Surgical and Radiologic Anatomy (2019) 41:415–421
https://doi.org/10.1007/s00276-018-2160-8

ORIGINAL ARTICLE

The radial head size in relation to osseous landmarks of the forearm

Valentin Rausch[1,2] · Sebastian Wegmann[1] · Michael Hackl[1] · Tim Leschinger[1] · Wolfram F. Neiss[2] · Martin Scaal[3] · Lars P. Müller[1] · Kilian Wegmann[1]

Received: 5 July 2018 / Accepted: 8 December 2018 / Published online: 12 December 2018
© Springer-Verlag France SAS, part of Springer Nature 2018

Abstract

Purpose Radial head fractures are regularly treated with radial head arthroplasty. To prevent limited motion or pain, the implant's size should match its normal anatomy. Preoperative estimation of the radial head size helps in finding the correct head component. The aim of this study was to measure bony landmarks in proximity to the radial head to estimate the required size of a prosthesis preoperatively.

Methods Anatomical landmarks on 82 elbows from 41 embalmed specimens (19 male, 22 female) were measured using a digital caliper after removal of the specimens' tissue: the largest and smallest radial head diameter, length of the radius (styloid tip to radial head articular surface), and the length of the ulna (styloid tip to coronoid base). Additionally, cranio-caudal and antero-posterior diameters of the capitulum on scaled lateral elbow X-ray images were measured.

Results The mean largest and smallest radial head diameters were 24.2 mm (± 2.2, range 19.9–30.3; ICC = 0.992) and 22.5 mm (± 2.0, range 18.9–27.5; ICC = 0.985). The mean radius length was 23.8 cm (± 1.6, range 20.1–27.1; ICC = 0.986), and the mean ulna length was 23.1 cm (± 1.6, range 19.3–26.3; ICC = 0.969). The mean antero-posterior capitulum diameter was 16.2 mm (± 2.4, range 10.4–21.0; ICC = 0.506), and the mean cranio-caudal diameter was 17.0 mm (± 3.3, range 10.0–23.9; ICC = 0.529). The highest correlation to radial head diameters could be shown for diameters of the contralateral radial head and the radius length.

Conclusions For preoperative estimation of the radial head, the diameters of the contralateral radial head or the radius length are the most accurate.

Keywords Elbow surgery · Radial head · Anatomy · Forearm · Radial head prosthesis · Radial head fracture

Introduction

Fractures of the radial head are common injuries of the elbow and account for around 30% of all elbow fractures [1]. In comminuted fractures of the radial head, surgical therapy comprises osteosynthesis or the implantation of a radial head prosthesis. Prosthetic replacement is warranted in case of an unreconstructable fracture of the radial head, when additional ligamentous injuries destabilize the joint [2]. Radial head prostheses have proven to restore the kinematics of the radiocapitellar joint and have shown satisfactory clinical results [3–11]. They have therefore become an established means of treatment [8, 9]. The anatomy of the radial head is of complex nature making a perfectly matching prosthesis difficult. Nevertheless, size and shape of a radial head prosthesis should mimic the natural anatomy as close as possible to avoid degenerative changes or loss of motion [12–15].

In prosthetic replacement of any joint, adequate sizing of the components is key to proper function. In the radiohumeral joint, kinematic changes could be shown by shortening or lengthening with a radial head prosthesis [16]. In a series of 44 patients, van Riet et al. found radiological signs of overlengthening prior to revision surgery in 25% [15]. Biomechanical investigations revealed overtensioning of the interosseous membrane with increasing radial head diameter

✉ Valentin Rausch
rauschv@gmail.com

1 Center for Orthopedic and Trauma Surgery, University Medical Center, University Hospital Cologne, Kerpener Str. 62, 50937 Cologne, Germany

2 Department of Anatomy I, University of Cologne, Cologne, Germany

3 Department of Anatomy II, University of Cologne, Cologne, Germany

[17]. Such biomechanical changes can result in pain or loss of motion [13, 14]. In multi-fragmentary fractures, proper estimation of the affected radial head size is practically not possible. Computer tomography (CT) images of the contralateral elbow could be helpful in preoperative planning [18]. Yet, additional CT images bear the disadvantage of higher radiation exposure and validation of the contralateral radial head size is unclear. Measurements solely based on conventional radiographs using a scaling ball can precisely estimate sizes, however, diameters of the patient's radial head are dependent on the rotational position of the forearm. Furthermore, even though clinical relevance of such measures has not yet been established, two-dimensional radiographs do not necessarily allow for correct identification of the minimal or maximal diameter.

To correctly estimate the size of the fractured radial head, anatomical landmarks that reliably correlate to the size of the radial head can be helpful. Few studies estimating the radial head based on other anatomical or radiographic landmarks have been performed [19–26]. For example, one possibility to estimate the size of a prosthesis is the congruency with the lesser sigmoid notch, although this method has shown to be insufficiently reliable [20].

The aim of this study was to measure morphometric parameters of landmarks in close proximity to the radial head to estimate the required size of the radial head in preoperative planning.

Materials and methods

82 elbows from 41 embalmed specimens (19 male, 22 female) were used for this study. The median age of the donors was 83.6 years (±9.2, range 62–101).

Specimens suffering previous injuries or arthritic changes to the elbow were excluded. The specimens' soft tissue was carefully removed from the elbow and the entire forearm to visualize the styloid process of the radius and the ulna. The following parameters were then measured macroscopically (Fig. 1): the largest (Rh_{max}) and smallest (Rh_{min}) radial head diameter using a digital caliper; radius length measured from the tip of the radial styloid process to the most proximal extension of the radius (R_{length}); ulna length measured from the tip of the ulna styloid process to the base of the coronoid (U_{length}) using a measuring tape. Conventional radiographs of the elbow in the lateral view were then acquired with a scaling ball (of 0.62 mm) close to the capitulum. The conventional radiographs were then digitalized with a video-capturing device attached to the imaging intensifier and saved as .jpeg-Images. Distances on the digitalized images were measured using the ImageJ software [27]. The diameter of the capitulum was measured in cranio-caudal (C_{cc}) and antero-posterior orientation (C_{ap}). For the cranio-caudal orientation, the distance was measured in extension of the anterior edge of the humerus, while for the antero-posterior orientation, the largest distance in a 90° orientation to the cranio-caudal distance was measured (Fig. 2). For statistical analysis, SPSS Statistics (IBM Corp. Released 2018. Version 25.0. Armonk, NY, USA), Microsoft Excel (Microsoft Corp., Redmond, WA, USA) and GraphPad Prism 7 (GraphPad Software, La Jolla, CA, USA) was used. Minimum,

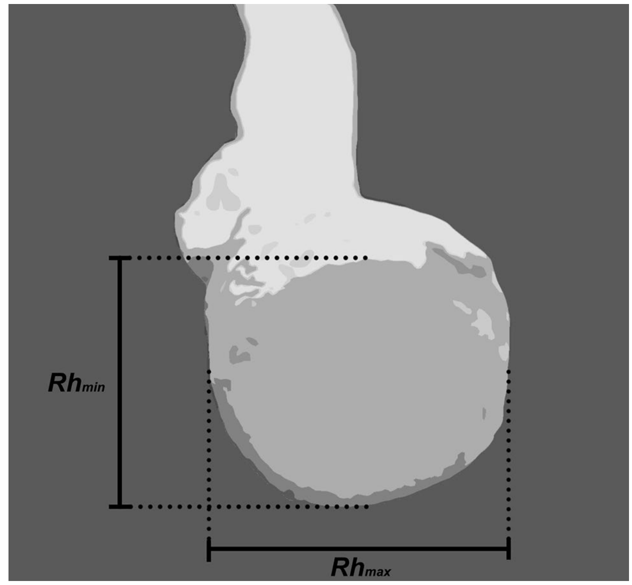

Fig. 1 Illustration of radial head and the respective measurements. The smallest (Rh_{min}) and largest (Rh_{max}) radial head diameter was measured

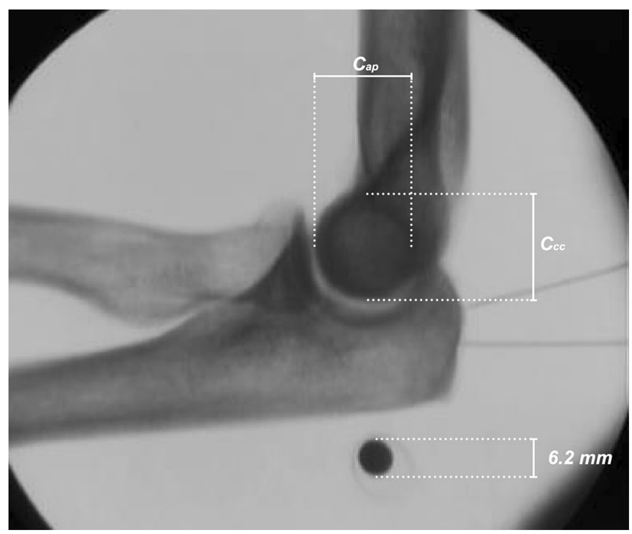

Fig. 2 Exemplary lateral radiograph with cranio-caudal (C_{cc}) and antero-posterior (C_{ap}) distance. The scaling ball had a diameter of 6.2 mm

maximum and standard deviations of all measured distances were calculated. All distances were measured by two investigators that were blinded for the other investigators' result. The intraclass correlation coefficient (two-way mixed average measures) (ICC) was calculated for the determination of inter-rater reliability.

To correlate the measured distances with the largest (Rh_{max}) and smallest (Rh_{min}) radial head diameters, the Pearson coefficient ("*r*") was calculated. Also, the correlation of Rh_{min} and Rh_{max} between sides of the respective specimens was calculated using Pearson correlation. P-values < 0.05 were classified as significant, p-values < 0.001 were classified as highly significant.

Then, ratios between the measured distances (R_{length}, U_{length}, C_{cc}, C_{ap}) and the corresponding Rh_{max} and Rh_{min} were calculated. Using the mean calculated ratios, the (smallest and largest) radial head diameters were estimated and absolute difference between the measured diameters was calculated. To test whether these ratios would result in a correct estimation of the size of a radial head prosthesis, the percentage of estimations with an absolute difference > 2 mm to the measured diameters was calculated.

The study was approved by the local ethics committee (registration number 18–112).

Results

The measured distances are shown in Table 1. The largest radial head diameter was on average 24.2 mm (SD 2.2 mm, range 19.9–30.3 mm), the smallest radial head diameter was on average 22.5 mm (SD 2.0 mm, range 18.9–27.5). The inter-rater reliability for the radial head diameters was excellent (largest diameter: ICC = 0.992, smallest diameter: ICC = 0.985). Largest and smallest diameters showed an excellent correlation to each other ($p = 0.959$). On average, the largest diameter was 1.07 times larger than the smallest diameter (SD 0.03, range 1.01–1.17).

The radius had an average length of 23.8 cm (SD 1.6 cm, range 20.1–27.1 cm), and the ulna had an average length of 23.1 cm (SD 1.6 cm, range 19.3–26.3 cm). The inter-rater reliability of these measurements was also excellent with ICC = 0.986 for the radius and ICC = 0.969 for the ulna.

In the radiographic images of the lateral elbow, the average diameter of the capitulum in antero-posterior orientation was 16.2 mm (SD 1.3 mm, range 13.5–19.1 mm), and in cranio-caudal orientation 17.0 mm (± 1.4 mm, range 12.6–20.0 mm) (Table 2). The inter-rater correlation of these measurements was only moderate with an ICC = 0.529 for the cranio-caudal distances and ICC = 0.506 for the antero-posterior distance.

Table 1 Measured diameters and length of the respective anatomical landmarks

	Mean	SD	Range	95% confidence interval
Smallest radial head diameter (mm)	22.5	2.0	18.9–27.5	0.3
Largest radial head diameter (mm)	24.2	2.2	19.9–30.3	0.4
Ulna length (cm)	23.0	1.6	19.3–26.3	0.4
Radius length (cm)	23.8	1.6	20.1–27.1	0.5
Radiographic capitulum diameter c.c. (mm)	17.0	3.3	10.0–23.9	0.7
Radiographic capitulum diameter a.p. (mm)	16.2	2.4	10.4–21.0	0.5

Table 2 Correlation between the anatomical landmarks and radial head diameters

	Correlation (Pearson)/*p* value				Quotient (mean, SD and range)	
	Smallest radial head		Largest radial head		Smallest radial head/	Largest radial head/
Ulna length to	0.66	< 0.001	0.67	< 0.001	0.98 (SD 0.07, range 0.86–1.18)	1.05 (SD 0.07, range 0.92–1.30)
Radius length to	0.711	< 0.001	0.711	< 0.001	0.95 (SD 0.06, range 0.84–1.11)	1.02 (SD 0.07, range 0.90–1.22)
Radiographic diameter capitulum AP to	0.49	< 0.001	0.509	< 0.001	0.72 (SD 0.06, range 0.55–0.91)	0.68 (SD 0.06, range 0.52–0.86)
Radiographic diameter capitulum CC to	0.476	< 0.001	0.493	< 0.001	0.76 (SD 0.07, range 0.59–0.92)	0.71 (SD 0.06, range 0.55–0.91)
Smallest radial head (contralateral)					1.00 (SD 0.02, range 0.94–1.06)	–
Largest radial head (contralateral)					–	1.00 (SD 0.03, range 0.94–1.06)

Besides the radial head of the contralateral side, the highest correlation to radial head diameters could be shown for the radius length (Fig. 3).

When using the measured distances for estimation of the radial head diameter, radial head diameters of the contralateral side could predict the smallest and largest radial head diameter within 2 mm absolute distance in all cases. When using R_{length} for estimation of Rh_{min}, 86.6% could be projected within 2 mm, 79.3% for Rh_{max}. When using U_{length} for the estimation of radial head diameters, Rh_{min} could be predicted within 2 mm in 84.2%, Rh_{max} in 76.8%. Estimations for radial head diameters using distances from the lateral radiograph were within 2 mm of the measured size in 67.1–74.4% of the cases (Table 3).

The correlation of the smallest and largest diameter of the radial head with the respective diameters of the contralateral side was excellent ($r = 0.963$, $p < 0.001$ for the smallest, $r = 0.969$, $p < 0.001$ for the largest diameter of the radial head, Fig. 4).

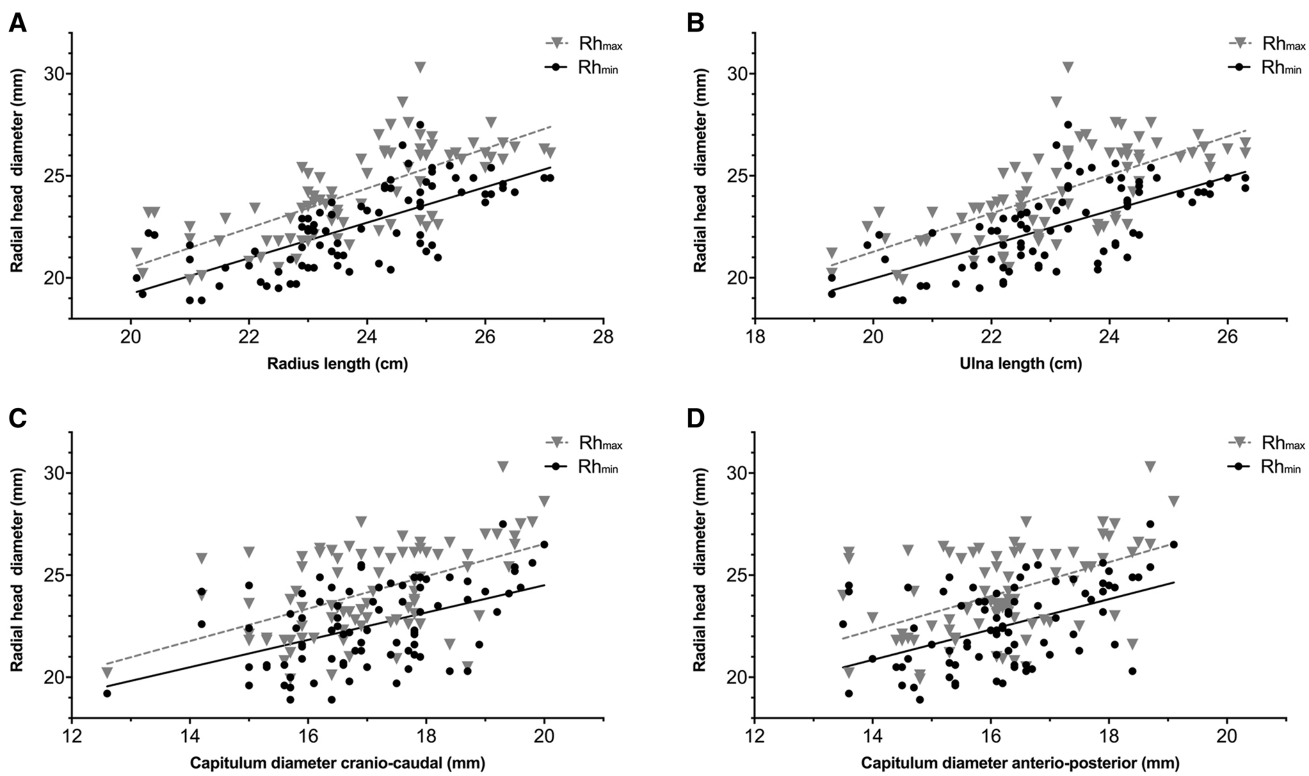

Fig. 3 Scatter plots of the smallest (Rh_{min}) and largest (Rh_{max}) radial head diameter in relation to **a** the radial length, **b** the ulna length, **c** the radiographic measured capitulum diameter in a.p. direction and **d** the radiographic measured capitulum diameter in c.c. direction

Table 3 Correct estimations within 2 mm of radial head diameter using measured distances in 82 elbows

	Estimated Rh_{max}				
	U_{length}	R_{length}	Rh_{max} (contralat.)	C_{cc}	C_{ap}
Correct estimation	63/82	65/82	82/82	55/82	55/82
Percentage	76.83%	79.27%	100.00%	67.07%	67.07%
	Estimated Rh_{min}				
	U_{length}	R_{length}	Rh_{min} (contralat.)	C_{cc}	C_{ap}
Correct estimation	69/82	71/82	82/82	57/82	61/82
Percentage	84.15%	86.59%	100.00%	69.51%	74.39%

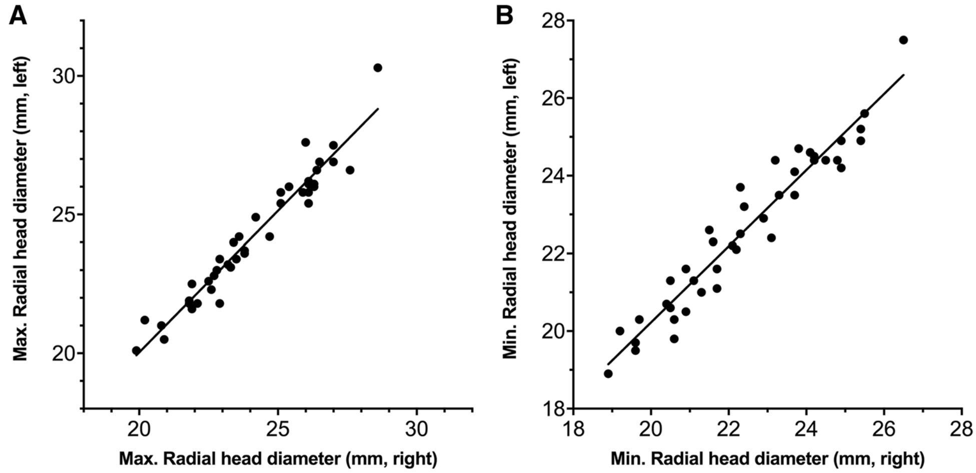

Fig. 4 Correlation of the **a** smallest and **b** largest radial head diameter between the left and right side

Discussion

In the present study, we investigated morphometric data of the radial head in correlation to the macroscopic length of the radius, length of the ulna and to diameters of the capitulum in antero-posterior and cranio-caudal orientation measured on radiographic images of the lateral elbow. The results for the values of the radial head diameters in our study are in line with dimensions of the radial head previously described in the literature [21–25, 28–31]. The highest correlation of the largest and smallest radial head diameter could be found to the respective distance of the opposite side, followed by the total length of the radius and the ulna. For the correlation of the largest and smallest radial head diameters to radiographically assessed diameters of the capitulum, only a moderate correlation could be found. Estimating the radial head size within 2 mm using the measured distances (R_{length}, U_{length}, C_{cc}, C_{ap} and diameters of the contralateral side) revealed 100% correct estimations for diameters of the contralateral side followed by R_{length} and U_{length} for estimation of the smallest radial head diameter. These estimations are particular important, since commercially available radial head prosthesis (such as the Tornier radial head system, the MoPyC radial head prosthesis or the Acumed anatomical radial head system) are available in steps of 2 mm between 18 and 28 mm. Our results therefore suggest that for estimation of the radial head size, measurement of the contralateral side or length of the radius or ulna is the most accurate. On the other hand, radiographically assessed diameters of the capitulum should be used carefully and cannot fully be relied upon for estimation of radial head size.

Estimates of radial head diameters are particularly important prior to an implantation of radial head prostheses following a comminuted radial head fracture, for which different sizes of most commercially available prostheses are offered. Surgeons have to base their choice of the relevant implant on their experience in approximation of the native radial head. There have been few studies on the correlation of anatomical structures to radial head size to help estimating the size of the radial head. Alolabi et al. investigated the lesser sigmoid notch as an anatomical landmark for the sizing of the head components of a radial head prosthesis [20]. They could show that orientation on the curvature of the lesser sigmoid notch shows only moderate correlation to the radial head diameter or a selected radial head implant size making this method unfavorable [20].

Abdulla et al. investigated the accuracy of measuring the radial head size in comminuted fractures [19]. In a cadaveric model with osteotomized radial heads, they could show a high correlation of distances measured before and after a simulated (multi-fragmentary) fracture [19]. However, this method is unsuitable for preoperative planning, as a reconstructed radial head is not available.

King et al. investigated the diameter of the radial head on human cadaveric specimens and compared them to the smallest diameter of the radial stem canal in unscaled antero-posterior and lateral radiographs. The authors found only a poor correlation between the radial head diameter and the diameter of the stem canal [22]. These results implicate that measuring the radial stem canal in radiographic images is not helpful in estimating the native radial head size.

Vanhees et al. measured the largest and smallest radial head diameter with a digital caliper and correlated these distances to the width and vertical height of the capitulum [25]. In their study, correlation coefficients (Pearsons r^2) of these distances ranged between 0.38 and 0.90 [25]. The mean vertical height on the specimens was 23 mm compared to 17 mm in our study [25]. The differences in the height of the capitulum can be explained by different techniques of measurement: We used conventional radiographs for imaging of the anatomical structures, missing the cartilaginous structures on the images. Vanhees et al. measured the height of the capitulum with use of a digital caliper. In our study, the correlation for the vertical height of the capitulum and the largest or smallest diameter of the capitulum did not exceed $r = 0.49$. Lateral radiographs of the elbow could have been less accurate than anatomical measurements, leading to a lower correlation to other, more accurately measured distances.

Vaquero-Picado et al. besides other distances, also measured the humeral condyle diameter on unscaled lateral and antero-posterior radiographs and correlated these distances to intraoperatively measured sizes of the radial head [26]. They found the highest correlation of their measurements between the humeral condyle diameter on lateral radiographs of the elbow to the radial head size [26]. However, their interobserver concordance was only moderate for the humeral condyle diameter. In their study, a prediction of the correct radial head size was only possible in 67% of the cases [26]. In our study, using the contralateral radial head size for estimation of the radial head size could correctly predict its size within 2 mm in all cases. The correlation of radiographic measured distances of the cranio-caudal distance (which corresponds to the vertical height) was, however, only moderate with $r = 0.48–0.49$ as was the inter-observer correlation with ICC = 0.53, resulting in correct estimations in 67.1–74.4% of the cases, which could also be confirmed by Popovic et al. [24]. Therefore, using the contralateral elbow could be the most correct estimation for the radial head size, although the additional radiation exposure of the opposite side must be balanced against the advantage of preoperative planning. However, due to the cumulation effect of conventional radiographs, the largest radial head diameter could probably only be measured in more accurate CT scans. In addition, X-ray measurements are in general prone to error, as differences in positions in the beam path cause errors due to a different projection. In our study, distances in radiographs were measured in relation to a scaling ball to avoid mistakes due to projection. However, even with scaled measurements, the inter-rater correlation of measurements on native X-rays in our study was insufficient for preoperative planning of radial head size. Moreover, using external templates for scaling has shown to produce less precise estimations of implant sizes on other joints than 3D imaging [32, 33].

We found other landmarks that could easily be collected preoperatively for preoperative planning. Length measurements of the radius and the ulna can be performed with a simple measuring tape as well as radiologically on radiographs of the forearm. The anatomical measurements of these landmarks showed an excellent inter-rater correlation. These measurements should therefore be less prone to error, moreover since rotation of the forearm should not influence the length of the radius on radiographic images. Taken together, correlation of these measurements in our work was strong, although reliable determination should not solely be based on these parameters.

This study has certain limitations: first, measurements of the radial head and length of the radius were based on anatomical specimens. For preoperative estimation of the radial head size, distances of the opposite site or length of the radius or the ulna can only be measured on radiographic images. However, the high inter-rater reliability of anatomical measurements suggests that these distances can be measured reliably. Generally, our study was performed on embalmed specimens. Nonetheless, bony structures are typically unaffected by shrinkage of the tissue due to fixation. Also, with 83.6 years the average age of the embalmed specimens was high. However, since we excluded specimens with previous procedures to the upper extremity or degenerative changes to the elbow, we do not believe the high age influences bony distances in a relevant extent. Following studies on actual radiographic images and correlation to intraoperative chosen implants should confirm our results in the future.

Conclusion

Estimation of the radial head size based on the contralateral radial head diameters shows the highest correlation followed by estimation based on the length of the radius and the ulna. Estimations based on radiographic measurements such as the capitellar diameter (antero-posterior or cranio-caudal) do not show equivalent levels of correlation and, therefore, should not be used.

Acknowledgments We would like to thank Oda C. Goetzke for helping with the preparation of the manuscript.

Author contributions VR and KW conceived the presented idea and designed the study; VR, SW, WFN and MS carried out the anatomical measurements after preparation of the specimens; VR, KW and TL wrote the manuscript in consultation with LPM and MH; VR and KW aided in interpreting the results; LPM and KW supervised the project.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Mason ML (1954) Some observations on fractures of the head of the radius with a review of one hundred cases. Br J Surg 42:123–132. https://doi.org/10.1002/bjs.18004217203
2. Ring D (2011) Radial head fracture: open reduction–internal fixation or prosthetic replacement. J Shoulder Elb Surg 20:S107–S112. https://doi.org/10.1016/j.jse.2010.11.011
3. Burkhart KJ, Mattyasovszky SG, Runkel M et al (2010) Mid- to long-term results after bipolar radial head arthroplasty. J Shoulder Elb Surg 19:965–972. https://doi.org/10.1016/j.jse.2010.05.022

4. Chanlalit C, Shukla DR, Fitzsimmons JS et al (2011) Influence of prosthetic design on radiocapitellar concavity-compression stability. J Shoulder Elb Surg 20:885–890. https://doi.org/10.1016/j.jse.2011.03.009
5. Chanlalit C, Shukla DR, Fitzsimmons JS et al (2012) Stress shielding around radial head prostheses. J Hand Surg Am 37:2118–2125. https://doi.org/10.1016/j.jhsa.2012.06.020
6. Chanlalit C, Shukla DR, Fitzsimmons JS et al (2012) The biomechanical effect of prosthetic design on radiocapitellar stability in a terrible triad model. J Orthop Trauma 26:539–544. https://doi.org/10.1097/BOT.0b013e318238b3a2
7. Cohn M, Glait SA, Sapienza A, Kwon YW (2014) Radiocapitellar joint contact pressures following radial head arthroplasty. J Hand Surg Am 39:1566–1571. https://doi.org/10.1016/j.jhsa.2014.05.021
8. Grewal R, MacDermid JC, Faber KJ et al (2006) Comminuted radial head fractures treated with a modular metallic radial head arthroplasty: study of outcomes. J Bone Jt Surg Ser A 88:2192–2200. https://doi.org/10.2106/JBJS.E.00962
9. Katthagen JC, Jensen G, Lill H, Voigt C (2013) Monobloc radial head prostheses in complex elbow injuries: results after primary and secondary implantation. Int Orthop 37:631–639. https://doi.org/10.1007/s00264-012-1747-7
10. Levy JC, Formaini NT, Kurowicki J (2016) Outcomes and radiographic findings of anatomic press-fit radial head arthroplasty. J Shoulder Elb Surg 25:802–809. https://doi.org/10.1016/j.jse.2015.11.014
11. Pomianowski S, Morrey BF, Neale PG et al (2001) Contribution of monoblock and bipolar radial head prostheses to valgus stability of the elbow. J Bone Jt Surg Ser A 83:1829–1834. https://doi.org/10.2106/00004623-200112000-00010
12. Athwal GS, Frank SG, Grewal R et al (2010) Determination of correct implant size in radial head arthroplasty to avoid overlengthening: surgical technique. J Bone Jt Surg Ser A 92:250–257. https://doi.org/10.2106/JBJS.J.00356
13. Birkedal JP, Deal DN, Ruch DS (2004) Loss of flexion after radial head replacement. J Shoulder Elb Surg 13:208–213. https://doi.org/10.1016/j.jse.2003.11.007
14. Van Riet RP, Van Glabbeek F, Verborgt O, Gielen J (2004) Capitellar erosion caused by a metal radial head prosthesis: a case report. J Bone Jt Surg Ser A 86:1061–1064. https://doi.org/10.2106/00004623-200405000-00028
15. van Riet RP, Sanchez-Sotelo J, Morrey BF (2010) Failure of metal radial head replacement. J Bone Jt Surg Br 92:661–667. https://doi.org/10.1302/0301-620X.92B5.23067
16. Van Glabbeek F, Van Riet RP, Baumfeld JA et al (2004) Detrimental effects of overstuffing or understuffing with a radial head replacement in the medial collateral-ligament deficient elbow. J Bone Jt Surg Ser A 86:2629–2635. https://doi.org/10.2106/00004623-200412000-00007
17. Lanting BA, Ferreira LM, Johnson JA et al (2015) Radial head implant diameter: a biomechanical assessment of the forgotten dimension. Clin Biomech 30:444–447. https://doi.org/10.1016/j.clinbiomech.2015.03.012
18. Ten Berg PWL, Dobbe JGG, van Wolfswinkel G et al (2016) Validation of the contralateral side as reference for selecting radial head implant sizes. Surg Radiol Anat. https://doi.org/10.1007/s00276-016-1625-x
19. Abdulla I, Langohr GDG, Gladwell M et al (2015) The effect of fracture comminution on the reliability and accuracy of radial head sizing. J Shoulder Elb Surg 24:364–368. https://doi.org/10.1016/j.jse.2014.10.026
20. Alolabi B, Studer A, Gray A et al (2013) Selecting the diameter of a radial head implant: an assessment of local landmarks. J Shoulder Elb Surg 22:1395–1399. https://doi.org/10.1016/j.jse.2013.04.005
21. Itamura JM, Roidis NT, Chong AK et al (2008) Computed tomography study of radial head morphology. J Shoulder Elb Surg 17:347–354. https://doi.org/10.1016/j.jse.2007.07.019
22. King GJW, Zarzour ZDS, Patterson SD, Johnson JA (2001) An anthropometric study of the radial head: implications in the design of a prosthesis. J Arthroplasty 16:112–116. https://doi.org/10.1054/arth.2001.16499
23. Koslowsky TC, Germund I, Beyer F et al (2007) Morphometric parameters of the radial head: an anatomical study. Surg Radiol Anat 29:225–230. https://doi.org/10.1007/s00276-007-0197-1
24. Popovic N, Djekic J, Lemaire R, Gillet P (2005) A comparative study between proximal radial morphology and the floating radial head prosthesis. J Shoulder Elb Surg 14:433–440. https://doi.org/10.1016/j.jse.2004.10.012
25. Vanhees M, Shukla DR, Fitzsimmons JS et al (2018) Anthropometric study of the radiocapitellar joint. J Hand Surg Am. https://doi.org/10.1016/j.jhsa.2018.02.001
26. Vaquero-Picado A, Núñez de Armas J, Antuña S, Barco R (2018) Morphometry of the radiocapitellar joint: is humeral condyle diameter a reliable predictor of the size of the radial head prosthesis? J Shoulder Elb Surg 27:1092–1096. https://doi.org/10.1016/j.jse.2018.01.017
27. Rueden CT, Schindelin J, Hiner MC et al (2017) ImageJ2: ImageJ for the next generation of scientific image data. BMC Bioinform. https://doi.org/10.1186/s12859-017-1934-z
28. Beredjiklian PK, Nalbantoglu U, Potter HG, Hotchkiss RN (1999) Prosthetic radial head components and proximal radial morphology: a mismatch. J Shoulder Elb Surg 8:471–475. https://doi.org/10.1016/S1058-2746(99)90079-4
29. Captier G, Canovas F, Mercier N et al (2002) Biometry of the radial head: biomechanical implications in pronation and supination. Surg Radiol Anat 24:295–301. https://doi.org/10.1007/s00276-002-0059-9
30. Puchwein P, Heidari N, Dorr K et al (2013) Computer-aided analysis of radial head morphometry. Orthopedics 36:e51–e57. https://doi.org/10.3928/01477447-20121217-18
31. Van Riet RP, Van Glabbeek F, Neale PG et al (2003) The noncircular shape of the radial head. J Hand Surg Am 28:972–978. https://doi.org/10.1016/S0363-5023(03)00426-X
32. Pietrzak JRT, Rowan FE, Kayani FB et al (2018) Preoperative CT-based three-dimensional templating in robot-assisted total knee arthroplasty more accurately predicts implant sizes than two-dimensional templating. J Knee Surg. https://doi.org/10.1055/s-0038-1666829
33. Sariali E, Mauprivez R, Khiami F et al (2012) Accuracy of the preoperative planning for cementless total hip arthroplasty. A randomised comparison between three-dimensional computerised planning and conventional templating. Orthop Traumatol Surg Res. https://doi.org/10.1016/j.otsr.2011.09.023