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SCIENTIFIC ARTICLE

Single slice MR image estimation of 3D supraspinatus intramuscular fatty infiltration in older adults: relevance for clinical practice and research

Ranyah Almardawi[1,2] · Leopoldo Garcia Zapata[3] · Ramnik Gill[4] · Jacqueline Addona[4] · Irina Kapustina[5] · Sagheer R. Ahmed[6] · Kimia Kani[6] · Derik L. Davis[6]

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Abstract

Objective (1) To compare older adults stratified by supraspinatus tendon tear status (STT status)—no tear (Intact), partial-thickness (PT) tear, full-thickness (FT) tear—by 3D Dixon fat fraction (3D-FF); 2D fat fraction (2D-FF); and 2D Goutallier grade (2D-GG) at the Y-shaped view, and 1.4 cm and 2.8 cm medial to the Y-shaped view. Stratified by STT status to determine (2) correlation of 3D-FF with 2D-FF and 2D-GG and (3) inter-rater reliability at and medial to the Y-shaped view.

Materials and methods Forty-five volunteers ≥ 60 years recruited prospectively received shoulder MRI. 3D-FF and 2D-FF were measured on 6-point-Dixon MRI by three trainees. Goutallier grade was assessed on T1-weighted MRI by three fellowship-trained diagnostic radiologists. Descriptive, reliability, and correlation analyses were performed.

Results Groups showed no difference in age. The FT group showed higher ($p < 0.05$) mean 3D-FF (14.09% ± 10.99%), mean 2D-FF (1.4 cm medial to Y-shaped view, 14.91% ± 12.11%; 2.8 cm medial to Y-shaped view, 13.32% ± 9.48%), and mean 2D-GG (Y-shaped view, 1.71 ± 0.78; 1.4 cm medial to Y-shaped view, 1.71 ± 0.69; 2.8 cm medial to Y-shaped view, 1.71 ± 0.72), relative to Intact/PT groups. 3D-FF showed strong correlation with 2D-FF among all groups/all analyses (rho, 0.80–0.98; $p < 0.001$). 3D-FF showed strong correlation with 2D-GG for all FT group analyses (rho, 0.85–0.91; $p < 0.05$). 3D-FF showed moderate-to-strong correlation considering all Intact/PT group analyses (rho, 0.51–0.79; $p < 0.50$). Dixon fat fraction showed excellent reliability for all groups (≥ 0.884, intraclass correlation coefficient). Goutallier grade showed excellent reliability for FT group (0.771, weighted Fleiss's kappa) but poor (0.294) and fair (0.502) for Intact and PT groups, respectively.

Conclusion Single slice MR image estimation of 3D supraspinatus intramuscular fatty infiltration has merit for continued use in clinical populations requiring potential rotator-cuff-repair surgery. However, Dixon fat fraction should be prioritized for use in research over Goutallier grade due to superior reliability.

Keywords 3D · Dixon fat fraction · Goutallier grade · Intramuscular fatty infiltration · MRI · Rotator cuff · Shoulder

✉ Derik L. Davis
ddavis@som.umaryland.edu

[1] University of Maryland Baltimore, Baltimore, MD, USA

[2] University of Maryland Baltimore County, Baltimore, MD, USA

[3] Department of Diagnostic Radiology and Nuclear Medicine, University of Maryland Medical Center, Baltimore, MD, USA

[4] University of Maryland School of Medicine, Baltimore, MD, USA

[5] MRI & CT Diagnostics, Chesapeake, VA, USA

[6] Department of Diagnostic Radiology and Nuclear Medicine, University of Maryland School of Maryland, 22 S. Greene Street, Baltimore, MD 21201, USA

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Introduction

Rotator cuff (RC) disorders are common, and nearly five million patients present for clinical evaluation every year in the USA [1]. RC tear is highly prevalent in middle-aged and older populations, with most tears involving the supraspinatus tendon [1–3]. Orthopedic surgeons are the lead specialists to identify which patients are most likely to receive more favorable outcomes from operative interventions rather than conservative management. Given that a plethora of shoulder disorders often present with similar clinical symptoms and signs, diagnostic imaging is important to aid in establishing a definitive diagnosis [4]. Best practices remain controversial for when rotator cuff repair (RCR) surgery is indicated, but evaluation of RC intramuscular fatty infiltration (FI) is a key metric for clinical decision-making [5–9]. Magnetic resonance imaging (MRI) is the leading modality in the USA to identify an RC tear and to quantify FI [7, 10].

Single slice two-dimensional (2D) estimation of RC FI by semi-quantitative Goutallier grade on shoulder MRI at the Y-shaped view has been the most common technique in clinical practice for more than 20 years [9, 11–13]. Recently, investigators have questioned this practice with concern that single slice estimation of FI on MRI is not predictive of volumetric FI. Vidt et al. reported that volumetric three-dimensional (3D) Dixon fat fraction (3D fat fraction) poorly correlated with single slice 2D Goutallier grade at the Y-shaped view on oblique sagittal T1-weighted MR images in a sample of 20 older adults [14]. In a follow-up study, Addona et al. were unable to reproduce these findings and instead reported that 3D fat fraction had strong correlation with both 2D fat fraction and 2D Goutallier grade for supraspinatus FI at the Y-shaped view in a study population of 10 older adults [15]. These investigators posited that reasons for differences were most likely related to differing methodology between the studies, such as improvements in the follow-up study with respect to controlling for medial retraction of the supraspinatus muscle at the Y-shaped view and use of the same imaging plane for FI assessment correlation [15]. However, persistent questions remain as to (1) if there are differences in strength of correlation for volumetric 3D FI with 2D FI, and also inter-rater reliability for FI, when shoulders are stratified into separate groups by supraspinatus tendon tear-status (no tear, partial-thickness tear, and full-thickness tear); and (2) which single slice 2D MR image(s) medial to the Y-shaped view, if any, are most appropriate for estimation of supraspinatus volumetric 3D FI in the setting of full-thickness tear with medial retraction.

Therefore, the aims of this study in a population of older adults are (1) to determine differences for 3D fat fraction, and also for 2D fat fraction and 2D Goutallier grade at multiple locations in the supraspinatus muscle at and medial to the Y-shaped view, among groups with no tear, partial-thickness tear, and full-thickness tear of the supraspinatus tendon; (2) to determine strength of correlation of 3D fat fraction with 2D fat fraction, and also 2D Goutallier grade, at the Y-shaped view and also medial to the Y-shaped view stratified by supraspinatus tendon tear-status; and (3) to determine the inter-rater reliability for Dixon fat fraction and Goutallier grade in groups stratified by no tear, partial-thickness tear, and full-thickness tear of the supraspinatus tendon.

Materials and methods

Study population

This study was approved by the authors' institutional review board and complied with Health Insurance Portability Compatibility and Accountability Act guidelines. Participants signed informed written consent to participate. A convenience sample of older adult volunteers, aged ≥ 60 years, received shoulder MRI and completed self-reported questionnaires at one time point at our institution's MRI research facility between November 2017 and November 2020 following recruitment via advertisement in the local area. Exclusion criteria included age < 60 years or > 85 years; upper extremity paralysis; history of shoulder joint replacement or rotator cuff repair; and contraindication to MRI. A total of 45 participants were stratified into three groups by supraspinatus tendon tear-status: Intact ($n = 15$), partial-thickness (PT) tear ($n = 15$), and full-thickness (FT) tear ($n = 15$). The Intact group included shoulders with no tear (normal or tendinopathy).

MRI

Older adult volunteers received one shoulder MRI ipsilateral to the dominant hand if no symptoms were present or ipsilateral to the symptomatic shoulder if self-reported complaints were reported. Shoulder MRI was performed at 3.0 T (Magnetom Prismafit; Siemens Healthcare, Erlangen, Germany) with a four-channel flexible coil. The protocol for all participants included a 3D volumetric 6-point Dixon sequence (matrix, 320 × 250; repetition time (TR), 9.31 ms, echo time (TE), 1.35, 2.65, 3.95, 5.25, 6.55, 7.85 ms; flip angle, 9; FOV 400 × 324 mm^2; slice thickness, 3.5 mm; number of averages, 1) obtained in the sagittal orientation with automated reconstruction of 2D oblique sagittal 6-point Dixon fat fraction maps. Also, 2D turbo spin-echo oblique

sagittal T1-weighted (matrix, 448 × 202; TR/TE ms, 600/24; field of view (FOV), 160 × 160 mm^2; number of averages, 1; slice thickness, 4 mm); and axial, oblique coronal, and oblique sagittal 2D short tau inversion recovery (matrix, 256 × 202; TR/TE ms, 4420/51; inversion time 180 ms; FOV, 160 × 160 mm^2, number of acquisitions, 1; slice thickness, 4 mm) sequences were performed [16].

MRI analysis

De-identified DICOM 6-point Dixon fat fraction image modules were created corresponding to a volume of supraspinatus muscle for each study participant [15]. After completing the same training module, a blinded diagnostic radiology resident and two blinded medical student research assistants

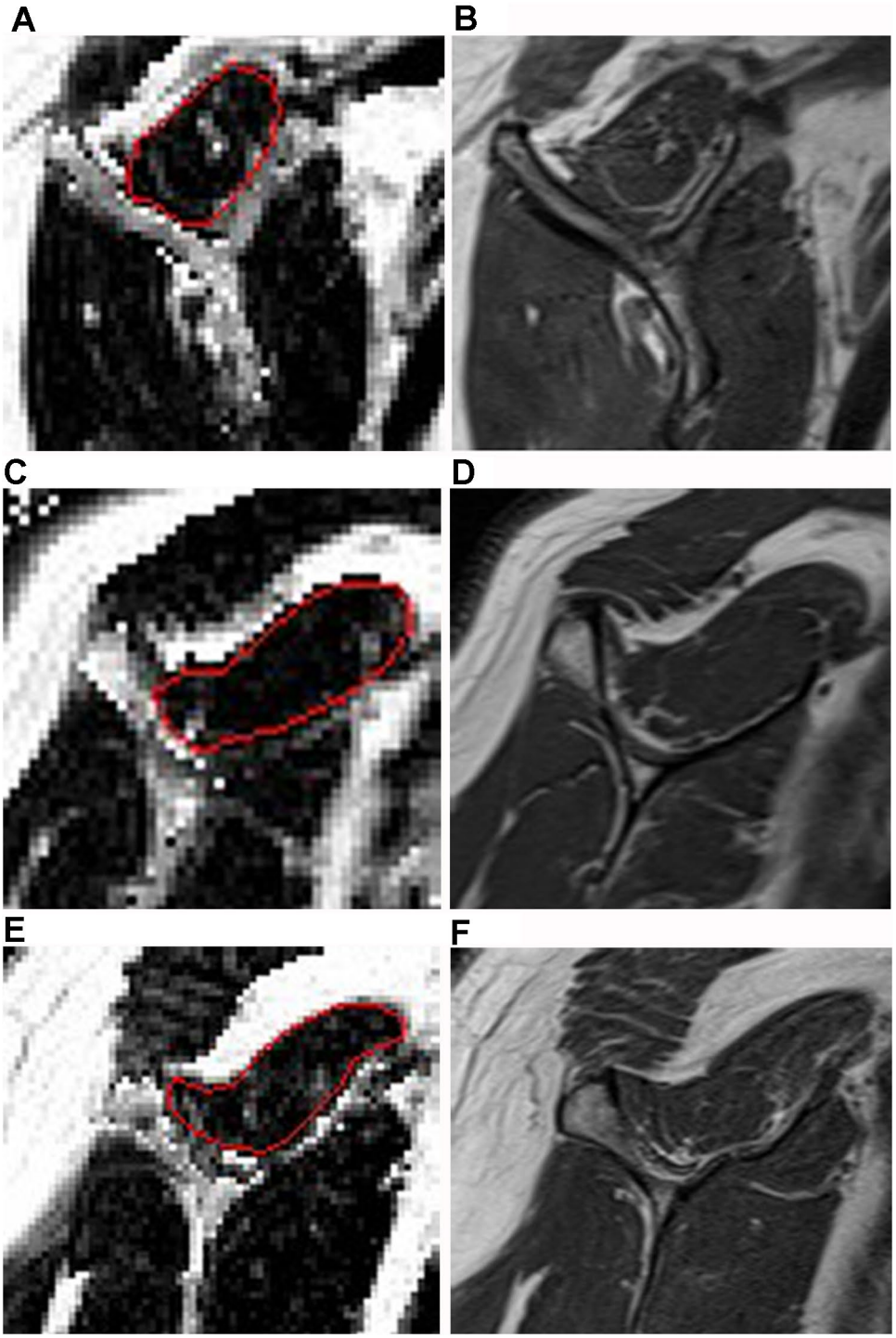

Fig. 1 Example supraspinatus muscle images from three participants showing technique for quantitative two-dimensional (2D) 6-point Dixon fat fraction map (2D fat fraction) and semi-quantitative 2D Goutallier grade analyses. **A** Oblique sagittal Dixon fat fraction map at the Y-shaped view MR image with drawn region of interest (red line) and **B** corresponding oblique sagittal T1-weighted MR image for analyses of supraspinatus muscle 2D fat fraction and 2D Goutallier grade, respectively. **C**, **D** Representative oblique sagittal Dixon fat fraction map and oblique sagittal T1-weighted MR images used for supraspinatus muscle 2D fat fraction and 2D Goutallier grade analyses 1.4 cm medial to the Y-shaped view, respectively. **E**, **F** Representative oblique sagittal Dixon fat fraction map and oblique sagittal T1-weighted MR images used for supraspinatus muscle 2D fat fraction and 2D Goutallier grade analyses 2.8 cm medial to the Y-shaped view, respectively

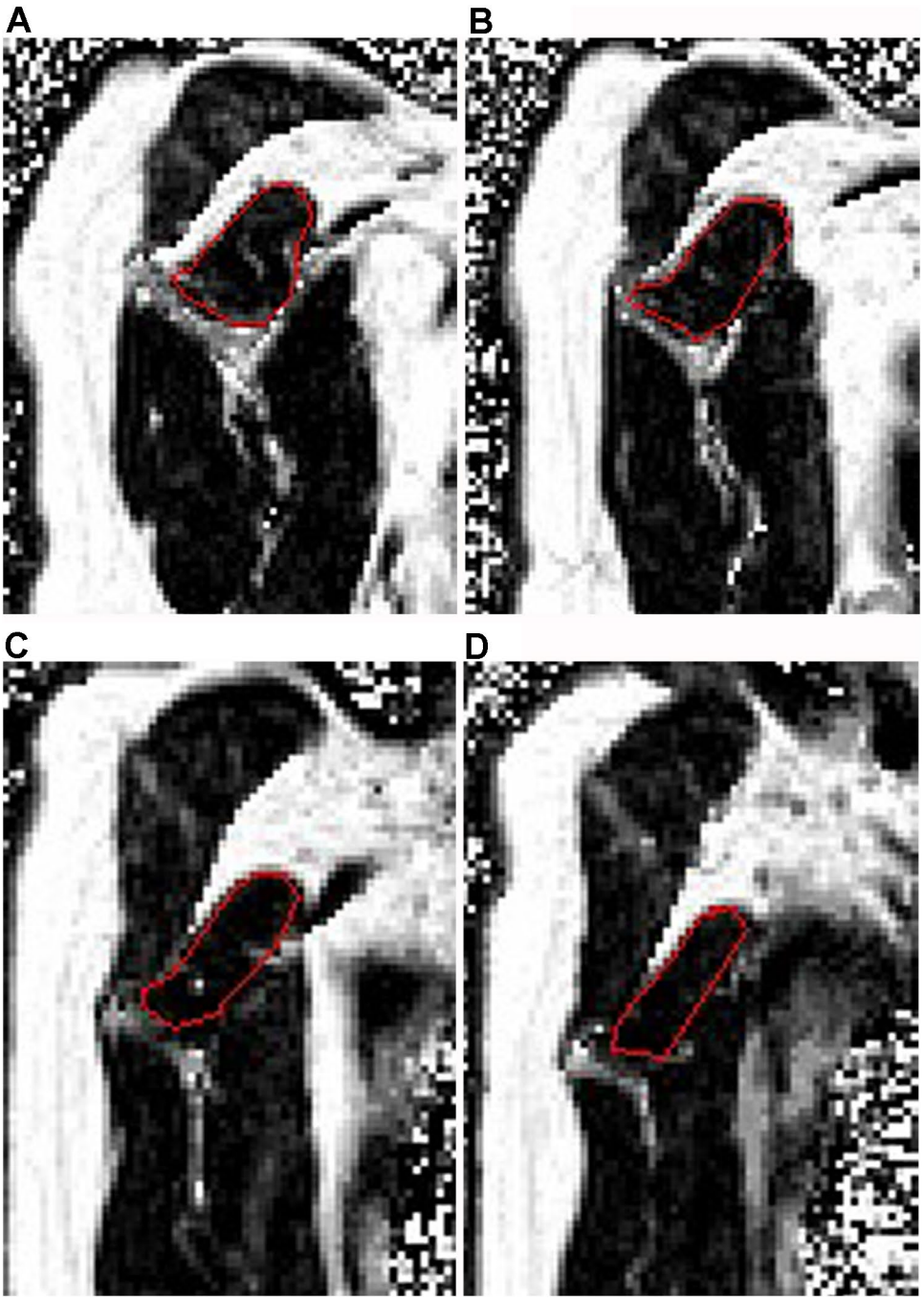

Fig. 2 Representative images from the same participant in Fig. 1A and B showing technique for volumetric 3D 6-point Dixon fat fraction analysis. **A**–**D** Example oblique sagittal 6-point Dixon fat fraction map images medial to the Y-shaped showing placement of regions of interest (red lines) for calculation of mean 3D fat fraction

independently performed manual segmentation with Medical Image Processing, Analysis and Visualization (MIPAV) software (version 10, National Institutes of Health, Bethesda, MD, USA) to measure the supraspinatus 2D fat fraction for each participant on the single slice oblique sagittal Dixon fat fraction map MR image corresponding to the Y-shaped view MR image where the lateral-most aspect of the spine joins the scapular body (Fig. 1) [15–17]. Then, each rater also independently quantified the supraspinatus Dixon fat fraction by manual segmentation on the next contiguous nine oblique sagittal Dixon fat fraction map images medial to the Y-shaped view, corresponding to a volume of supraspinatus muscle spanning 31.5 mm along the oblique coronal plane in order to obtain the volumetric 3D data (Fig. 2) [15]. Dixon fat fraction values are quantitative, on a continuous scale (0–100). The mean value among the three raters was determined for each supraspinatus Dixon fat fraction map image, and mean values were used for statistical analysis.

De-identified DICOM T1-weighted oblique sagittal modules were created for each participant corresponding

to the Dixon fat fraction map Y-shaped view MR image and also corresponding to the Dixon fat fraction map oblique sagittal images 1.4 cm and 2.8 cm medial to the Y-shaped view, respectively. After completing the same training module, three blinded diagnostic radiologists with fellowship training in musculoskeletal radiology independently evaluated the DICOM module using MIPAV software and assigned a Goutallier grade for the supraspinatus muscle on T1-weighted oblique sagittal images corresponding to the Y-shaped view and the T1-weighted oblique sagittal images 1.4 cm and 2.8 cm medial to the Y-shaped view, respectively. Goutallier grade is a semi-quantitative categorical variable based on a 5-point scale: grade 0, no fat; grade 1, streaks of fat; grade 2, more muscle than fat; grade 3, muscle equal to fat; grade 4, less muscle than fat [12, 13]. The mean value among the musculoskeletal radiology fellowship-trained diagnostic radiologists was determined for each supraspinatus T1-weighted oblique sagittal image, and mean values were used for statistical analysis.

In a separate analysis, a fourth diagnostic radiologist with musculoskeletal radiology fellowship training independently reviewed each participant's shoulder MRI to evaluate the supraspinatus tendon. The supraspinatus tendon was assigned one of three classifications: no tear (intact or tendinopathy), partial-thickness tear, or full-thickness tear. The mediolateral dimension of full-thickness supraspinatus tendon tears also was determined using a 3D visualization system viewer (version 4.4, Aquarius iNtuition Edition, TeraRecon, Durham, NC, USA).

Clinical evaluation

Each older adult volunteer completed demographics questionnaires and a self-reported shoulder function survey at the MRI research center on the same day that shoulder MRI was performed. All participants were evaluated with the American Shoulder and Elbow Surgeons (ASES) survey for the shoulder ipsilateral to the MRI. Weight and height were recorded to determine body mass index (BMI).

Statistical analysis

Statistical analysis was performed with SAS version 9.4 statistical software (Cary, NC, USA). Descriptive statistics were performed to characterize the study sample with categorical variables reported as *n* (%) and continuous variables reported as mean ± standard deviation. Comparison among groups was performed with the one-way ANOVA test, Welch's ANOVA test, Kruskal-Wallis test, and chi-square test as appropriate. Pairwise comparisons were performed with the Dwass-Steel-Critchlow-Fligner method as appropriate. Spearman rank order correlation (rho) with 95% confidence intervals was used to determine strength of correlation. Rho correlation was interpreted as weak, 0.00–0.35; moderate, 0.36–0.67; or strong, 0.68–1.00 [18]. Inter-observer reliability for continuous variables was determined by the intraclass correlation coefficient (ICC) and inter-observer reliability for categorical variables was determined by weighted Fleiss's kappa. Inter-observer reliability was interpreted as poor, 0.00–0.39; fair, 0.40–0.59; good, 0.60–0.74; or excellent, 0.75–1.00 [19]. A p-value < 0.05 was considered to indicate statistical significance.

Table 1 Characteristics of the study population stratified by supraspinatus tendon tear status

	Intact ($n = 15$)	Partial-thickness tear ($n = 15$)	Full-thickness tear ($n = 15$)	p
Age (years)	68.80 ± 6.85	70.27 ± 6.43	72.40 ± 5.30	0.292
Male (%)	8 (53)	7 (47)	8 (53)	0.915
Body mass index (kg/m^2)	29.17 ± 6.86	26.10 ± 2.75	27.36 ± 4.44	0.252
ASES score (0–100)	81.08 ± 20.38	70.86 ± 19.60	84.29 ± 11.29	0.146
3D fat fraction (%)	6.98 ± 3.58	8.57 ± 4.85	14.09 ± 10.99	**0.044**
2D fat fraction (%)				
Y-shaped view	6.82 ± 3.08	8.63 ± 5.68	14.08 ± 12.33	0.206
1.4 cm medial to Y-shaped view	7.06 ± 3.89	8.58 ± 4.85	14.91 ± 12.11	**0.042**
2.8 cm medial to Y-shaped view	7.09 ± 4.07	8.53 ± 4.84	13.32 ± 9.48	**0.035**
2D Goutallier grade				
Y-shaped view	0.84 ± 0.40	1.13 ± 0.45	1.71 ± 0.78	**0.004**
1.4 cm medial to Y-shaped view	1.13 ± 0.25	1.13 ± 0.41	1.71 ± 0.69	**0.009**
2.8 cm medial to Y-shaped view	1.13 ± 0.27	1.27 ± 0.40	1.71 ± 0.72	**0.039**

Values are given as mean ± standard deviation or *n* (%). *2D*, two-dimensional; *3D*, three-dimensional; *ASES*, American Shoulder and Elbow Surgeons (0, worst; 100, best); *fat fraction*, on 6-point Dixon fat fraction oblique sagittal sequence; *Goutallier grade*, on T1-weighted oblique sagittal sequence; values in bold indicate statistical significance

Results

The characteristics of participants stratified by supraspinatus tendon tear-status are shown in Table 1. There were no significant differences among groups for age, gender, body mass index, or ASES score. The mean quantitative volumetric 3D fat fraction differed among groups ($p=0.044$), as the FT group demonstrated the highest amount of supraspinatus FI with a significant pairwise comparison between FT group versus Intact group ($p=0.047$). At the Y-shaped view, the FT group also demonstrated the highest amount of supraspinatus FI for mean quantitative 2D fat fraction and mean semi-quantitative 2D Goutallier grade, although only the latter reached statistical significance ($p=0.004$). Similarly, the FT group demonstrated a significantly higher amount of supraspinatus FI compared to the Intact and PT groups for mean quantitative 2D fat fraction on MR images 1.4 cm ($p=0.042$) and 2.8 cm ($p=0.035$) medial to the Y-shaped view and also the mean semi-quantitative 2D Goutallier grade on MR images 1.4 cm ($p=0.009$) and 2.8 cm ($p=0.039$) medial to the Y-shaped view. Pairwise comparisons were significant between the FT group versus Intact group for mean quantitative 2D fat fraction on MR images 1.4 cm ($p=0.036$) and 2.8 cm ($p=0.029$) medial to the Y-shaped view; mean semi-quantitative 2D Goutallier grade at the Y-shaped view ($p=0.007$); and mean semi-quantitative 2D Goutallier grade at MR images 1.4 cm ($p=0.021$) and 2.8 cm ($p=0.038$) medial to the Y-shaped view. The FT group versus PT group pairwise comparison was significant for the mean semi-quantitative 2D Goutallier grade at the MR image 1.4 cm ($p=0.036$) medial to the Y-shaped view. There were no significant pairwise comparisons for the PT group versus the Intact group for all analyses.

The minimum and maximum for mean 3D fat fraction for individual participants were 2.79% and 16.61% for the Intact group, 1.51% and 23.58% for the PT group, and 5.78% and 37.38% for the FT group, respectively. The minimum and maximum for mean 2D fat fraction for individual participants were 2.60% and 19.30% for the Intact group, 1.10% and 26.57% for the PT group, and 4.40% and 41.07% for the FT group, respectively. The minimum and maximum for mean 2D Goutallier grade for individual participants were 0.00 and 1.67 for the Intact group, 0.00 and 2.00 for the PT group, and 0.67 and 3.33 for the FT group, respectively.

The mean and standard deviation of the mediolateral dimension for supraspinatus tendon full-thickness tear in the oblique coronal plane among participants in the FT group were 1.97 ± 1.96 cm, with small tears (< 1.0 cm) the most frequent ($n=8$), followed by massive tears (≥ 5.0 cm) ($n=3$), large tears (3.0–4.9 cm) ($n=2$), and moderate tears (1.0–2.9 cm) ($n=2$). Table 1 lists 3D and 2D estimates of supraspinatus FI for the FT group. Isolated supraspinatus full-thickness tears ($n=9$) were the most prevalent among participants in the FT group. Five participants presented with full-thickness tears spanning the supraspinatus and infraspinatus tendons, while one participant had full-thickness tear of the supraspinatus, infraspinatus, and subscapularis tendons.

In a sub-analysis of the FT group, comparison among participants showed significant differences for mean 3D fat fraction ($p=0.041$) when stratified by tendon tear size, with massive ($32.27\% \pm 8.54\%$) and large tears ($16.66\% \pm 11.17\%$) demonstrating the highest values, followed by small ($8.44\% \pm 2.79\%$) and moderate tears ($6.87\% \pm 1.53\%$). There were significant differences for mean 2D fat fraction ($p<0.050$) at the Y-shaped view and at 1.4 cm and 2.8 cm medial to the Y-shaped view (ranges: massive, 28.91–35.00%; large, 14.32–18.47%; small, 7.58–8.99%; moderate, 6.05–6.54%). Similarly, there were significant differences for mean 2D Goutallier grade ($p<0.050$) at the Y-shaped view and 1.4 cm medial to the Y-shaped view but 2.8 cm medial to the Y-shaped view did not reach statistical significance (ranges: massive, 2.77–2.88; large, 1.67–1.84; moderate, 1.34–1.50; small, 1.33–1.38).

The strength of correlation showed relative homogeneity for mean quantitative 3D fat fraction with mean quantitative 2D fat fraction (Table 2). There was strong correlation of quantitative mean 3D fat fraction with mean quantitative 2D Dixon fat fraction among all groups and all MR image analyses (rho, 0.80–0.98; $p<0.001$).

The strength of correlation showed heterogeneity for mean quantitative 3D fat fraction with mean semi-quantitative 2D Goutallier grade stratified by supraspinatus tendon tear-status (Table 3). The FT group demonstrated strong

Table 2 Spearman correlation of volumetric 3D fat fraction with single slice 2D fat fraction map MR images for the supraspinatus muscle stratified by tendon tear status

	Rho (95% CI)	*p*
Y-shaped view		
Intact	0.94 (0.83, 0.98)	< 0.001
Partial-thickness tear	0.80 (0.49, 0.93)	< 0.001
Full-thickness tear	0.94 (0.81, 0.98)	< 0.001
1.4 cm medial to Y-shaped view		
Intact	0.95 (0.85, 0.98)	< 0.001
Partial-thickness tear	0.85 (0.59, 0.95)	< 0.001
Full-thickness tear	0.98 (0.93, 0.99)	< 0.001
2.8 cm medial to Y-shaped view		
Intact	0.96 (0.87, 0.99)	< 0.001
Partial-thickness tear	0.80 (0.50, 0.93)	< 0.001
Full-thickness tear	0.90 (0.71, 0.97)	< 0.001

95% CI, 95% confidence interval

Table 3 Spearman correlation of volumetric 3D fat fraction with single slice 2D Goutallier grade on T1-weighted MR images for the supraspinatus muscle stratified by tendon tear status

	Rho (95% CI)	*p*
Y-shaped view		
Intact	0.51 (−0.00, 0.81)	0.052
Partial-thickness tear	0.73 (0.35, 0.90)	0.002
Full-thickness tear	0.85 (0.61, 0.95)	< 0.001
1.4 cm medial to Y-shaped view		
Intact	0.70 (0.29, 0.89)	0.004
Partial-thickness tear	0.60 (0.13, 0.85)	0.018
Full-thickness tear	0.91 (0.75, 0.97)	< 0.001
2.8 cm medial to Y-shaped view		
Intact	0.79 (0.46, 0.93)	< 0.001
Partial-thickness tear	0.61 (0.15, 0.86)	0.015
Full-thickness tear	0.86 (0.62, 0.95)	< 0.001

95% CI, 95% confidence interval

Table 4 Inter-observer reliability among three raters for quantitative fat fraction on 6-point Dixon fat fraction map MR images, and semi-quantitative Goutallier grade on T1-weighted MR images, for supraspinatus muscle assessments stratified by tendon tear status

	Inter-observer reliability	
	Dixon fat fraction[A]	Goutallier grade[B]
Intact	0.884	0.294
Partial-thickness tear	0.845	0.502
Full-thickness tear	0.974	0.771

[A]Intraclass correlation coefficient; [B]weighted Fleiss's kappa

correlation for mean 3D fat fraction with mean semi-quantitative 2D Goutallier grade for the Y-shaped view and also at 1.4 cm and 2.8 cm medial to the Y-shaped view (rho, 0.85–0.91; $p < 0.05$) and for the PT group at the Y-shaped view (rho = 0.73; $p = 0.002$). However, the PT group showed only moderate correlation at 1.4 cm and 2.8 cm medial to the Y-shaped view (rho, 0.60–0.61; $p < 0.05$). The Intact group showed strong correlation for Goutallier grade at 1.4 cm and 2.8 cm medial to the Y-shaped view (rho, 0.70–0.79; $p < 0.05$) and moderate correlation at the Y-shaped view (rho, 0.51; $p > 0.05$).

Inter-observer reliability was excellent among the three raters for assessment of supraspinatus muscle Dixon fat fraction on 6-point Dixon MR map images for all three groups (Table 4). The degree of agreement among the three raters for assessment of supraspinatus muscle Goutallier grade on T1-weighted MR images was non-uniform when stratified by supraspinatus tendon tear-status. Inter-rater reliability was excellent for the FT group, while fair and poor for the PT group and Intact group, respectively.

Discussion

The findings of this study suggest that single slice 2D MR image estimation of volumetric 3D supraspinatus intramuscular fatty infiltration has merit for continued use in current practice for patients receiving clinical evaluation for potential RCR surgery, in contrary to recent concerns in the literature that single image 2D estimation of supraspinatus 3D fat volume may be inappropriate. In our sample of older adult volunteers, the FT group had the highest volume of supraspinatus FI by 3D 6-point Dixon MRI, relative to groups of participants with no tear or partial-thickness tear of the supraspinatus tendon. As expected, the FT group had the highest 2D fat fraction and 2D Goutallier grade on Y-shaped view MR images, as well as on MR images 1.4 cm and 2.8 cm medial to the Y-shaped view. Volumetric 3D fat fraction demonstrated strong correlation with 2D fat fraction for all groups, and also with FT group 2D Goutallier grade at the Y-shaped view and at 1.4 cm and 2.8 cm medial to the Y-shaped view. Volumetric 3D fat fraction showed moderate to strong correlation with Goutallier grade for the Intact and PT groups. These findings suggest that quantitative 2D Dixon fat fraction has superior correlation with volumetric 3D Dixon fat fraction relative to semi-quantitative 2D Goutallier grade regardless of location in the supraspinatus muscle, although this study also lends support that 2D Goutallier grade provides a reasonable estimate of supraspinatus FI in older adults with a full-thickness supraspinatus tendon tear when performed by diagnostic radiologists with subspecialty fellowship training in musculoskeletal radiology. As expected 2D fat fraction showed excellent inter-rater reliability, with a higher strength of reliability for all groups relative to 2D Goutallier grade. However, the study also demonstrated that 2D Goutallier grade shows excellent inter-rater reliability among musculoskeletal radiology fellowship-trained diagnostic radiologists for older adults with full-thickness supraspinatus tendon tears.

Full-thickness RC tear is associated with higher levels of FI on shoulder MRI relative to no tear or partial-thickness tear of the rotator cuff at the Y-shaped view [7, 17, 20]. In older populations, incremental increases in supraspinatus FI are expected with aging [21]. However, human and animal studies suggest that the rate of FI increases shortly after the onset of full-thickness RC tear [9, 11, 22–25]. The findings of our study are in line with prior literature, which show significantly higher mean supraspinatus FI in the FT group, as compared to the PT group and Intact group, at the Y-shaped view and also demonstrating the same for volumetric 3D supraspinatus FI and 2D supraspinatus FI medial to the

Y-shaped view. No significant differences existed between the PT and Intact groups for supraspinatus FI, consistent with the literature. Our study is also in line with prior literature that suggests an association between tendon tear size and FI, with larger tear size presenting with higher amounts of FI relative to smaller tears [7, 9, 20]. As expected, participants in the FT group with massive and large supraspinatus tendon tears demonstrated the highest degree of 3D and 2D supraspinatus FI, respectively.

Dixon fat fraction offers favorable reliability and 2D estimation of volumetric 3D supraspinatus FI. Quantitative MR CSI techniques have excellent reliability, and our study is in line with prior studies demonstrating superior reproducibility relative to semi-quantitative Goutallier grade [15, 16, 20, 26, 27]. Our study demonstrated excellent reliability for 6-point Dixon fat fraction for all groups, regardless of supraspinatus tendon tear-status. This study reproduced the findings of Addona et al. demonstrating strong correlation of 3D fat fraction with 2D fat fraction at the Y-shaped view [15]. In addition, volumetric 3D supraspinatus FI showed strong correlation with 2D supraspinatus FI medial to the Y-shaped view for all groups regardless of supraspinatus tendon tear status. These results suggest that 2D fat fraction is an appropriate measure for estimation of volumetric 3D FI in RC muscles on shoulder MRI for clinical practice and research studies. Although all measures for Dixon fat fraction showed excellent reliability and strong correlation, our findings suggest that estimating supraspinatus FI medial to the Y-shaped view on MRI is acceptable and potentially beneficial. The 95% confidence intervals were less wide at 1.4 cm medial to the Y-shaped view. Hypothetically, quantitative measurement of 2D fat fraction medial to the Y-shaped view may allow for more confident placement of a region of interest when differentiating RC muscle from surrounding extramuscular adipose tissue and adjacent neurovascular structures, especially for full-thickness tendon tear with medial retraction. However, the lack of widespread inclusion of quantitative MR CSI techniques in routine protocols for shoulder MRI is one current barrier for use in current clinical practice, although many commercially available software packages for 1.5-T and 3-T MRI scanners are now available to perform multiecho Dixon sequences in less than 1 min and to support creation of automated Dixon MRI fat fraction maps which can be rapidly analyzed by simple region of interest tools on PACS in less than 1 min for single image 2D Dixon fat fraction analysis [16].

Goutallier grade offers reasonable 2D estimation of volumetric 3D supraspinatus FI for clinical patients when performed by medical professionals with advanced fellowship training but are limited by inferior reproducibility relative to quantitative MRI CSI techniques for research studies. The major drawback of 2D Goutallier grade at the Y-shaped view has been reproducibility, which ranges from poor to good [7, 13, 15, 16, 20]. When stratified by supraspinatus tendon tear status, our study showed different strengths of inter-rater reliability among three diagnostic radiologists with musculoskeletal radiology fellowship training. The Intact, PT, and FT groups showed poor, fair, and excellent inter-rater reliability for Goutallier grade, respectively. For shoulders with no RC tear or partial-thickness RC tear, our results suggest that radiologists with advanced training in musculoskeletal imaging are less likely to agree about what constitutes no fat (grade 0) versus streaks of fat (grade 1) or streaks of fat (grade 1) versus muscle more than fat (grade 2); but in contrast are more likely to find consensus for shoulders with full-thickness RC tear where the highest amounts of FI are most often encountered. This study reproduced the findings of Addona et al. showing moderate to strong correlation of 3D fat fraction with 2D Goutallier grade for supraspinatus muscles with no expected medial retraction at the Y-shaped view [15]. However, our findings were contrary to the conclusion of Vidt et al. that suggested volumetric 3D supraspinatus FI correlates poorly with 2D Goutallier grade [14]. Also, the strength of correlation of supraspinatus 3D fat fraction with 2D Goutallier grade for the FT group was superior relative to the Intact and PT groups at and medial to the Y-shaped view; and strong correlation for the FT group was found at the Y-shaped view and also at 1.4 cm and 2.8 cm to the Y-shaped view.

The observation of excellent inter-rater reliability and strong correlation for the FT group in our study suggests that single slice 2D Goutallier grade provides reasonable estimation of volumetric 3D supraspinatus FI for clinical patients. Symptomatic patients with full-thickness RC tear are a key population that orthopedic surgeons consider for potential RCR surgery [7]. Although 3D volumetric FI would be an ideal measurement to consider for pre-operative planning, timely quantification of this metric is not practical in current clinical practice where rapid turn-around time is a ubiquitous expectation [16, 28]. Our findings suggest that assessing supraspinatus Goutallier grade medial to the Y-shaped view on MRI is acceptable and potentially beneficial during pre-operative evaluation for RCR surgery, especially when evaluating clinical patients with medially retracted full-thickness RC tears. This is in keeping with literature that suggests that reliance on the Y-shaped view, a static landmark on MRI, is a source of misclassification error for FI in cases of medially retracted full-thickness RC tendon tear [15, 29, 30]. Measurement of 2D Goutallier grade at 1.4 cm and 2.8 cm medial to the Y-shaped view for the FT group showed the strongest correlation with 3D fat fraction and narrowest 95% confidence intervals in our study for this semi-quantitative technique. However, reliance on the oblique sagittal image 1.4 cm medial to the Y-shaped view may be the most practical strategy to evaluate supraspinatus Goutallier grade for clinical patients receiving shoulder

MRI, since not all protocols currently in use are likely to produce images that demonstrate the entire medial extent of the rotator cuff musculature.

The study is not without limitations. The study design only included diagnostic radiologists with fellowship training in musculoskeletal radiology for evaluation of Goutallier grade. The results of the study may not be representative of general radiologists or radiologists-in-training, and future research is needed to determine reproducibility for Goutallier grade among these groups. Our findings also may not reflect reproducibility for Goutallier grade among other stakeholders such as orthopedic surgeons and residents, although a prior study suggests reasonable inter-rater reliability exists among experienced orthopedic surgeons with fellowship training in shoulder and elbow surgery [7]. Participants were recruited prospectively by local advertisement as a convenience sample, and the study may be limited by selection bias. The study design analyzed participants with supraspinatus tendon partial-thickness tears as one group, and with stratification into high-grade and low-grade tear not done. The rationale for this was based on prior studies suggesting no expected significant differences in supraspinatus FI, between low-grade and high-grade partial-thickness tears, and also no expected significant differences between shoulders with partial-thickness tear and no tear [4, 17, 20]. Animal and human studies support the observation that significant increases in FI occur following full-thickness RC tear, with high-grade partial-thickness tears not significantly contributing to increases in supraspinatus FI relative to full-thickness tears [7, 9–11, 17, 20–25]. The study may not be generalizable to populations with a Goutallier grade of 4, since no participant had a mean grade in this range. However, clinical patients with muscle less than fat (Goutallier grade 4) are typically not a challenge for clinical decision-making in the context of eligibility for RCR surgery, with most orthopedic surgeons considering this degree of FI a relative contra-indication [7, 13, 21]. Participants with a prior history of RCR surgery were excluded from the study and future research for inter-rater reliability and strength of single slice 2D estimation of volumetric 3D FI is needed for this population. Future research is also warranted to determine which fat fraction value from quantitative MR CSI techniques should serve as a relative contraindication to RCR surgery.

Conclusion

Single slice 2D MR image evaluation has merit for continued use in estimation of volumetric 3D supraspinatus intramuscular fatty infiltration for relevant clinical patients receiving pre-operative imaging assessment for RCR surgery. For clinical populations, evaluation of rotator cuff FI by quantitative 2D fat fraction on Dixon fat fraction maps where available, or 2D Goutallier grade on oblique sagittal T1-weighted images when performed by diagnostic radiologists with fellowship training in musculoskeletal radiology, has strong correlation with volumetric 3D FI. Our study suggests that for patients with medially retracted full-thickness tear of the supraspinatus tendon, evaluation on a single slice 2D MR image 1.4 cm or 2.8 cm medial to the Y-shaped view is appropriate. Future research is needed to vet the inter-rater reliability and strength of correlation of supraspinatus volumetric 3D FI with 2D Goutallier grade when performed by general radiologists and radiologists-in-training. Quantitative MR CSI techniques, such as Dixon fat fraction, should be favored over semi-quantitative Goutallier grade for measurement of FI in research studies due to a relative superior reproducibility and the lack of requirement for advanced clinical training and experience.

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Declarations

Conflict of interest The authors declare no competing interests.

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