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Radial head volume measurements using quantitative three-dimensional computed tomography images for radial head deformation following missed Monteggia lesions

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Background: In chronic radial head dislocation cases, the radial head may enlarge and become dome-shaped. To date, there is no validated tool to quantify radial head deformation and predict its influence on surgical outcomes. This study assesses the potential value of volume and surface calculations obtained by quantitative three-dimensional computed tomography scanning (Q3DCT) in the workup for a corrective surgery in pediatric patients with missed Monteggia lesions.

Material and methods: Ten consecutive pediatric patients with a missed Monteggia lesion were included (2012-2020). The volume and articular surface size of the radial head were calculated using Q3DCT, and a three-dimensional reconstruction of the articular surface relief was depicted in a heat map. The head-neck ratio was calculated and compared to Q3DCT data of missed Monteggia patients and their age-/sex-matched controls.

Results: The radial head volume and radial articular surface size did not differ significantly between patients with missed Monteggia lesions and age-/sex-matched controls (volume 1487 mm^3 vs. 1163 mm^3, $P = .32$; articular surface size 282 mm^3 vs. 236 mm^3, $P = .33$). Optically, heat maps of the articular surface of missed Monteggia patients did not differ notably from control heat maps. A higher head-neck ratio correlated to a larger radial head volume (Pearson $r = 0.73$; $P = .2$).

Discussion and conclusion: Q3DCT may be an interesting tool in the preoperative workup of pediatric missed Monteggia lesions. Prospective research with larger cohort sizes and data that compares the affected side to the contralateral elbow is needed to assess its true clinical potential.

Radial head dislocations are frequently missed at presentation, especially when a Monteggia lesion is present.[13,38] Initial complaints can be mild, but increasing deformity during growth may give rise to pain,[8,9,27,40] restricted range of elbow motion,[2,4,10,15,16,20,25,30,42,43] neuropathy,[18,27,39] instability,[37,43] a prominent radial head,[35,39,43] and valgus deformity[17,18,24,36,37,39,40,43] of the elbow.

If a radial head dislocation exists chronically, growth disturbances may occur. In previous studies, the onset of radial head deformation was noted between 3 months and 3 years following a trauma.[7,10,28,32] Presumably the lack of pressure on the radial head causes it to become dome-shaped.[8,16,23,32] Other dysplastic features are radial head overgrowth, widening or rounding and hypertrophy of the radial head, a slender radial neck, and flattening of the capitellum.[2] Many authors suggest that the success rate of a corrective surgery depends on the amount of dysplastic changes of the radial head.[12,16,22,23,25,30,37]

The recommendations for preoperative workup of chronic missed Monteggia lesions vary, some include three-dimensional (3D) computed tomography (CT) scans,[32,37] magnetic resonance imaging scans,[12] arthrography,[18] or lateral x-rays with calculation of the head-neck (H/N) ratio.[2,23,30] No threshold is known for any of the imaging techniques named above to distinguish between a "normal" and a "deformed" radial head. Most authors compare to the unaffected side, but clinical implications for the amount of radial head deformation remain vague. Currently, the H/N ratio is

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often used to objectify radial head deformation. It was conceived based on the typical formation of a slender radial neck and radial head widening in posttraumatic radial head dislocation, compared to the contralateral elbow.[23] The significance of the H/N ratio is controversial,[5] and there have been no validation studies to identify a threshold that indicates a higher risk of postoperative complications. In a small cohort study from our clinic, the intraoperative aspect of the radial head, noted by the operating surgeon, deviated substantially from the estimated dysplastic changes by preoperative H/N ratio on lateral x-rays.[26]

Quantitative 3D CT analysis (Q3DCT) of the radial head proved to be useful in understanding intra-articular fractures.[29] It may also be a helpful noninvasive technique to measure the volume and articular surface features of the radial head.[14]

This study aimed to measure and visualize the following dysplastic features: (1) radial head volume, (2) articular surface size of the radial head, and (3) concavity of the radial head using Q3DCT of chronic missed Monteggia lesions. Radial head Q3DCT features were then correlated to the radial head redislocation rate.

It was hypothesized that the articular surface shape would deform due to repetitive radial head dislocations.

Material and methods

All consecutive patients that reported to the Amphia hospital in Breda, the Netherlands, between January 2012 and January 2020 with a chronic radial head dislocation following a missed Monteggia lesion were approached to participate in this retrospective study. A fellowship-trained musculoskeletal radiologist and the senior author identified missed Monteggia lesions. Inclusion criteria were a trauma-to-presentation interval of at least four weeks, age under 18 years, and workup that included a preoperative CT scan of adequate quality. Congenital dislocations and acute presentations were excluded. Postoperative follow-up was following hospital protocol; all patients were followed up with plain radiographs of the elbow at six weeks and one year postoperatively. Several patients had longer follow-up at the surgeons' or parents' preference.

Our institutional medical ethics review committee approved our research protocol, and all patients agreed on anonymous use of their data for scientific purposes.

Given the retrospective study design, it was impossible to obtain a CT scan from the nonaffected elbow at the moment of presentation. Therefore, each patient with a missed Monteggia lesion (cases) was 1:1 matched to a patient without a Monteggia lesion (hereafter referred to as "control patients"). Subjects were matched based on age (within 0.4 years) and sex.

Surgical procedure

All surgical procedures were performed by this study's principal investigator (D.E.) and included an open reduction of the radiocapitellar joint, a corrective osteotomy of the ulna, and a reconstruction of the annular ligament. Before repositioning the radial head, the surgeon judged the optical dysplastic features of the radial head (concavity, widening of the radial head) and the effort that was required for radial head repositioning. Postoperatively, a cast in 90-degree flexion and neutral forearm rotation was applied for the duration of four weeks. After cast removal, physiotherapy was started for all patients.

Outcome measures and explanatory variables

Medical records were reviewed to extract the baseline CT scan and data at presentation, details of the performed surgery, perioperative aspect of the radial head, and the postoperative radiograph at follow-up consultation.

The outcome measures for the Q3DCT analysis were radial head volume, radial head articular surface size, and heat map depiction of radial head articular surface concavity. CT scans were saved as Digital Imaging and Communications in Medicine files and uploaded in 3D Slicer (version 4.10.2; Slicer Community, Boston, MA, USA). Cortical outline of the radial head was manually marked on transverse, sagittal, and coronal CT slides using a cutoff of 200 to 250 Hounsfield units in 3D Slicer. The radial head was defined as all bone proximal to the physis or physeal scar. The 3D Slicer software renders a 3D polygon mesh model, which was imported into Rhinoceros (Rhinoceros 5.0; McNeel, Seattle, WA, USA). The volume of the radial tuberosity was measured in mm^3 (mm = millimeter) and the articular surface area in mm^2, standard features in Rhinoceros. Assessment of radial head concavity was a visual assessment using the heatmap projected over the radial head articular surface.

The H/N ratio as described by Kim et al was calculated on plain radiographs for both missed Monteggia patients and their controls[23] and then compared to Q3DCT data.

Statistical analysis

Categorical variables are reported as frequencies and percentages, and continuous variables as mean with standard deviation. We used a paired t-test to assess differences in outcome measures between cases and controls. A two-tailed *P* value below.05 was considered statistically significant. To assess correlation, a Pearson correlation coefficient was calculated. IBM SPSS Statistics 25

Table I
Patient characteristics.

Case no.	Side	M/F	Trauma CT (y)	Age at CT (y)	H/N MM	Age at surgery (y)	Perioperative aspect	Repositioning	Complications	H/N C
1	R	F	2.2	9.3	1.81	9.45	30-40% def.	Easy		1.20
2	L	F	2.1	7.7	1.41	7.59	Mild def. cap. overgr.	Impossible		1.33
3	L	F	ns	5.9	2.21	15.55	Slight def.	Easy	Nonunion with redislocation	1.38
4	R	F	0.3	11.3	1.4	11.69	Bipolar def.			1.73
5	L	F	5.4	12.0	1.43	12.18	Some def.	Impossible		1.34
6	L	M	5.8	12.5	1.52	13.04	Slight def.	Easy		1.27
7	R	M	0.4	12.3	1.5	12.58	Slight def.	Easy	Subluxation	1.29
8	L	F	1.1	7.7	1.53	8.07	Slight def.	Easy		1.36
A	L	M	9.3	15.4	1.97					1.55
B	R	M	2.0	15.5	1.64					1.56
Mean			3.2	9.8	1.64	11.3				1.40

M/F, male/female; *trauma CT*, time between trauma and CT, scan in years; *H/N MM*, head-neck ratio; *def.*, deformed; *cap. overgr.*, caput overgrowth; *H/N C*, head-neck ratio control; *ns*, not specified; *CT*, computed tomography.
Case A and B are patients that were treated conservatively.

Table II
Radial head volume and articular surface area of the radial head in missed Monteggia lesion patients vs. age- and sex-matched control cases.

	Missed Monteggia cases (n = 10)	Controls (n = 10)	*P* value
	Mean (±standard deviation)	Mean (±standard deviation)	
Volume of the radial head in mm^3	1487 (±1180)	1163 (±836)	*.317*
Articular surface area of the radial head in mm^2	282 (±143)	236 (±128)	*.331*

P-value in a paired Student-T test.

(IBM Corp., Armonk, NY, USA) was used for all statistical analyses, and there were no missing values for any of the variables.

Results

Fourteen pediatric patients with a missed Monteggia lesion were eligible for inclusion. One patient denied participation, 1 patient had a potential congenital component (dysmorph radial head on the contralateral side), and two patients had preoperative CT scans of insufficient quality. Hence, ten patients could be included for the Q3DCT analysis.

The average age of the included patients was 11 years, range 5.9 to 15.5 years; there were six girls and four boys. The mean time between trauma and the CT scan at presentation was 3.2 years (0.3 - 9.3) (Table I). The mean follow-up duration was 1.7 years (0.8-5.8 years).

Indications for elbow CT scan in control patients were olecranon trauma (n = 3), medial extraarticular calcifications (n = 2), medial condyle fractures (n = 1), supracondylar fracture (n = 2), radial neck fracture (n = 1), and osteochondritis dissecans of the capitellum (n = 1).

The mean age difference between the included patients and their age/sex matches was 0.02 year (range 0-0.4 year) (Table II).

Eight patients underwent a surgical correction of the chronic radial head dislocation (cases 1-8 in Table I). There were two complications (case 3: ulna nonunion and redislocation of the radial head, and case 7: subluxation of the radial head). Two patients were treated conservatively (case A and B) because the surgeon considered the radial head too dysplastic on preoperative radiographs and CT scans.

Radial head volume analysis

The volume of the radial head was not significantly larger in missed Monteggia patients than that in the control group (1487 mm^3 vs. 1163 mm^3, $P = .32$). There was no correlation between the trauma-CT interval and radial head volume (Pearson test, r = 0.65, $P = .64$) or the articular surface size of the RH (r = 0.54, $P = .14$).

Articular surface size analysis

The radial head articular surface size was also not significantly larger in missed Monteggia patients than that in the control group (282 vs. 236 mm^3, $P = .32$). Unfortunately, calculations of the percentage of the articular surface that was concave turned out unreliable.

Heat map articular surface analysis

The articular surface of the radial head was depicted in a heat map using Q3DCT (Fig. 1). Some heat maps of patients that were not operated either due to suspicion of radial head dysmorph changes on a plain radiograph (cases A and B) or because they sustained a redislocation (case 3 and 7) appeared flattened or convex. However, Q3DCT heat map images could have a similar flattened aspect in the control group. A supplement is available that contains an overview of all MM and C heat maps. Optically, there were no evident differences in articular surface shape for cases vs. controls.

Comparison to the H/N ratio

The H/N ratios in patients with missed Monteggia lesions were significantly higher than those in the control cases (the mean H/N ratio in missed Monteggia lesions was 1.64, and the mean H/N ratio for controls was 1.40; $P = .48$). We also found a significant correlation between the H/N ratio and the radial head volume in missed Monteggia patients (Pearson r = 0.73; $P = .2$).

Discussion

This study describes a small cohort of missed Monteggia patients, whose radial head was examined using Q3DCT. Currently, the assessment of preoperative radial head deformation is subjective; Q3DCT seemed a promising and easily accessible method to quantify the amount of radial head deformation.

Unfortunately, measurements of the concavity of the radial head turned out to be unreliable, and the interpretation of a heat map of the articular surface is highly subjective. Its value is therefore still debatable in individual cases. Our cohort was thereby too small to be able to make any statement regarding the peroperative aspect of the radial head and Q3CT heat map images, and the value of a statistic analysis is limited due to the small number of patients. Future research should be prospective and should contain a CT scan of the contralateral elbow. Also, an interobserver or intraobserver

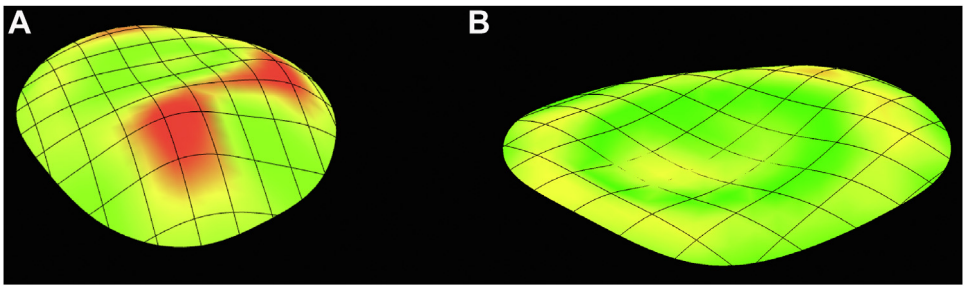

Figure 1 Heat map image of the radial head articular surface relief (case 4). (**A**) Missed Monteggia patient; (**B**) age-/sex-matched control.

evaluation would be interesting to assess the clinical value of Q3DCT heat map images.

Multiple factors influence the stability of the radial head. Pulling forces of surrounding muscles[11] or the interosseous ligament may play a role.[1,3,16,18-20] A (posttraumatic) length discrepancy between the radius and ulna may also interfere with tension on the radial head and hence complicate radial head reduction.[21] The ulna nonunion in one of the cases that experienced a redislocation, hence, may have had more influence than the shape and size of the radial head. Dysplastic changes to surrounding bony structures, such as the radioulnar joint and the capitellum, may also be of interest.[32] Dysplasia of the radial head is hence just 1 of several factors that may lead to a redislocation following a surgery for missed Monteggia lesions.

In literature, many authors discuss the time between injury and surgery and the age of the patient in the workup to surgery. Some indicate a maximum age for surgery (potentially because less remodeling is possible at older age),[33,41] and others indicate a maximum time between injury and surgery because the dysplastic radial head changes may increase over time.[31,34] In this study, there was no correlation between time since trauma or the age of the child and the volume of the radial head, like in several other publications.[6,36,39,40] We advise that in every individual case, an assessment of radial head dysplastic features should be made regardless of the time since trauma or patient age. However, a study with a larger cohort is necessary to be able to adequately test this statistically.

Conclusions

There were no significant differences in Q3DCT calculations for radial head volume and articular surface size between missed Monteggia patients and age-/sex-matched control cases. A heat map analysis of the radial head articular surface showed no specific differences in articular surface shape compared to the control group. A higher H/N ratio was correlated to higher Q3DCT radial head volumes. Q3DCT may still be an interesting tool in the preoperative workup for missed Monteggia patients, but prospective research that combines preoperative, peroperative, and postoperative findings in a larger case series that includes a contralateral CT scan analysis is mandatory to assess its clinical potential.

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Supplementary Data

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