the entire rotator cuff. Third, most studies analyzing muscle volume have been based on MRI, using techniques that generate more accurate quantitative fat-fraction maps that distinguish fat and muscle from other tissues such as vessels; however, we chose to investigate CT imaging with a soft tissue algorithm for 4 main reasons: (1) MRI and CT have been shown to be equally effective in assessing supraspinatus atrophy[36] and in measuring rotator cuff cross-sectional area; (2) CT imaging allowed us to automatically segment the scapula using a validated 3D software (BluePrint, version 2.1.6) and calculate the volume of the scapula in cubic centimeters; (3) the proportion of pixels not clearly attributable to muscle or fat was neglectable compared to the number of pixels that are clearly identifiable as muscle or fat; (4) it is easy to obtain CT scans including the whole scapula with enough slices to perform multiplanar and 3D reconstructions, whereas this is more challenging to obtain on MRI; and (5) CT is widely available, fast, and routinely used in preoperative planning for shoulder arthroplasty,[4] where adding soft tissue algorithms to bone algorithms is simple, fast, and relatively inexpensive. At the present time, the method described in our study is not intended to be incorporated into routine surgical practices until automation of this process will easily allow us to accurately and objectively determine rotator cuff muscle mass and muscle loss.

Conclusion

Assessment of FI in rotator cuff muscles is important for predicting shoulder conditions. Since 1994, the Goutallier score has been helping surgeons by using 2D CT scan slices. However, this 2D grading is associated with suboptimal interobserver agreement. In this article, we proposed 3 CT-based measurements for a 3D quantitative assessment of FI (ie, 3DFI), muscle mass (ie, 3DMM), and muscle loss (ie, 3DML). These new measures seem to provide a more consistent assessment that still correlates well with Goutallier's principles. As 3DML measurements incorporate atrophy and FI, they have the potential to become a very reliable index for assessing shoulder muscle function. Future algorithms capable of automatically calculating the 3DML of the rotator cuff could be of great help in the decision process for rotator cuff repair and the choice of anatomic or reverse shoulder arthroplasty.

Disclaimer

Jean-David Werthel receives royalties for shoulder prosthesis design from FH Orthopedics. François Boux de Casson is an employee of Wright Medical. Gilles Walch receives royalties for shoulder prosthesis design from Wright Medical. Philipp Moroder receives royalties from Arthrex Inc. and NCS Lab for shoulder related products. Joaquin Sanchez-Sotelo receives royalties for shoulder prosthesis design from Wright Medical-Stryker. Jean Chaoui owns stocks and stock options from Wright Medical.

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