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A proposal for computed tomography–based algorithm for the management of radial head and neck fractures: the Proximal and Articular Radial fractures Management (PARMa) classification

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Background: Owing to the great variety of fracture patterns and limitations of the standard radiographic investigation, all the already available classification systems for radial head and neck fractures (RHNFs) are limited by a poor-to-moderate degree of intraobserver and interobserver reliability. Although computed tomography (CT) is being increasingly used to better understand the fracture characteristics, a CT-based classification system of RHNFs is still lacking. Therefore, in this agreement study, we aimed to propose a classification system based on two-dimensional and three-dimensional (2D/3D) CT to test the hypothesis that this classification has good intraobserver and interobserver reliability. We have also provided a treatment algorithm.
Methods: Our proposed classification—Proximal and Articular Radial fractures Management (PARMa)—is based on 2D/3D CT imaging. It is divided into four types based on different fractures patterns. The 2D/3D scans of 90 RHNFs were evaluated in a blinded fashion by eight orthopedic and one radiology consultant, according to the proposed classification. The first phase of observation aimed to estimate the interobserver agreement. The second phase involved a new observation, 4 weeks after the first analysis, and estimated the intraobserver reliability. The standard radiographs of these 90 fractures were also evaluated by the same observers, with the same timing and methods, based on the same classification. Cohen's Kappa was applied for intraobserver agreement. Fleiss's Kappa was used both within and among the evaluators. Kendall's coefficient of concordance was employed to determine the strength of association among the appraisers' rankings. Furthermore, Krippendorff's alpha was chosen as an adjunctive analysis to assess between evaluators' agreement.
Results: For the intraobserver agreement, Fleiss' Kappa statistics confirmed the consistency (overall kappa values: 0.70-0.82). Cohen's Kappa statistics aligned with Fleiss' Kappa, with similar kappa values and significant *P* values ($P < .001$). For interobserver agreement, Fleiss' Kappa statistics for between appraisers showed moderate-to-substantial agreement, with kappa values ranging from 0.54 to 0.82 for different responses. The results relating to the appraisers' observation of standard radiographs showed that the overall Fleiss' Kappa values for intraobserver agreement ranged from 0.34 to 0.82, whereas Fleiss' Kappa statistics for interobserver agreement ranged from 0.40 to 0.69.

Approval for this study was provided by the Area Vasta Emilia Nord Ethical Committee (study No. 789/2021/OSS*/Prot. 42502).

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Conclusions: The proposed classification system is expected to be reliable, reproducible, and useful for preoperative planning and surgical management. Both 2D and 3D CT allow the identification of the magnitude and position of displacement and articular surface involvement.

Radial head fractures are common, with an estimated incidence of 2.5-2.9 per 10,000 per year and account for approximately one-third of all elbow fractures.[26,43,47] Radial neck fractures have a prevalence of about one-third that of radial head fractures.[26] Several classification systems for radial head and neck fractures (RHNFs) based on radiographic examination have been described over the years.[10,38,40,42,54,56] However, RHNFs do not yet have a standardized treatment. In particular, guidelines regarding the management of displaced partial articular fractures of the radial head (PARFs) are still quite scarce, and the results are conflicting.[1,3,4,11,12,27,43,47,49,51,60,67,69,79,80,81] This discrepancy is probably because of the objective difficulty in determining the exact pattern of fractures by using only radiographic images and classifications based on two-dimensional (2D) criteria.

Because of the great variety of fracture patterns in RHNFs and the limits of the standard radiographic investigation, these classification systems are also limited by a poor-to-moderate degree of intraobserver and interobserver reliability.[23,24,26,40,55,59,72]

Although many recent studies have emphasized the use of computed tomography (CT) to better understand the fracture patterns,[12,35,33,79] a universally accepted CT-based classification system for RHNFs is still lacking. Therefore, we aimed to propose a classification system for RHNFs based on two-dimensional and three-dimensional (2D/3D) CT to suggest a treatment algorithm and test the hypothesis that this classification has good intraobserver and interobserver reliability.

Materials and methods

In this agreement study, we aimed to test the hypothesis that the proposed classification has good intraobserver and interobserver reliability.

Features of classification and proposal of algorithm treatment

The classification of RHNFs proposed by the senior author (F.C.)—Proximal and Articular Radial fractures Management (PARMa)—is based on 2D and 3D CT images. It is divided into four types depending on different fractures patterns. The drawings and descriptions of each type are presented in Table I.

Type A1

Includes undisplaced or minimally displaced fractures of the radial head or neck without any significant impact on the range of motion.

- Undisplaced PARFs.
- Displaced simple PARFs involving the nonarticulating portion of the radial head (non articular portion of the radial head [NAPRH]) without complete loss of cortical contact. (Fig. 1).

Both for undisplaced PARFs and displaced simple PARFs involving the NAPRH without complete loss of cortical contact, nonoperative treatment should be recommended.[12,43,47,69]

Type A2

Includes undisplaced radial neck fractures or collapse of radial head on the neck with a radial head-shaft angle (RHSA) < 30°. The degree of metaphyseal collapse can be well assessed using RHSA[46] (Fig. 2). The physiologic RHSA ranges from 12° to 21°.[16,62] For this subtype, the suggested treatment is nonoperative.[1,2,26,25,28,37,69,70,81]

Type B

Includes different patterns of PARF in which dislocation can restrict the range of motion. These are further divided into three subtypes:

Subtype B1. Displaced PARFs of the NAPRH, also including more than two fragments (Fig. 3), with complete loss of the cortical contact between fracture fragments and the rest of the proximal radius.

Subtype B2. PARFs with displacement, any obliquity, with or without complete loss of cortical contact, involving the APRH (articulating portion of the radial head (APRH), also including more than two fragments (Fig. 4). PARFs involving the APRH are mostly responsible for forearm blockage[20,64]

Subtype B3. These fractures show an impaction >2 mm of the central articular surface (Fig. 5).

These three subtypes are characterized by different fracture patterns and only partially correspond to type II of the Mason classification with modifications by Hotchkiss, Johnston, Broberg, and Morrey. However, all of these have been included in type B, as they share the same type of treatment. This comprises surgical reduction, eventually with elevation of the impacted fragment, addressing the metaphyseal void with the use of local autograft,[52,68,69] allograft, or bone-graft substitute and synthesis with screws or resorbable pins fixation[31,77] with or without ligament stabilization[3,12,31,68,67,69,72,74,76,81] The goals of open reduction and internal fixation (ORIF) include stable fixation of the joint surface and restoration of joint congruencies to facilitate early active motion.

Type C

Subtype C1. Multifragmentary/comminuted fractures of the whole radial head. These pattern fractures match those of Type III of the Mason, Hotchkiss, Broberg, and Morrey classifications (Fig. 6).

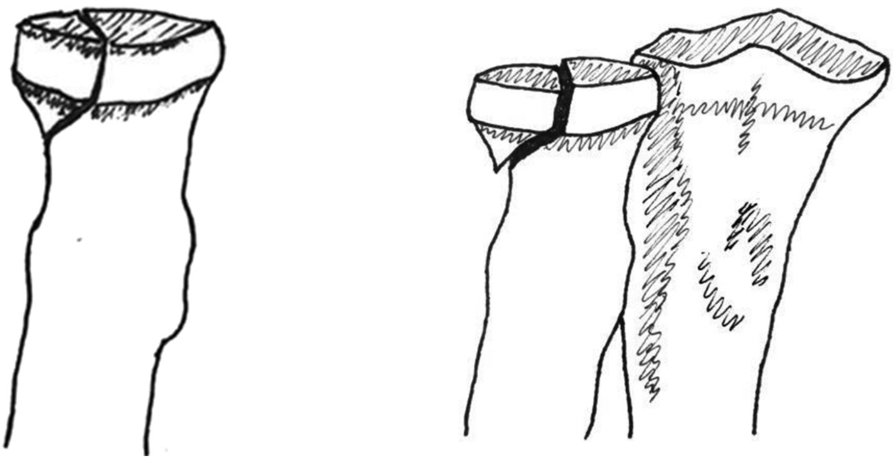
Subtype C2. Both fractures of the radial neck with metaphyseal collapse ≥30° and displaced/comminuted fractures of the radial neck are included (Fig. 7).

The treatment of Type C fractures consists of ORIF with plates and screws (eventually with elevation of the collapsed head and use of local autograft, allograft, or bone-graft substitute), crossed screws and tripod technique, or radial head prosthesis.[2,3,12,22,27,32,36,43,44,45,46,61,68,67,69,73,74,75,64,78,79,81]

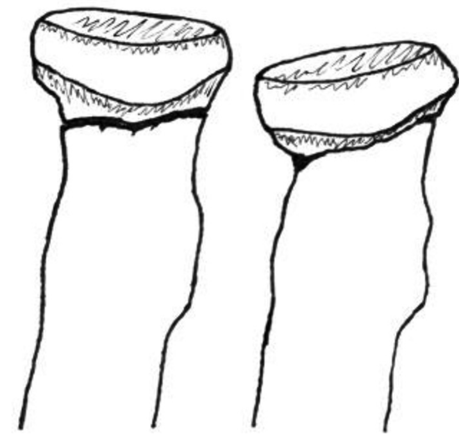
These procedures should be performed along with ligamentous stabilization.[18,30,43,47,69,78] Indeed, Type C fractures are often a component of complex fracture-dislocation patterns above the elbow and forearm (>75%)[41,43,68,74,63] (Fig. 8).

Apart from ligamentous stabilization, other concomitant injuries should be treated within their own merit and are not discussed in this paper.

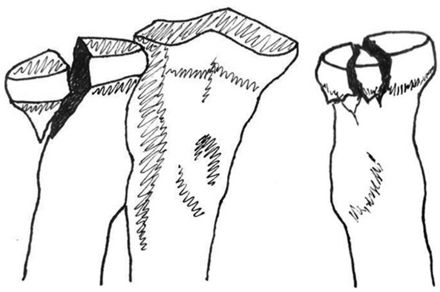
Table I
Proposed CT classification for radial head and neck fractures.



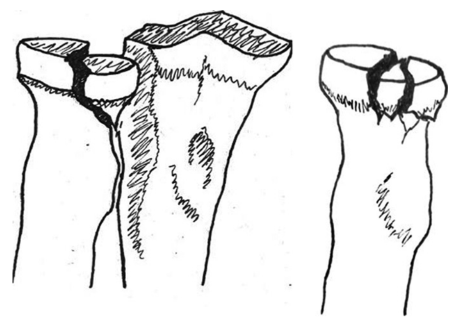
Type A1: undisplaced partial articular fractures, or displaced partial articular fractures of **the nonarticular portion of the radial head**, any obliquity, ***without complete loss of cortical contact***



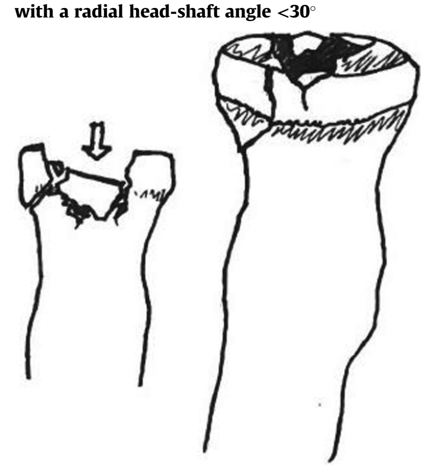
Type A2: undisplaced radial neck fractures or collapse of radial head on the neck **with a radial head-shaft angle <30°**



Type B subtype 1: displaced partial articular fractures, nonarticular portion of the radial head, any obliquity, ***with complete loss of cortical contact, also including more than two fragments***

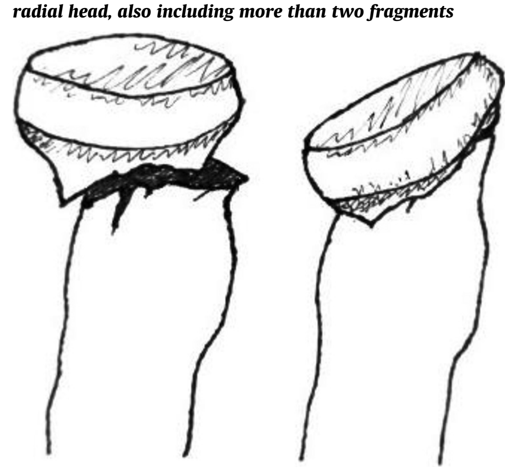


Type B subtype 2: displaced partial articular fractures, any obliquity, ***with or without complete loss of cortical contact, involving the articulating portion of the radial head, also including more than two fragments***



Type B subtype 3: split-depression > 2 mm of the articular surface

Type C subtype 1: complete **c**omminuted fracture of the whole radial head



Type C subtype 2: displaced radial neck fractures or collapse of radial head on the neck **with a radial head-shaft angle ≥ 30°**

Figure 1 Type A1 fracture. Displaced simple PARF without complete loss of cortical contact. *PARF*, partial articular radial fractures of the radial head.

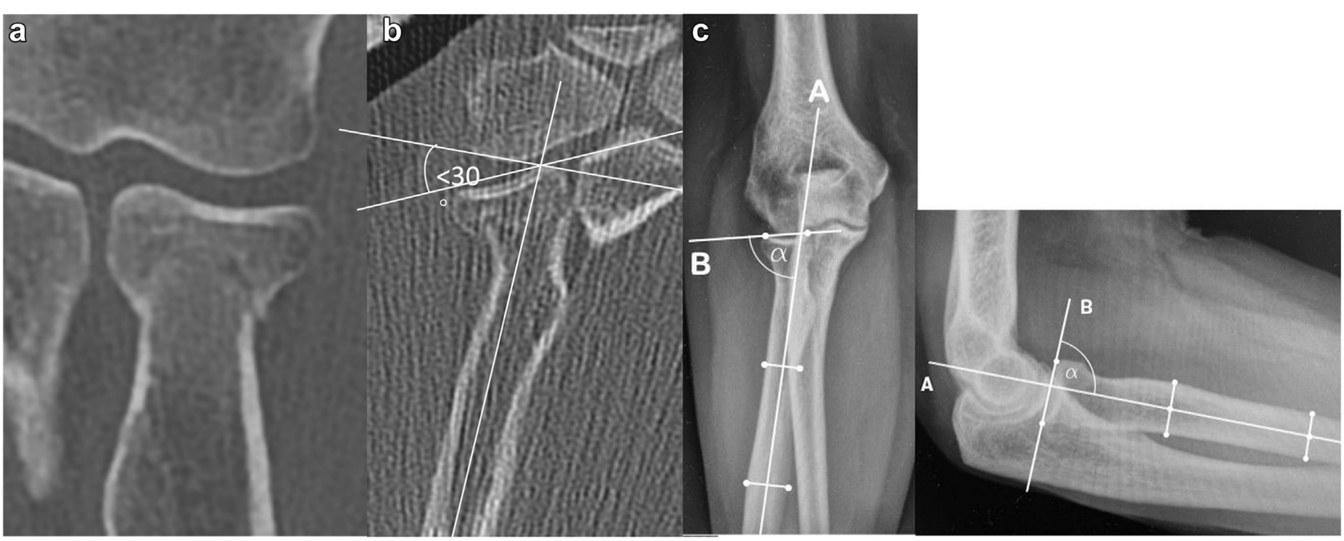


Figure 2 Type A2 fracture. (**a**) undisplaced radial neck fracture. (**b**) collapse of radial head on the neck with a radial head-shaft angle (RHSA) of <30°. (**c**) Determination of the RHSA in coronal and lateral view: a line following the axis of the radial shaft is drawn by finding the center of the radial shaft in two locations (line A). Then, a line is created by connecting the edges of the radial head (line B). The alfa angle between the two lines is the angle of the radial head towards the radial shaft. The RHSA is defined as the opposite angle to alpha.[46]

In ORIF, removal of the smallest fragments that cannot be synthesized is allowed, whereas excision of radial head fragments totaling >25% of the surface area of the articular disc should be avoided.[9,69,74,79]

Study protocol

To estimate the reliability and reproducibility of this classification, we reviewed the images of 149 patients with RHNFs treated at our Level

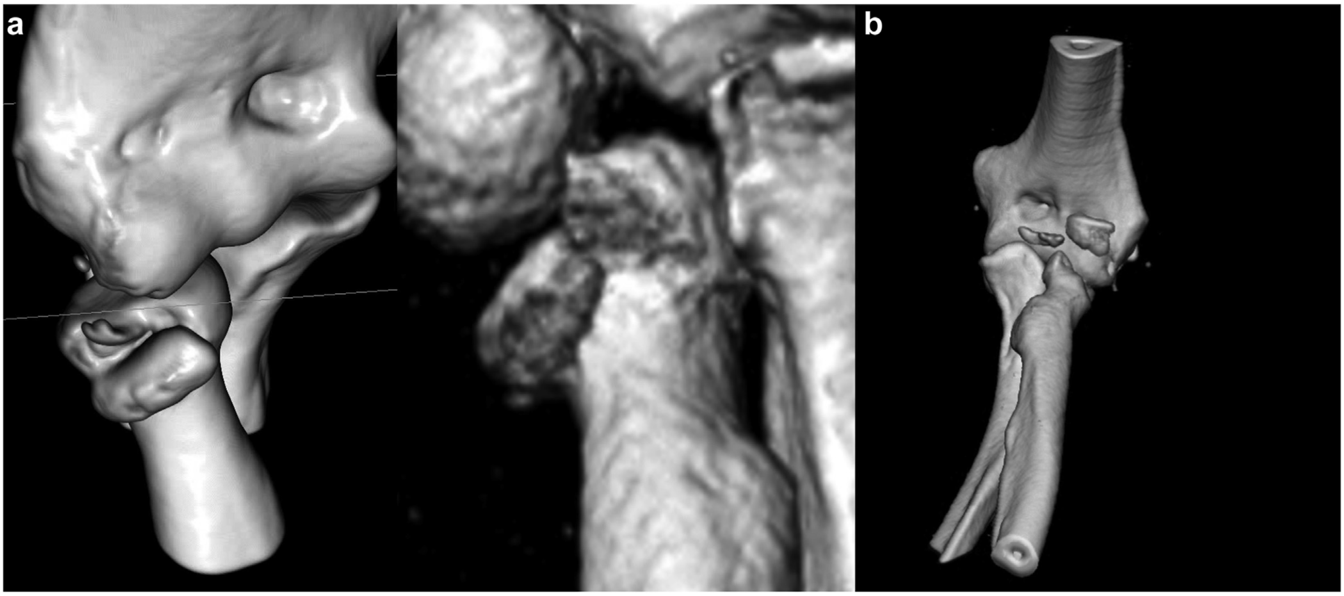


Figure 3 Type B subtype B1 fracture. (**a**) Displaced PARF with complete loss of cortical contact (**b**) Displaced PARF with more than two fragments. *PARF*, partial articular radial fractures of the radial head.

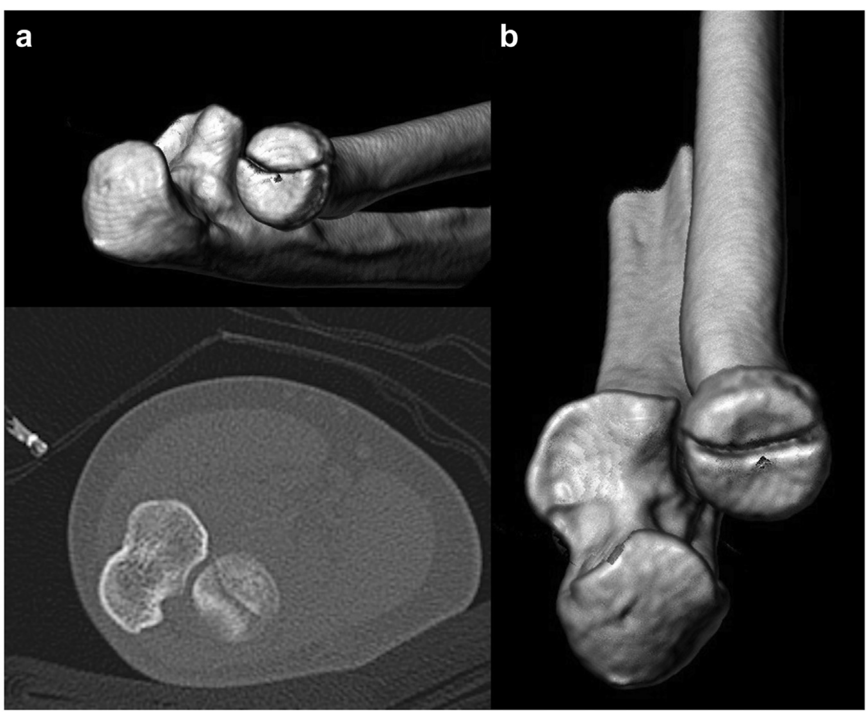


Figure 4 Type B subtype B2 fracture. (**a**) CT axial view of PARFs with displacement, without complete loss of cortical contact, involving the APRH. (**b**) Three-dimensional CT reconstruction. *CT*, computed tomography; *PARF*, partial articular radial fractures of the radial head; *APRH*, articulating portion of the radial head.

I Trauma Center from January 2011 to April 2021 and who underwent both elbow radiography and CT. Different CT scanners were used with up to 140 Kv and 500-700 mAs and slices from 8 to 64/dual source. 2D images were created in axial, coronal, and sagittal planes, and 3D images were created with rotations in both the sagittal and coronal planes. Then, we applied the following exclusion criteria: (1) patients<18 years; (2) CT scans of inadequate quality to create 3D reconstructions (a slice thickness of ≥1.25 mm); (3) images with poor resolution quality (i.e., presence of a plaster cast); and (4) patients in whom CT reconstructions had been performed on dislocated joints. Finally, 90 patients (40 males and 50 females, mean age: 46.01 years, range: 19-78 years) were included in the study. Associated lesions are listed in Table II. The protocol for the use of these images was approved by the Local Bioethics Committee (study no. 789/2021/OSS*/Prot. 42502). The selected images were collected in folders for the exclusive use of the studio manager. The names of the patients were deidentified and replaced with numeric codes, and the diagnostic images were anonymously submitted for the attention of the observers. The images of all 90 patients,

Figure 5 Type B subtype B3 fracture. Impaction of >2 mm of the central articular surface. Standard radiography cannot detect the central impaction (**a**), contrary to coronal CT-scan (**b**). *CT*, computed tomography.

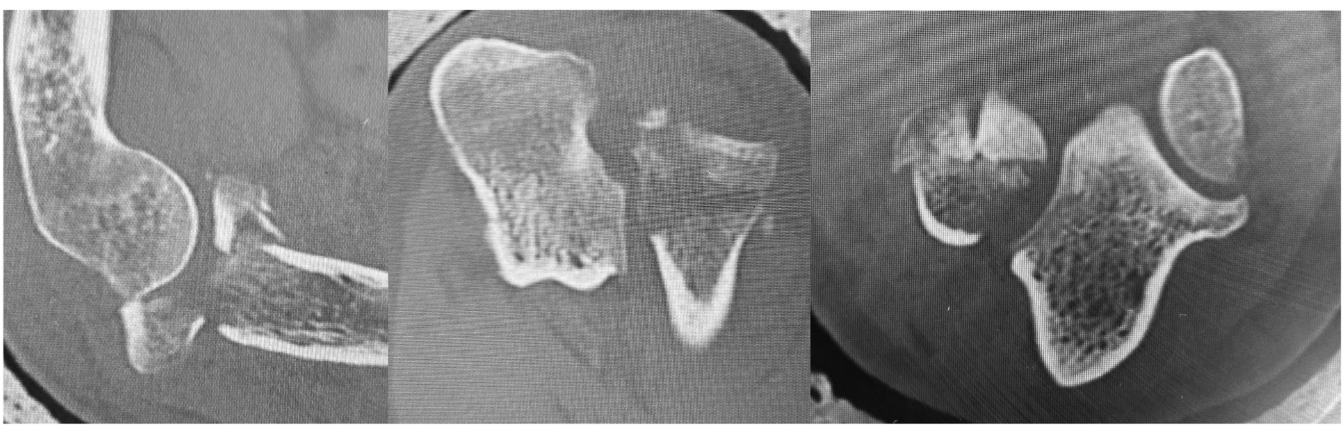


Figure 6 Type C subtype 1 fracture. The whole radial head is involved.

sorted in a random and different order for each observer, were sent to nine independent observers working across eight different national hospital units: eight orthopedic consultant surgeons, with >5 years' experience in general and elbow trauma surgery and one radiology consultant, skilled in the diagnosis of musculoskeletal trauma disorders. Each of the observers was also given a copy of the classification scheme (Table I) and asked to classify the fractures of the 90 patients according to the classification proposed by the senior author for proximal radial fractures, based on both standard radiographs and the provided 2D/3D CT scans. They were also asked whether they would have formally requested for a CT scan after viewing the standard radiographs.

Each observer noted their results in a Microsoft Excel worksheet for Windows (Microsoft Corp., Redmond, WA, USA) that was then sent back to the principal investigator. The first phase of observation was aimed to estimate the interobserver agreement by comparing the data collected by each participant and evaluating the degree of agreement between the observers, and therefore the reproducibility of the proposed classification. The second phase involved a new observation of the diagnostic images, 4 weeks after the first analysis. The order of presentation of the radiographs and CT images of each patient was changed randomly, generating a new sequence to minimize the risk of bias. The randomization sequence was determined by using a random number generator in Microsoft Excel. Once the images were classified and the results collected, a new statistical analysis was performed to estimate the intraobserver agreement; this second phase allowed to have an estimation on the reliability of the proposed classification.

Statistical analysis

Statistical analyses were performed using Minitab (version 20.3; Minitab LLC, State College, PA, USA), Microsoft Office Excel, and R Statistical Software (version 4.3.2; R Foundation for Statistical Computing, Vienna, Austria). The analysis involved nine appraisers who evaluated the images of 90 patients by using four different options.

Cohen's Kappa[19] was applied within appraisers (intraobserver agreement) to measure pairwise agreement, to assess how the agreement exceeded what might be expected by chance. Fleiss's Kappa[29] was used both within and between appraisers (interobserver agreement) to identify systematic agreements or disagreements across the cases. Kendall's coefficient of concordance (0: no agreement; 1: complete agreement) was utilized to determine the strength of association among the appraisers' rankings, both within and between appraisers, complementing the Kappa statistics by evaluating not just agreement but ranking concordance (in order of severity: A1<A2<B < C). In addition to the previously described

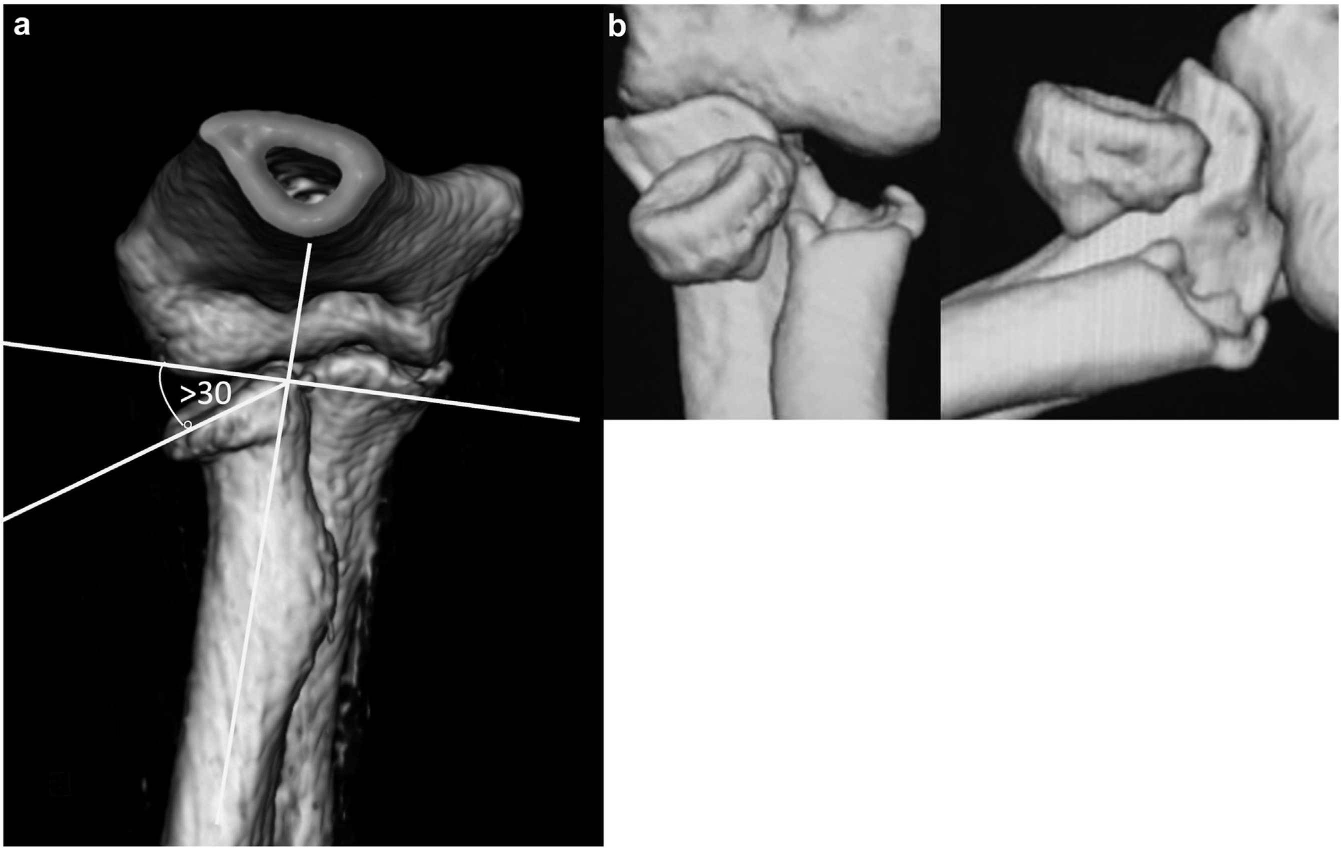


Figure 7 Type C subtype 2 fracture. (**a**) Fracture of the radial neck with metaphyseal collapse ≥ 30°, (**b**) displaced fracture of the radial neck.

Figure 8 Type C subtype 2 fracture associated with trans-olecranon fracture.

Table II
Associated lesions.

Isolated radial fractures	67
Elbow dislocation	7
Terrible triad	8
Transolecranic fractures	4
Capitellum/trochlea fractures	4
Total cases	90

statistical methods, Krippendorff's alpha was chosen as an adjunctive analysis for between appraisers' agreement. The inclusion of Krippendorff's alpha offered a more versatile assessment, given its ability to deal with multiple raters and various levels of measurement, including nominal data, as in this study. The observed agreement was compared with Fleiss's Kappa, and confidence intervals (CIs) were computed to estimate the accuracy of these statistics. These methods were combined to provide a better

Table III
Intraobserver assessment agreement of CT scan.

CT-based assessments	Cohen's kappa (95% CI)	P value	Fleiss's kappa (95% CI)	P value	Kendall's Tau-b	P value
Orthopedic surgeon 1	0.71 (0.57-0.85)	<.001	0.71 (0.56-0.85)	<.001	0.93	<.001
Orthopedic surgeon 2	0.73 (0.6-0.86)	<.001	0.73 (0.60-0.86)	<.001	0.93	<.001
Radiologist consultant 3	0.82 (0.69-0.96)	<.001	0.82 (0.69-0.96)	<.001	0.95	<.001
Orthopedic surgeon 4	0.74 (0.61-0.88)	<.001	0.74 (0.61-0.88)	<.001	0.92	<.001
Orthopedic surgeon 5	0.72 (0.59-0.86)	<.001	0.72 (0.59-0.86)	<.001	0.91	<.001
Orthopedic surgeon 6	0.79 (0.66-0.92)	<.001	0.79 (0.66-0.92)	<.001	0.94	<.001
Orthopedic surgeon 7	0.77 (0.63-0.91)	<.001	0.77 (0.63-0.91)	<.001	0.94	<.001
Orthopedic surgeon 8	0.83 (0.69-0.96)	<.001	0.82 (0.69-0.96)	<.001	0.95	<.001
Orthopedic surgeon 9	0.70 (0.57-0.84)	<.001	0.70 (0.57-0.84)	<.001	0.90	<.001

CT, computed tomography; *CI*, confidence interval.

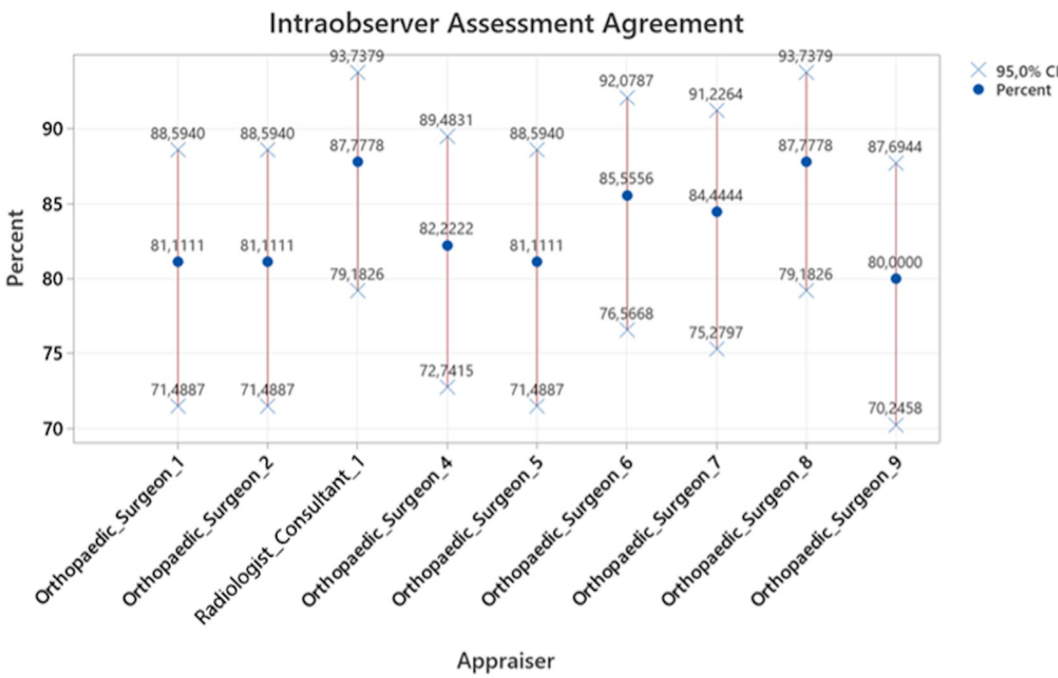


Figure 9 Plot showing intraobserver assessment agreement by percentages. *CI*, confidence interval.

understanding of the consistency and reliability of the appraisers' judgments, crucial for the validation of the classification.

According to Landis et al,[48] kappa coefficients <0 indicate no agreement; 0.0-0.2, slight agreement; 0.21-0.4, fair agreement; 0.41-0.6, moderate agreement; 0.61-0.8, substantial agreement; and 0.81-1.0, almost perfect agreement. $P < .05$ indicated that the null hypothesis was rejected, which means that the intraobserver and interobserver agreements were not because of pure chance alone. All *P* values reported in this study are two-tailed.

A power analysis for the required number of subjects was conducted with six evaluators to achieve an estimated Kappa value of 0.7 with the 95% CI ranging from 0.6 to 0.8, corresponding to 58 cases. Because our study included 90 patients and nine evaluators, the power of the study was considered adequate.

Results

Intraobserver agreement

The within-appraisers' analysis revealed a generally strong agreement in the assessments. Fleiss' Kappa statistics confirmed the consistency, with overall kappa values ranging from 0.70 to 0.83. Cohen's Kappa statistics aligned with Fleiss' Kappa, with similar kappa values and significant *P* values ($P < .001$). Kendall's coefficient of concordance also demonstrated significant consistency within appraisers, with coefficients ranging from 0.90 to 0.95 ($P < .001$) (Table III, Fig. 9).

However, the results relating to the appraisers' observation of standard radiographs showed an overall Fleiss' Kappa values for intraobserver agreement ranging from 0.34 to 0.82 and similar results for Cohen's Kappa values. Kendall's coefficient of concordance ranged from 0.55 to 0.89 ($P < .001$) (Table IV).

Interobserver agreement

Fleiss' Kappa statistics between appraisers showed moderate-to-substantial agreement, with kappa values ranging from 0.54 to 0.82 for different responses and an overall kappa of approximately 0.66. Kendall's coefficient of concordance demonstrated significant consistency between appraisers, with a value of 0.81 ($P < .001$) (Table V). The asymptotic two-sided 95% CI for Fleiss's K was found to be between 0.65 and 0.67, and the two-sided 95% Bootstrap CI ranged from 0.61 to 0.71.

Table IV
Intraobserver assessment agreement of radiographs.

Radiographs-based assessments	Cohen's kappa (95% CI)	P value	Fleiss's kappa (95% CI)	P value	Kendall's Tau-b	P value
Orthopedic surgeon 1	0.72 (0.60-0.83)	<.001	0.72 (0.60-0.83)	<.001	0.80	<.001
Orthopedic surgeon 2	0.82 (0.71-0.92)	<.001	0.82 (0.69-0.84)	<.001	0.89	<.001
Radiologist consultant 3	0.61 (0.48-0.74)	<.001	0.61 (0.49-0.73)	<.001	0.72	<.001
Orthopedic surgeon 4	0.73 (0.62-0.85)	<.001	0.73 (0.61-0.86)	<.001	0.84	<.001
Orthopedic surgeon 5	0.68 (0.56-0.80)	<.001	0.68 (0.55-80)	<.001	0.82	<.001
Orthopedic surgeon 6	0.51 (0.38-0.65)	<.001	0.51 (0.38-0.63)	<.001	0.73	<.001
Orthopedic surgeon 7	0.34 (0.20-0.47)	<.001	0.33 (0.20-0.45)	<.001	0.55	<.001
Orthopedic surgeon 8	0.41 (0.27-0.54)	<.001	0.40 (0.28-0.52)	<.001	0.59	<.001
Orthopedic surgeon 9	0.62 (049-0.74)	<.001	0.62 (049-0.74)	<.001	0.78	<.001

CI, confidence interval.

Table V
Interobserver assessment agreement of CT.

CT-based assessments	Fleiss's kappa (95% CI)	P value	Kendall's W	P value
A1	0.63 (0.61-0.64)	<.001		
A2	0.82 (0.8-0.84)	<.001		
B	0.54 (0.52-0.55)	<.001		
C	0.77 (0.76-0.79)	<.001		
Overall	0.66 (0.65-0.67)	<.001	0.81	<.001

CT, computed tomography; *CI*, confidence interval.

The results relating to the between appraisers' observation agreement for standard radiographic observation showed overall Fleiss' Kappa values ranging from 0.40 to 0.69 and an overall kappa of approximately 0.49; Kendall's coefficient of concordance had a value of 0.77 ($P < .001$) (Table VI).

With regard to the additional statistics of Krippendorff's alpha, the point estimator was determined to be 0.66 for CT agreement evaluation and 0.49 for X-rays agreement evaluation ($P < .0001$). The two-sided 95% Bootstrap CI for Krippendorff's alpha was between 0.60 and 0.71 (CT agreement evaluation) and between 0.42 and 0.55 (X-rays agreement evaluation), respectively. These results support a substantial level of agreement between the appraisers for CT findings, and the CIs provide further evidence of the consistency and reliability in the appraisers' evaluations, affirming the validity of the appraisers' findings.

The appraisers stated that, based on viewing the standard radiographs, they would have also formally requested for a CT scan in an average of 80.2% cases (Table VII).

Discussion

Current classifications of RHNFs are based exclusively on radiographic criteria and have several limitations.

The Mason–Johnston,[42,54] Broberg and Morrey,[10] and Hotchkiss[38] classifications have several shortcomings including their limited ability to guide treatment, because these do not consistently predict the amount of comminution or complexity of the fracture.[40] Moreover, in a large number of fractures, the classification of a specific injury will not be made consistently.[6,40]

The Arbeitsgemeinschaft für Osteosynthesefragen (AO) classification system accounts for the spectrum of injuries at the proximal part of the radius (radial head and/or neck fractures), regardless of whether isolated or associated with complex elbow/forearm fracture-dislocations.[56] A criticism of the AO classification system specific to radial head fractures is its subgroup classification for such fractures. Isolated PARFs could be classified as either type radius, proximal end segment articular, partial articular, simple fracture (simple) and radius, proximal end segment articular, partial articular, fragmentary fracture (multifragmentary). Both types include displaced and nondisplaced fractures. Treatment decisions based on this system may be limited, as nondisplaced simple/multifragmentary and displaced simple/multifragmentary fractures may require different interventions. Given that the treatment decisions are likely to be different, the outcomes may also be different, suggesting that this system may be limited in assisting clinical decision-making or evaluating outcomes.[72]

Moreover, all current classifications are burdened by fair-to-moderate interobserver and intraobserver reliability.[6,23,24,35,33,40,53,55,59,72,79] Moderate interobserver reliability affects communication among physicians and the utility of the classification in terms of guiding treatment.[40]

Nowadays, most radial head fractures, even if slightly displaced, are studied using 2D and 3D CT scans. This method can highlight characteristics of the fracture that are not always detectable with simple traditional radiographs, such as the number and entity of dislocated fragments, comminution of radial head and/or neck, articular fracture gap >2 mm, impacted fracture fragments, recognition of >3 articular fragments, and associated lesions, and are therefore important for diagnosis and timely treatment.[18,35,53] The proof of this lies is the high number of cases wherein the appraisers of this research would have requested a CT scan to better evaluate the fracture pattern (Table VII).

However, using the current classifications for RHNFs, the agreement between observers remains poor or moderate even with the introduction of CT and three-dimensional reconstructions[35,33,79]; thus, little has changed in the classification criteria, and therefore in the overall treatment algorithm.

This is probably because current classifications do not include all the fracture patterns detectable with 2D/3D CT. Thus, it becomes very challenging to classify a specific type of fracture if the classification itself does not include that type of fracture.

Therefore, the need for a new classification system that takes into account all the additional data provided by 2D/3D CT scans compared to conventional radiology, is the need of the hour. In addition to the above-mentioned information, these data help to comprehend whether there is a complete loss of cortical contact between the fracture fragments, which portion of the articular surface is involved in the fracture, and the amount of collapse of the radial head on the neck.

Our classification system takes advantage of all data detected by 2D/3D CT scans.

Each subgroup includes some new fracture patterns that were unknown or underestimated before use of 2D and 3D CT. This can help clinicians to better highlight and understand the fracture pattern, and possibly modify the required treatment.

For displaced simple PARFs, fracture fragment displacement >2 mm has sometimes been used as a criterion for consideration of operative treatment.[10,12,38,69,74] This displacement is clearly

Table VI
Interobserver assessment agreement of radiographs.

Radiographs-based assessments	Fleiss's kappa (95% CI)	*P* value	Kendall's W	*P* value
A1	0.50 (0.39-0.62)	<.001		
A2	0.40 (0.32-0.49)	<.001		
B	0.40 (0.29-0.50)	<.001		
C	0.69 (0.58-0.77)	<.001		
Overall	0.49 (0.42-0.55)	<.001	0.77	<.001

CI, confidence interval.

Table VII
Virtual request for CT scan for each appraiser.

Appraiser	5#Request for CT scan	Percentage
Orthopedic surgeon 1	67/90	74.4
Orthopedic surgeon 2	65/90	72.2
Radiologist consultant 3	71/90	78.8
Orthopedic surgeon 4	73/90	81.1
Orthopedic surgeon 5	79/90	87.7
Orthopedic surgeon 6	84/90	93.3
Orthopedic surgeon 7	81/90	90
Orthopedic surgeon 8	70/90	77.7
Orthopedic surgeon 9	60/90	66.6
Overall		80.2

CT, computed tomography.

emphasized on CT, whereas standard radiographs can underestimate this feature.[11,12,18,24,35,33,53,66,68,67,69] However, this amount of displacement can be seen in association with a stable fracture and preserved elbow and forearm motion.[24,28,27,69] Indeed, the optimal treatment of PARFs with >2 mm and <5 mm displacement without a mechanical block is still controversial.[24,27,43,47,49,56,68,74,64] Apart from Mulders et al,[60] there are still no other prospective randomized or case-control studies comparing surgical with nonsurgical management.[27,43,47,49,69] Only grade B/C recommendations exist for both nonoperative and operative treatment of these fracture types.[69]

More recently, the presence of complete cortical/periosteal disruption in displaced simple PARFs have been emphasized as a marker of instability.[11,27,34,66,68,69]

For fractures of the radial head, instability and displacement are not synonymous. Displaced simple PARFs without complete cortical disruption can also have a clear displacement (type A1); however, these fractures have a good outcome even if treated conservatively.[1,20,37,69,80] Indeed, as the periosteal sleeve is not completely disrupted, these fractures should be considered stable (Fig. 1). Stability of a displaced and/or impacted fragment may be preserved by the periosteal attachments.[11,69] Although the lack of subchondral bone[8] and its important buttress position against posterior elbow dislocation make the NAPRH prone to fracture and comminution,[1,15,17,34,57,66,69,50] isolated fractures involving only this portion are inherently stable even when displaced by 2 mm.[69,65] Based on these current concepts,[11,27,34,66,68,69] on the results of Lindenhovius and Yoon,[51,80] and the conclusions of the only randomized controlled trial found in the literature,[60] we have specified the stability (complete loss of cortical contact between the two fracture fragments) rather than the extent of dislocation as the criterion for classifying different PARFs. This allowed us to overcome the still relevant controversy on the best treatment for PARF.

Hence, we suggest nonoperative treatment for displaced simple PARFs involving the NAPRH without complete loss of cortical contact (types A1) and propose surgical treatment for displaced simple PARFs involving the NAPRH with complete loss of cortical contact (subtypes B1).[3,12,31,68,67,69,72,74,81] In the latter type, fractures have gross displacement of fracture fragments along with radiocapitellar articular incongruency and malalignment and block to the elbow and forearm motion: these features are strongly predictive of instability and disruption of soft-tissue attachments[41,66,67] (Fig. 3). Moreover, these unstable and widely displaced fractures are more often associated with fracture-dislocation patterns of the elbow and forearm.[66,69] Further randomized, prospective, and/or case-control cohorts are needed to elucidate the optimum treatment for PARFs.[5,12,24,27,74,79]

If subtype B2 is detected, the indication should be surgical, regardless of whether there is complete cortical loss of contact. Indeed, this lesion affects the portion of the radial head that simultaneously articulates with the lesser sigmoid notch and supports most of the axial load of the elbow and can be defined as a bi-articular fracture.[4,7,17,68] It is challenging to identify subtype B2 fractures even with the help of CT. While some methods have been described, all of these takes into account the position of the bicipital tuberosity with respect to the ulna in reference to the coronal plane[13,14,15,20,21,39,57,71,50] (Fig. 10).

B3 subtypes can be underestimated on conventional radiographs[12] (Fig. 5). The significant gap of the articular surface of the radial head requires surgical restoration.[52,69] Indeed, the central part of the articular surface (fovea capitis radii) is always stressed in axial loads. An alteration of the radiocapitellar congruence can lead to arthritic changes.[12] Hence, we suggest surgical treatment for B3 subtype fractures too.[52,68,69]

For A2 types/C2 subtypes, the degree and direction of the metaphyseal collapse can be assessed much more precisely using 2D and 3D CT than standard radiographs (Fig. 2*b*). Metaphyseal collapse is relatively frequent in childhood.[3,45,46,58] In pediatric patients, metaphyseal collapses with an RHSA $\geq 30^\circ$ are treated surgically, because of higher risk of avascular necrosis.[25,28,45,46,58,70,64] As there are still no randomized controlled trials for adults, we have to rely on the few studies on the angular cut-off beyond which the indication is definitely surgical.[46,58] Thus, using the same angular cut-off, adult metaphyseal collapses with an initial RHSA $\geq 30^\circ$ (subtype C2) have good medium-term outcomes when treated surgically.[46,58]

In adults, the reason for this is not the risk of avascular necrosis, rather the reduced radiocapitellar and proximal radio-ulnar joint congruency (Fig. 7*A*) that can result in limited forearm rotation and/or can lead to elbow instability and early onset osteoarthritis.[69,70] In case of metaphyseal collapse with RHSA < 30° (type A2), conservative treatment may be indicated because the reduction of radiocapitellar congruency does not compromise elbow stability[2,46,70] (Fig. 2). Further prospective studies may show a clear cut-off of RHSA requiring ORIF or radial head prosthesis.[46] We believe that the use of our classification and intraoperative check and/or clinical follow-up of treated patients will aid clinical decision-making.

The analysis of our classification system illustrates a strong intraobserver agreement and an overall substantial interobserver agreement, indicating a reliable and repeatable assessment process, especially considering the field of application.

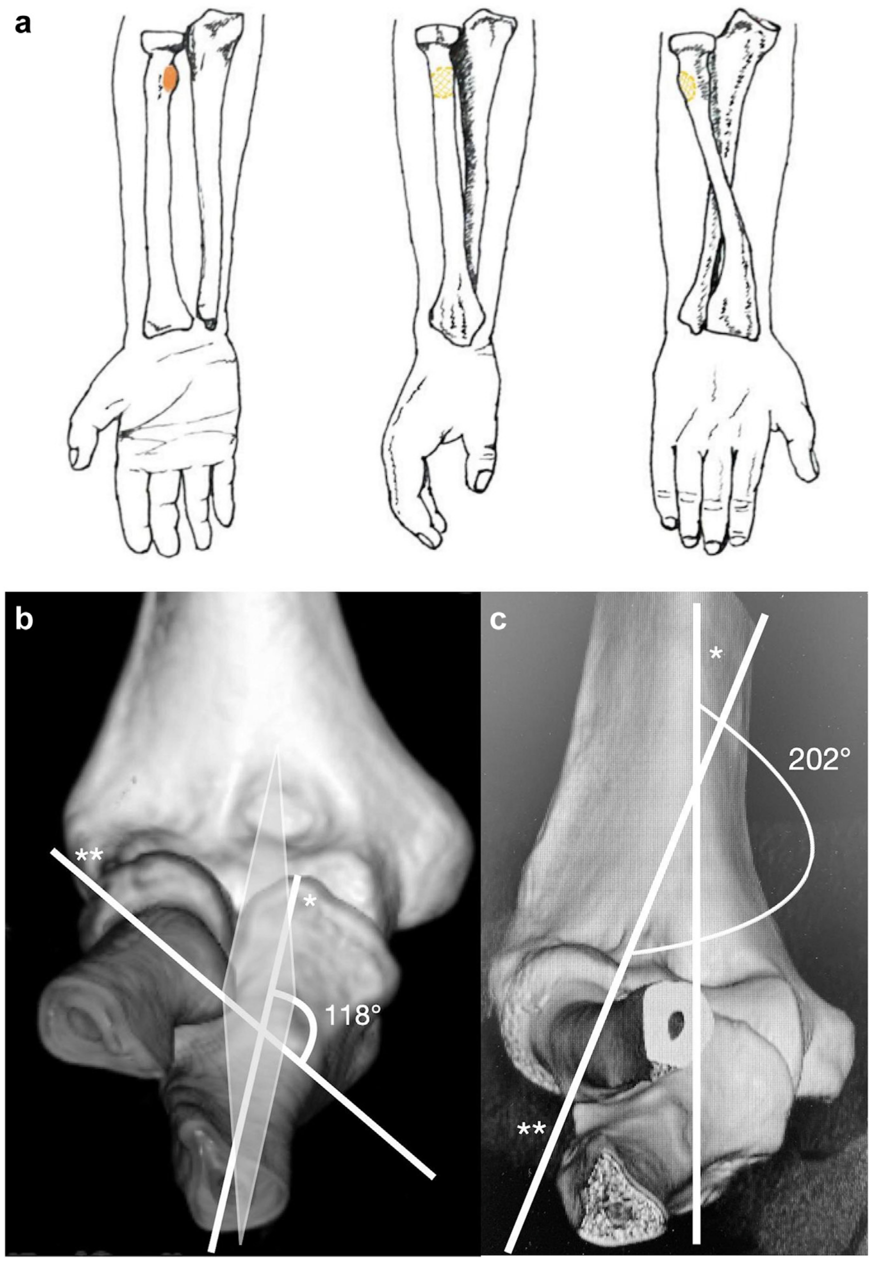


Figure 10 (**a**) Location of the bicipital tuberosity: at an average 42° from the coronal plane with the forearm in full supination (anteromedial position); at an average 127° with the forearm in neutral rotation (posteromedial position); and at an average 202° from the coronal plane with the forearm in full pronation (posterolateral position). (**b**) Three-dimensional CT reconstruction: the angular position of the bicipital tuberosity defined between the line passing through the coronal plane (*) and the line passing through the center of bicipital tuberosity (**). The ulna is assumed to be the 0°point on the coronal plane. In this case, the CT was carried out with the forearm in neutral rotation (118°). (**c**) Three-dimensional CT reconstruction: in this case, the CT was carried out with the forearm in full pronation (202°). *CT*, computed tomography.

It is also remarkable that both interobserver and intraobserver agreements using CT-images are higher than those detected with the evaluation of standard radiographic images alone. More specifically, Kendall's coefficient of concordance analysis showed that CT-scan evaluation allows easier distinction of rank of severity of a fracture pattern than standard radiographic evaluation. Understandably, this permits a better treatment strategy. However, it should be noted that the interobserver agreement was lower than the intraobserver agreement, suggesting potential disparities in assessment methodologies or criteria across different individuals.

As expected, interobserver agreement was better for type A2 and type C fractures than for type B and A1 fractures (Table V). The main factor distinguishing between B and A1 subtypes was the presence of complete cortical/periosteal contact loss, following Riiner's definition of stability.[66] Furthermore, presence of small free intra-articular fragments or of impacted fractures can be judged much better on CT images[11,12,24,34,35]; however, although the use of CT has improved the ability to assess the presence of complete cortical/periosteal contact loss[13,14,33,53,67,69] (Fig. 1), intraobserver and mostly interobserver agreement remains moderate.[11,12,33,53] Probably this is because of the inadequate definition of the 2D images provided by the CT-scan. Hence, further investigations are needed.

The proposed classification has some limitations. First, the classification is largely descriptive and has no prognostic value. To have prognostic value, the PARMa classification should also have a corresponding intraoperative finding and/or a clinical follow-up of the treatment carried out according to the classification. More specifically, the reliability of this classification in predicting complete loss of cortical/periosteal contact, fracture involvement in the APRH, and angular width of the RHSA should be assessed. Second, our classification does not consider associated lesions. Although some authors have proposed a classification system that also takes into account the associated injuries,[63,64] we believe that the treatment does not substantially change, even if other injuries are associated. Only the choice of surgical approach may change. Furthermore, we wish to make our classification simpler and more reproducible. Third, our classification does not consider the presence of osteoporosis: this condition can dramatically change the choice of treatment.[26] Last, most PARFs involve on average around 40% of the whole articular surface. Indeed, because of the angular geometrical issues, PARFs $\geq$ 40% of the articular surface necessarily also involve the APRH.[15,20,50] Therefore, all the above-mentioned methods of observation for detecting B2 fractures are relevant for those fractures that mainly involve the APRH, with fracture fragments smaller than 40% of the whole articular surface.

Although the PARMa classification has scope for further improvement, we believe it is a good starting point, especially in light of the coming available improved reality tools.

Conclusions

In this study we proposed a new CT-based classification system that is all-inclusive, reliable, reproducible, and can be used for preoperative planning and surgical management.

Declaration of generative AI and AI-assisted technologies in the writing process

The Authors did not use generative artificial intelligence (AI) and AI-assisted technologies in the writing process.

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