Influence of radial head prosthetic design on radiocapitellar joint contact mechanics

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Hypothesis: Our aim was to test whether anatomically designed metallic radial head implants could better reproduce native radiocapitellar contact pressure and areas than nonanatomic implants.

Methods: The distal humerus and proximal radius from 6 cadaveric upper extremities were serially tested in supination with 100 N of compression force at 4 angles of flexion (0°, 30°, 60°, and 90°). By use of a thin flexible pressure transducer, contact pressures and areas were measured for the native radial head, an anatomic implant, a nonanatomic circular monopolar implant, and a bipolar nonanatomic implant. The data (mean contact pressure and mean contact area) were modeled using a 2-factor repeated-measures analysis of variance with $P \leq .05$ considered to be significant.

Results: The mean contact areas for the prosthetic radial heads were significantly less than those seen with the intact radial heads at every angle tested ($P < .01$). The mean contact pressures increased significantly with all prosthetic radial head types as compared with the native head. The mean contact pressures increased by 29% with the anatomic prosthesis, 230% with the monopolar prosthesis, and 210% with the bipolar prosthesis. Peak pressures of more than 5 MPa were more commonly observed with both the monopolar and bipolar prostheses than with the anatomic or native radial heads.

Conclusions: The geometry of radial head implants strongly influences their contact characteristics. In a direct radius-to-capitellum axial loading experiment, an anatomically designed radial head prosthesis had lower and more evenly distributed contact pressures than the nonanatomic implants that were tested.

Level of evidence: Basic Science Study, Biomechanics.

Keywords: Contact pressure; contact area; radial head; prosthesis; anatomic radial head implant; circular radial head implant

Radial head arthroplasty may be indicated in the management of comminuted radial head fractures and for some chronic conditions after previous radial head excision. As described in a recent review by Giannicola et al., there are various types and designs of radial head prostheses available to use in such circumstances. They can be classified as anatomic or nonanatomic; monoblock or modular; unipolar or bipolar; and intentionally loose, press fit, or cemented. The overwhelming majority of radial head implants are metallic. Although good results at midterm follow-up have been reported, recent publications have documented complications such as painful...
capitellar erosion and degeneration arising from use of metallic radial head implants. The reasons for cartilage erosion and degeneration that have been suggested include initial trauma to the cartilage, capitellar osteopenia, stiffness of the metal implant, and overstuffing of the joint. Proximal radial overstuffing or over-lengthening occurs when the radial head is replaced with a radial head implant that is too long.

Biomechanical studies have shown that lengthening of the radial neck results in an increased transmission of force through the radiocapitellar joint. If a radial head implant is used without restoration of the proper axial length of the radius, there is potential for a number of complications, such as residual instability, as well as altered load transfer. Because pressures experienced by joint surfaces are inversely related to the contact areas over which the forces are applied, the contact area geometry and/or variations in prosthetic design and/or alignment may influence joint loading more than the prosthesis material composition. An implant of metallic design that resembles the radial head anatomy should theoretically generate more physiological contact pressures than an implant with a nonanatomic design. Of course, the use of an anatomic design does necessitate accurately aligning the prosthesis to match the orientation of the original radial head to avoid maltracking on the capitellum and the potential for cartilage damage.

Designs of radial head implants range from the Anatomic Radial Head implant (Acumed, Hillsboro, OR, USA) that was designed to mimic certain anatomic features of the native radial head to various bipolar implants that have been designed to accommodate for anatomic deformity. We hypothesized that a radial head implant designed to mimic the radial head anatomy will more closely reproduce radiocapitellar joint contact pressures and areas than an implant with a nonanatomic design. Our aim with this experiment was to measure and compare the radiocapitellar contact pressures and areas of the native radial head, an anatomic radial head design, a monopolar circular head design, and a bipolar circular radial head design.

Materials and methods

Specimen preparation

Six fresh-frozen elbows were used for this study. There were 4 male specimens, aged 64, 69, 74, and 76 years, and 2 female specimens, aged 50 and 60 years. The specimens were thawed for 24 hours at room temperature before the experiment. The specimens were then examined under fluoroscopy for pathologic abnormalities. The soft tissues surrounding the joint including the ligament, muscles, and capsule were completely removed. The radiocapitellar and ulnohumeral joints were disarticulated. None of the specimens showed any evidence of radial head or distal humerus arthritis or other pathology under fluoroscopic or gross examination. The humerus and the radius were potted in aluminum tubes.

Pressure transducer

A Tekscan sensor 4000 (Tekscan, South Boston, MA, USA) was used between the radius and humerus to record contact pressure and area. These sensors allow quantitative assessment of the contact areas and pressures. They are matrix-based thin (0.18-mm) sensors that have an array of a pressure-sensitive ink pattern and a conductive ink coating. When force is applied on the sensors, resistance is created at the intersection points of the columns and rows of the pressure-sensitive ink (called “sensels”) and an electrically conductive ink then conducts the electrical signal. The output from these sensels can be collected for analysis or displayed on a computer in the form of a color-coded map with the help of the I-Scan analysis software (Tekscan) provided by the manufacturer. The Tekscan sensor 4000 has been validated in earlier reports. It has a 28 × 33-mm matrix, made of 572 sensels, each with an area of 1.6 mm². The saturation pressure of the chosen sensor was 10.3 MPa. The size of this sensor was considered appropriate for a radial head. We validated this sensor in our pilot experiments by confirming that the total force that it recorded also matched the total load that was applied to it. The sensor was preconditioned and calibrated according to the manufacturer’s recommendations. Contact areas and pressure values were analyzed with the I-Scan software and with MATLAB software (The MathWorks, Natick, MA, USA).

Specimen mounting and testing

To test the specimens, we used a custom mechanical test machine that included a pneumatic-controlled actuator, a 6-axis load cell (JR3, Woodland, CA, USA), and a 2-df x-y stage, permitting free translation of the base of the construct (Fig. 1). This apparatus allowed the potted bones to be reproducibly aligned and tested at set flexion angles (0°, 30°, 60°, and 90°). The potted humerus was held vertically upside down (normal anatomic position). The radius was brought into contact with the capitellum and oriented in full extension and supination; the bicipital tuberosity was oriented medially as well. The radiocapitellar articulation was carefully checked for capitellum fitting in a well-seated position of the radial head dish. The lateral trochlear ridge was also in contact with the beveled rim of the radial head; the cement was then poured, and the radius was potted in this position. This automatically achieved the matched carrying angle. The bones were kept hydrated during testing with periodic application of saline solution spray. The bicipital tuberosity was oriented medially such that it would mimic a supinated position. In the mediolateral plane, the radius was positioned so that the radial head (native or prosthetic) was centered on the capitellum (Fig. 1, A). The Tekscan transducer was then positioned between the radial head and capitellum and held in place by modeling clay around the rim of the radial head (Fig. 1, B). With the sensor in place and activated, a 40-N load was applied to the system to provide real-time feedback of the pressure map by use of the I-Scan software. The position of the radial head was then optimized medially, laterally, and anteriorly by allowing the x-y stage to self-adjust so that the contact area was maximized. Registration marks were used on the radial heads and sensors to ensure reproducible alignment. We assessed this method for reproducibility by setting up the same specimen 7 times and measuring the areas and pressures of the native radial head using the Tekscan sensor under 100 N of compressive load. For the same
specimen, these 7 measurements had SDs of 2 mm² for area and 0.01 MPa for pressure.

Testing protocol

The specimens were tested in 0°, 30°, 60°, and 90° of flexion. An axial compressive load of 100 N was applied at each of the testing angles. A compressive load of 100 N was chosen to simulate the force of light-duty activities of daily living through testing angles. A compressive load of 100 N was applied at each of the available sizes are 18, 20, 22, and 24 mm. The second design, the circular RHS Radial Head System, has a circular head, straight neck, and lateral offset of the articulating dish. The available sizes are 20, 22, 24, 26, and 28 mm. The second design, the circular RHS Radial Head System, has a circular head, straight neck, and ±10° of bipolar tilt. A neck collar that was custom made for these experiments allowed the implant to be locked and thus effectively converted into a monopolar implant. The depth of the articulating dish is 1 mm, and the available sizes are 18, 20, 22, and 24 mm. The third design was a circular shaped RHS implant without the custom neck collar; it was thus permitted to function as a bipolar implant as it was originally designed to do. As previously described, the sizes of the implants were chosen per the manufacturers’ recommendations. The long and short diameters of the native radial head were measured (eg, 22 × 24 mm). The Anatomic Radial Head, which also has a long and short axis, was matched in size to the long axis of the native radial head. The RHS radial head was matched to the short axis of the native radial head. If the native head was between sizes, we opted for the smaller-diameter prosthetic radial head.

Data analysis

Contact areas and pressures

Within a few seconds of loading, the sensor equilibrium was reached and the data were recorded from the Tekscan software. I-Scan software was used to calculate mean and peak contact pressures as well as mean contact areas. All the data were rounded to 2 significant digits of precision and presented as mean ± standard error. The data were modeled by use of a 2-factor repeated-measures analysis of variance with P ≤ .05 considered to be significant.

Threshold contact pressures

The threshold contact pressures were defined as pressure values above a threshold of 5 MPa. Evidence suggests that cyclic pressures above 5 MPa initiate cartilage damage at the microscopic level. Peak contact pressures were analyzed with custom MATLAB software. The number of specimens that showed peak pressures above 5 MPa with each of the radial heads tested in 30° of flexion (because this forearm position is most commonly used in activities of daily living) was tabulated and analyzed with the Fisher exact test.

Results

Mean contact areas

The mean contact areas for the prosthetic radial heads were significantly less than those seen with the intact radial heads at every angle tested (P < .01) (Fig. 2). Similarly, the mean contact areas for the modified RHS prosthesis and RHS circular bipolar prosthesis were significantly less than those seen with the Anatomic Radial Head prosthesis (P < .0001). However, the mean contact areas were not significantly different between the modified RHS prosthesis and RHS bipolar prosthesis. Compared with the native radial head, the contact areas decreased by 25% after replacement with the Anatomic Radial Head prosthesis and 70% and 69% after replacement with the modified RHS prosthesis and RHS bipolar prosthesis, respectively. Contact areas with the native head initially increased as the angle increased. However, the areas decreased as the joint was flexed from 60° to 90°. At 30° of flexion, the mean contact areas were 200 ± 15 mm² with the native head, 150 ± 13 mm² with the Anatomic Radial Head prosthesis, 59 ± 5 mm² with the RHS circular monopolar prosthesis, and 56 ± 2.2 mm² with the RHS bipolar prosthesis.
Mean contact pressures

Mean contact pressures after implantation of the Anatomic Radial Head prosthesis were significantly higher than those of the native head (P < .05) (Fig. 3). The mean contact pressures with the modified RHS prosthesis and RHS bipolar prosthesis were significantly higher than those seen with the native radial head and the Anatomic Radial Head prosthesis (P < .0001). The mean contact pressures increased by 29% with the Anatomic Radial Head prosthesis, 230% with the modified RHS prosthesis, and 220% with the RHS bipolar prosthesis. At 30° of flexion, the mean contact pressures were 0.52 ± 0.04 MPa with the native radial head, 0.70 ± 0.06 MPa with the Anatomic Radial Head prosthesis, 1.7 ± 0.12 MPa with the modified RHS prosthesis, and 1.8 ± 0.06 MPa with the RHS bipolar prosthesis. The mean contact pressures did not significantly change when the joint was progressively flexed from 0° to 90° with the native radial head and the Anatomic Radial Head prosthesis. The contact pressures after replacement with the modified RHS prosthesis and RHS bipolar prosthesis did not significantly change from 0° to 60° but increased significantly from 60° to 90° (P < .02).

Peak contact pressures

The peak contact pressures were significantly different among the radial head types (P < .04). They were 2.3 ± 0.16 MPa with the native radial head, 3.2 ± 0.17 MPa with the Anatomic Radial Head prosthesis, 5.4 ± 0.15 MPa with the modified RHS prosthesis, and 4.5 ± 0.27 MPa with the RHS bipolar prosthesis (P < .04).

Threshold contact pressures

Peak contact pressures exceeding the threshold of 5 MPa, where cartilage damage would be initiated at the microscopic level,7,9 were not seen in any of the testing conditions with the native radial head and were seen in only 1 of the 24 testing conditions with the Anatomic Radial Head prosthesis. However, this threshold was exceeded commonly with the modified RHS prosthesis and RHS bipolar prosthesis (Fig. 4, Table I). At 30° of flexion, a significantly higher number of specimens with the modified RHS prosthesis exceeded the threshold pressure than did specimens with the Anatomic Radial Head or RHS bipolar prosthesis (P < .05). This was because of the distribution of the load into a smaller area of the head (Fig. 4).

Discussion

This study showed that a radial head prosthesis designed to mimic certain anatomic features more accurately reproduced contact pressures and contact areas of the native head than circular RHS nonanatomic radial head prostheses. We found that the RHS radial heads increased radiocapitellar contact pressures significantly. This can be explained by the differences in depth and radius of curvature. The RHS implant has a relatively shallow dish depth (1 mm). This provides a nonconforming articulating surface with the capitellum, resulting in a small contact area between the capitellum and prosthesis. Although the RHS bipolar design was created to achieve better radiocapitellar orientation, it did not provide a conforming surface because of the shallow dish depth. In contrast, the design of the Anatomic Radial Head prosthesis includes a 2.3-mm dish depth with a varying radius of curvature. This effectively created a more conforming articulating surface and provided a better area of contact with the capitellum. We also found that a shallow nonanatomic radial head caused significantly frequent peak pressures above 5 MPa. Because radial heads are often inserted in relatively young adults after trauma,5,16 prostheses that raise contact pressures to
high levels could cause cartilage erosion and degeneration in the long-term.

This study examined the contact pressure differences after the use of radial head prostheses and showed that the geometry of the articulating surface of radial head prostheses is important regarding its effects on radiocapitellar contact pressures. Our study showed that the nonanatomic RHS design showed much higher radiocapitellar contact pressures that could be destructive to the capitellar cartilage. Although it has been suggested that the stiffness of these metallic radial head implants is responsible for decreased contact areas, prior studies did not test other designs of implants.

It has been found that radial head prostheses can induce changes in capitellar cartilage such as erosion, osteopenia, and degeneration. Van Riet et al. found severe erosion of capitellar cartilage in 20 of 47 elbows. A recent study by Flinkkila et al. showed that capitellar erosion was present in 14 of 42 elbows (33%). Moreover, Smets et al. reported an increase in degenerative changes as compared with the normal elbow in 8 of 15 elbows (53%). Furthermore, because of the small contact areas produced by these implants, portions of the capitellum will be unloaded, which could potentially give rise to osteopenia in the long-term. Shore et al. noted osteopenia of the capitellum in 44% of their patients (14 of 32). They also observed moderate osteoarthritis in 11 of 32 patients and severe osteoarthritis in 1 of 32. Similarly, capitellar osteopenia was observed in 18 of 23 patients (78%) by Moro et al. at a mean follow-up of 39 months. The reasons behind these complications are poorly understood. Possible causes stated by some authors include the stiffness of the metal implant or overstuffing of the radiocapitellar joint. Although overstuffing of the joint has also been shown to increase radiocapitellar contact pressures, cartilage changes have been observed in the absence of overstuffing. We believe that the design of the radial head implant contributes significantly toward cartilage changes. The anatomic design used in the present study has a depth of 2.3 mm of the articulating surface, whereas the circular implant that we tested has a mean depth of 2.4 ± 0.5 mm. Thus, the Anatomic Radial Head is more similar in design to the native radial head. The Anatomic Radial Head has also been shown to provide more radiocapitellar stability because of its deeper dish. It is likely that peak pressures in the nonanatomic RHS implants, as shown in this study, may cause long-term cartilage damage. Thus, mimicking the anatomic features of the radial head in a prosthetic radial implant can result in more favorable joint contact characteristics and thus could reduce the occurrence of long-term capitellum damage. The anatomic prosthesis requires proper technique to avoid malpositioning.

Two earlier studies have shown that contact areas decrease with circular implants. Liew et al. showed that after radial head arthroplasty using circular prostheses, contact areas decreased by 68%, which is very similar to what we found in this study (70%). Moungondo et al. found that contact areas after radial head replacement with a bipolar Judet prosthesis (Tornier SA) were greater than those seen with the Evolve implant (Wright Medical Technology, Arlington, TN, USA). In the previously mentioned studies, polysiloxane silicone molds were used for testing contact areas. Our use of the Tekscan sensor to record contact areas and pressures provided us real-time and noncumulative measurements, whereas polysiloxane is known to overestimate contact areas because of a major concern regarding its ability to penetrate the joint.

A limitation of our study was that it was performed in vitro. Thus, the loading characteristics of the radiocapitellar joint may be different from those seen in vivo. However, compressive forces were applied in a similar way across all radial head types. It has also been reported that forces as high as 3 times the body weight may pass through the elbow joint and that the radius may transmit up to 60% of the total force. Because our main objective was to compare and study the contact patterns among different radial head types, our experiment does provide a good overview of the contact patterns.
sense of how the pressures will be transmitted across the different radial head designs when similar loads pass across the radiocapitellar articulation. Another limitation was that the joint was tested only in the supinated position. However, this position was chosen to mimic a heightened risk of subluxation and was kept constant in all the radial head types tested. In addition, because this testing model used only the radius and humerus, it was not possible to accurately gauge the proper axis of rotation that would allow us to test the effects of forearm rotation or dynamic loading. Future testing-model development will examine enhancements that will include the whole elbow so that pressure and area measurements can be made under such conditions. Another limitation was that all testing was performed statically. This has provided us with a first step toward understanding the contact mechanics of the radiocapitellar joint with native and prosthetic radial heads. It will be of significant value for future studies to involve modifications to this testing model to examine pressure and contact characteristics in the context of dynamic testing and perhaps even soft tissue constraints. Lastly, as a practical limitation, not all radial head designs were studied. The contact pressures and areas are directly related to the congruency of the capitellum over the long-term, it may be preferable to use implants that conform more anatomically to the capitellum.

Conclusion

The RHS nonanatomic radial heads with a shallow articulating dish depth (1 mm) generate high radiocapitellar contact pressures over small contact areas. Because high contact pressures can damage the cartilage of the capitellum over the long-term, it may be preferable to use implants that conform more anatomically to the capitellum.

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