Differences in the Radius of Curvature Between Femoral Condyles
Implications for Osteochondral Allograft Matching

Peter Z. Du, MD, Keith L. Markolf, PhD, Benjamin D. Levine, MD, David R. McAllister, MD, and Kristofer J. Jones, MD

Investigation performed at the David Geffen School of Medicine at UCLA, Los Angeles, California

Background: The radius of curvature (ROC) is an important variable related to potential cartilage incongruities in the transplantation of a large femoral osteochondral allograft. The anterior-posterior length (APL) of a condyle is used as a criterion for donor-graft acceptance. We hypothesized that there would be a linear correlation between the ROC and APL of a condyle, that the ROC and APL would differ significantly between the medial femoral condyle (MFC) and the lateral femoral condyle (LFC), and that a donor graft from the LFC would be suitable for an MFC defect.

Methods: Knee magnetic resonance imaging scans of 147 patients with no cartilage defects were analyzed. Best-fit circles in the sagittal plane were determined at standardized locations on each condyle. Assuming the use of a 20-mm graft that was flush to the edges of the native cartilage, the central graft prominence was calculated for potential donor-host differences in the ROC.

Results: There was a linear correlation between the ROC and APL. There were significant differences in the mean ROC and APL between the MFC and LFC. Based on calculations of the central graft prominence among all ROC combinations within the patient group, 100% of potential medial-to-medial, 97.8% of lateral-to-lateral, and 92.5% of lateral-to-medial transplantations would produce a central graft prominence of <1 mm. On average, an allograft harvested from an LFC (mean ROC, 25.7 mm; mean APL, 69.8 mm) implanted into an MFC defect site (mean ROC, 31.9 mm; mean APL, 66.6 mm) would have a central graft prominence of 0.4 ± 0.3 mm.

Conclusions: Assuming a maximum central graft prominence tolerance of +1 mm, our findings demonstrate that matching the ROC or APL would not be necessary for potential medial-to-medial or lateral-to-lateral allograft transplants within this patient group. Implantation of an LFC donor allograft into an MFC defect is also supported by our findings.

Osteochondral allograft transplantation is an increasingly popular surgical choice for large (>20-mm) focal femoral condylar articular cartilage defects. This procedure involves transplantation of a cadaveric donor allograft into a prepared condylar recess that encompasses the defect. At present, the anterior-posterior length (APL) of a condyle is an important criterion used in accepting or rejecting a potential allograft. The appropriate threshold for an acceptable difference in APL between a donor graft and the recipient site is not consistently agreed on within the orthopaedic community, with cited values ranging from up to ± 2 mm to up to ± 5 mm. Unfortunately, size matching or orthotopic matching (e.g., medial donor to medial recipient) is not always possible. The majority of femoral articular cartilage defects occur on the medial femoral condyle (MFC). This has led to an increase in demand for MFC grafts, and a donor graft is often unavailable, leading to unacceptably long wait times for the patient. In these situations, a surgeon can choose to accept a donor graft from the lateral femoral condyle (LFC). However, the surface geometry and articular cartilage thickness of MFCs and LFCs can differ considerably, both of which could affect congruity at the host-donor interface.

The radius of curvature (ROC) is a parameter that has been used to describe the surface geometry of the femoral condyle. Prior studies have measured the condylar ROC for the subchondral bone, but these data are not useful for...
matching grafts for osteochondral allograft transplantation since the ROC of the cartilage surface is the relevant clinical parameter. A smaller donor-graft ROC could lead to elevation of the graft’s central portion relative to the surrounding host native cartilage at the perimeter of the graft. A prominent graft has been shown to increase contact stress and contact force and possibly contribute to poor clinical outcomes. To our knowledge, the relationship between the articular cartilage ROC and APL for the medial and lateral femoral condyles has not yet been studied at locations representative of femoral articular cartilage defects. These data are important to help surgeons and tissue banks find the optimum allograft match for the patient.

The purpose of this study was to measure medial and lateral ROCs of the articular cartilage surface by an analysis of standard magnetic resonance imaging (MRI) scans made for patients with no femoral articular condylar defects. We hypothesized that (1) there would be a linear correlation between the ROC of a condyle and its APL, (2) the ROC and APL would differ significantly between the MFC and the LFC, and (3) a donor graft from the LFC would be suitable for an MFC defect.

**Materials and Methods**

Knee MRI scans for 147 patients with no cartilage defects were analyzed. All MRI scans were initially ordered by physicians at our institution for various clinical indications and were selected chronologically starting with the latest MRI available in the database and moving backward in time. Patients were excluded if there were any articular cartilage pathologies apparent on the MRI scan, if there was a prior anterior cruciate ligament injury, or if the patient had prior surgery on the knee. Sagittal proton density-fast spin echo (PD-FSE), coronal PD-FSE, and axial turbo spin echo (TSE) T2 fat-saturated MRI sequences were performed for all patients using a 3-T MAGNETOM Skyra scanner (Siemens Medical Solutions), and image measurements were made using software from the Centricity PACS (picture archiving and communication system) Radiology RA1000 Workstation (GE Healthcare). All images were obtained by MR technologists at our institution. The MR technologist positioned the patient such that the leg of the affected knee was fully extended. Cushions were placed within the coil along the lateral and medial sides of the knee to help stabilize knee rotation. The MR technologist acquired scout imaging in the axial, sagittal, and coronal planes, and then used the medial and lateral femoral condyles as the guiding line to ensure all slice orientations were in-plane to the knee joint. All MRI measurements were performed by a single observer, and intraobserver variability was determined by comparing APL and ROC measurements for 20 randomly selected MRI scans examined on 2 separate occasions.

An institutional review board approved the review of the demographic data and MRI scans for the purpose of this study.

All ROC measurements of the articular cartilage surface were obtained from a single sagittal-plane section at standardized anterior-posterior locations representative of clinical cartilage defects. We analyzed a preliminary series of 37 patients with femoral cartilage defects (19, MFC; and 18, LFC) to determine the average distance between the center of the defect and the anterior margin of the condyle (Table I).

**TABLE I Average Anterior-Posterior Location of Common Clinical Cartilage Defects**

<table>
<thead>
<tr>
<th>Defect</th>
<th>APL (mm) ± SD</th>
<th>Distance to Lesion (mm) ± SD</th>
<th>% from Anterior (mm) ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medial femoral condyle</td>
<td>62.1 ± 5.9</td>
<td>37.4 ± 4.8</td>
<td>60.4 ± 7.8 (45.5-76.5)</td>
</tr>
<tr>
<td>Lateral femoral condyle</td>
<td>67.0 ± 4.5</td>
<td>45.6 ± 5.5</td>
<td>68.0 ± 6.0 (57.1-76.5)</td>
</tr>
</tbody>
</table>

*From a preliminary series of 37 patients with femoral cartilage defects. The values are given as the mean and standard deviation, with the range, where indicated, in parentheses. †APL = anterior-posterior length. ‡Distance from the anterior cartilage margin of the condyle to the center of the defect. §Percentage of the APL of the measured distance to lesion.

**Fig. 1**

Axial TSE T2 fat-saturated MRI scan showing measurement of the APL for both medial and lateral femoral condyles. Measurement lines have been colored yellow for greater emphasis.
The APL of the MFC was measured by scrolling through axial images and selecting the section that displayed the largest distance between the most anterior and posterior points on the cartilage surface of the condyle (Fig. 1). This methodology is consistent with that used by tissue banks to measure the APL from patient MRI scans and from physical measurements of donor condyles (per personal communication with the Musculoskeletal Transplant Foundation and Joint Restoration Foundation).

Sagittal sections of the MFC were scrolled through until the most anterior margin of the MFC cartilage was visualized, and a vertical screen marker was placed at this margin (Fig. 2-A). This anterior screen marker corresponded to the same anterior cartilage margin visualized on the axial view. Using this sagittal section, a second screen marker was placed at a horizontal distance that was 60% of the condyle’s APL posterior to the anterior screen marker (Fig. 2-A). While scrolling through sagittal sections with the posterior screen marker indicated, coronal-plane sections were simultaneously viewed. The sagittal-plane section that roughly bisected the coronal medial-lateral width of the condyle was selected for ROC analysis. Using this section, a vertical line was drawn at the location of the posterior screen marker, and its intersection with the cartilage surface was defined as the central point (Fig. 2-A). Vertical lines 10 mm anterior and 10 mm posterior to the central point were drawn, and their intersections with the cartilage surface defined the anterior and posterior points, respectively (Fig. 2-A). These vertical lines were meant to represent the anterior-posterior boundaries for a 20-mm allograft. A best-fit circle was drawn that passed through the anterior, central, and posterior points, and its ROC was tabulated for analysis.

A similar protocol was used for the LFC, with the screen marker placed at a horizontal distance that was 68% of the LFC’s APL posterior to its most anterior cartilage margin. In clinical practice, surgeons do not normally harvest an LFC graft that includes the condyle’s flattened sulcus region. Accordingly, if the vertical line 10 mm anterior to the central point fell within the sulcus region of the LFC, a new (more posterior) vertical line was placed at the posterior sulcus boundary. In such instances, the intersection of this line with the cartilage surface defined a new anterior point for best-fit circle for the LFC (Fig. 2-B).

Assuming that the graft was flush to the edges of the surrounding native cartilage surface, the differences in the vertical distance of the central graft surfaces were calculated between different ROCs using a simple plane geometry formula, as shown in Figure 3, where \( r \) = radius of curvature, \( h \) = central graft height, and \( d \) = distance from center of circle to chord: 

\[
 h = r - \sqrt{r^2 - 100} 
\]

Clinically, this quantity represents the central graft prominence that would result if a donor graft with a smaller ROC were transplanted into a host condyle with a larger ROC.

**Statistical Methods**

A standard linear regression model was used for an analysis of ROC versus APL. Paired Student t tests were used to determine the significance of differences in mean ROC and mean APL.
between the MFC and the LFC and between measurement sessions (20 MRI scans). The significance level was set at $p < 0.05$.

Results

ROC Versus APL

The linear correlation between the ROC and APL was strong ($r^2 = 0.558$) for the MFC (Fig. 4-A) and moderate ($r^2 = 0.446$) for the LFC (Fig. 4-B). The slopes of the linear-regression lines were similar for both condyles (Fig. 4).

Differences Between Condyles in ROC and APL

The mean ROC was 31.9 mm (standard deviation [SD], 3.2 mm; range, 25.0 to 41.0 mm) for the MFC and 25.7 mm (SD, 3.3 mm; range, 18.6 to 35.8 mm) for the LFC. The mean APL was 66.6 mm (SD, 6.1 mm; range, 55.8 to 84.6 mm) for the MFC and 69.8 mm (SD, 5.9 mm; range, 60.5 to 87.2 mm) for the LFC. The mean ROC ($p < 0.001$) and APL ($p < 0.001$) values were significantly different between the condyles.

Intraobserver Variability

There were no significant differences in APL or ROC values between the measurement sessions (Table II). The mean differences in the intraobserver measurements of the APL and ROC were $+0.2$ mm (95% confidence interval [CI], $-0.4$ to $+0.8$ mm) and $+0.2$ mm (95% CI, $-0.6$ to $+1.0$ mm), respectively, for the MFC and $+0.02$ mm (95% CI, $-0.9$ to 0.9 mm) and $-0.5$ mm (95% CI, $-1.1$ to 0.2 mm), respectively, for the LFC.

Discussion

The main findings of this study were (1) the ROC was linearly correlated with the APL for both femoral condyles, (2) there were significant differences in the ROC and APL between the condyles, and (3) on the basis of central graft prominence calculations, an LFC donor graft would be suitable for an MFC defect in most cases.

One common criterion for accepting a graft for osteochondral allograft transplantation is the APL of the condyle. We found a strong linear correlation between the ROC and APL for the MFC. For the LFC, the correlation was only moderate, and this was presumably due to variability in the anterior point location that was included in the best-fit circle. As described in the Materials and Methods section, this anterior point was moved posteriorly (from the standard $110$-mm location) in some specimens to avoid placement within the sulcus region of the LFC.

Our finding that the ROC and APL of the lateral condyle differed significantly from those of the medial condyle agrees with the results of a prior study. Yue et al.23 constructed 3-dimensional (3D) computed tomographic (CT) models of 40

---

### Table II: Intraobserver Variability of Radius of Curvature (ROC) and Anterior-Posterior Length (APL) Measurements

<table>
<thead>
<tr>
<th></th>
<th>Medial Femoral Condyle</th>
<th></th>
<th>Lateral Femoral Condyle</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ROC (mm)</td>
<td>APL (mm)</td>
<td>ROC (mm)</td>
<td>APL (mm)</td>
</tr>
<tr>
<td></td>
<td>Mean and SD</td>
<td>Range</td>
<td>Mean and SD</td>
<td>Range</td>
</tr>
<tr>
<td>Original†</td>
<td>32.5 ± 3.6</td>
<td>25.7-41.6</td>
<td>68.1 ± 5.1</td>
<td>59.4-78.5</td>
</tr>
<tr>
<td>Remeasure†</td>
<td>32.7 ± 3.4</td>
<td>26.8-41.3</td>
<td>68.3 ± 4.7</td>
<td>60.1-77.7</td>
</tr>
</tbody>
</table>

*SD = standard deviation. †No significant differences between original and remeasure.
On the basis of ROC averages, a graft taken from the LFC and transplanted into the MFC would produce an average central graft prominence of \(0.4 \pm 0.3\) mm, and 92.5% of all lateral-to-medial transplantations would produce a central graft prominence of \(<1\) mm. This is within the currently accepted \(+1\)-mm central graft height tolerance, and our findings support the use of an LFC donor graft for an MFC defect. This finding is supported by clinical outcomes as well, with a study by Wang et al.\(^2\) showing no significant differences in clinical outcomes between patients treated with size-matched orthotopic or non-orthotopic osteochondral allograft transplantations. Similarly, although rare, a graft taken from the MFC and transplanted into the LFC would produce an average central graft depression of \(0.4 \pm 0.3\) mm.

One important limitation to this study was related to knee positioning for the MRI scans. MR technicians position all patients in the supine position, with the knee close to full extension. However, there was limited rotational control of the femur, and some knees could have been rotated from the true frontal and sagittal views of the femur. Femoral rotation was not a factor when measuring the APL because these measurements were made from an axial plane image. However, femoral rotation could have affected measurements of the ROC, which were made from a sagittal plane image. These errors were unavoidable and unknown. However, similar errors are also present for tissue banks that provide size-matched allografts that are based on patient MRI scans provided by the requesting physician. In addition, because of the large number of images assessed for this study, ROC measurement errors due to internal and external femoral rotation could cancel each other out and our mean ROC measurements would approximate the ideal femoral position.

Another study limitation was related to the analysis of ROC measurements from a single sagittal MRI scan. The position of this sagittal image was chosen such that the MRI scans for every patient at that standardized location would have a smooth, distinct articular cartilage surface for measurement. Our ROC measurements did not reflect the 3D contours of the condyle's surface and, in particular, its curvature in the coronal plane. Similarly, our central graft height calculations do not reflect potential graft prominence in other sectional planes.

There were several strengths to our study. Our analysis included a relatively large sample group of patients, providing strong statistical power. ROC measurements were made at standardized locations on the femoral condyles that are representative of common focal defects seen in patients. The relationship between ROC and APL, differences in ROC and APL between the condyles, and calculated central graft prominence values for same-condyle and cross-condyle implantations have direct bearing on decisions related to donor-host acceptance criteria for large femoral allografts.

In conclusion, in common clinical practice, a central graft prominence of \(+1\) mm is tolerated. According to central graft prominence calculations using ROC differences, all medial orthotopic and the vast majority of lateral orthotopic

knees of patients from a Chinese population to measure differences in distal femoral APL and ROC. They found that, on average, the LFC had a larger APL than did the MFC (62.0 versus 58.7 mm). They also measured the ROC of various distal femoral locations. Their defined "distal circle" encompassed the region we measured in our study. They found that the MFC distal circle had a larger ROC compared with the LFC (35.6 versus 30.2 mm).

The use of the ROC to determine the suitability of a donor-host match for osteochondral allograft transplantation has been studied previously. Bernstein et al.\(^1\) performed 3D reconstructions of 14 human cadaveric distal femoral condyles to determine if matching on the basis of ROC would increase the number of acceptable donors. They defined a donor graft as acceptable if its height was within \(\pm 1\) mm of the surrounding cartilage surface. The authors found an 84% and 69% rate of match for the MFC and LFC, respectively, by the ROC method compared with a 24% rate of match for each by conventional matching criteria, where orthotopic pairs were matched by APL and medial-lateral length tolerances within \(\pm 2\) mm. We found a much higher match rate of 100% and 97.8% for orthotopic medial and lateral transplantations, respectively. This difference in findings could be due to differences in ROC measurements (bone surface versus articular cartilage surface). In addition, Bernstein et al. examined differences in graft prominence along the entire surface of the graft, while we calculated graft prominence from a single sagittal view\(^1\).

Mologne et al.\(^2\) studied 20 medial and 20 lateral human cadaveric femoral condyles to determine if an LFC allograft implanted into a recipient MFC could provide a favorable cartilage surface contour when compared with use of an MFC allograft. They utilized micro-CT imaging to measure height differences between the original intact surface and the transplanted graft, and defined a graft as acceptable if the height difference between the donor graft and the recipient condyle and the average circumferential step-off was within \(\pm 1\) mm. They found no significant differences in acceptable grafts between MFC and LFC donors to an MFC recipient, with an average central graft prominence of 0.63 mm for each. These results compare well with our calculated mean central graft prominence of \(0.4 \pm 0.3\) mm for this situation.

For our sample group of 147 patients, we found that 100% of potential medial-to-medial mismatches in ROC and 97.8% of potential lateral-to-lateral mismatches in ROC would produce a central graft prominence of \(<1\) mm. On the basis of these findings, the current APL tolerance of up to \(\pm 5\) mm between a host and a donor condyle may be far too restrictive in terms of potential central graft prominence. Although it is impossible to generalize our results, we believe that, because of the large number of patients measured, our APL and ROC ranges are good approximations for the general population. Therefore, if the findings for our sample group hold true for the general population, the potential pool of allografts could be expanded greatly and potentially reduce patient wait times for an appropriate allograft.

For our sample group of 147 patients, we found that 100% of potential medial-to-medial mismatches in ROC and 97.8% of potential lateral-to-lateral mismatches in ROC would produce a central graft prominence of \(<1\) mm. On the basis of these findings, the current APL tolerance of up to \(\pm 5\) mm between a host and a donor condyle may be far too restrictive in terms of potential central graft prominence. Although it is impossible to generalize our results, we believe that, because of the large number of patients measured, our APL and ROC ranges are good approximations for the general population. Therefore, if the findings for our sample group hold true for the general population, the potential pool of allografts could be expanded greatly and potentially reduce patient wait times for an appropriate allograft.
transplantations would be acceptable regardless of ROC or APL differences within our knee sample group. This means that the ROC and APL were not important criteria for donor-host matching at this defect site location. Finally, our findings support the implantation of an LFC donor graft into an MFC defect. In light of these results, current clinical criteria for size-matching of large osteochondral grafts may need to be reconsidered.

Peter Z. Du, MD1
Keith L. Markolf, PhD2
Benjamin D. Levine, MD2

References