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Overlapping Allografts Provide Superior and More Reliable Surface Topography Matching Than Do Oblong Allografts

A Computer-Simulated Model

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INTRODUCTION

Focal cartilage defects of the knee can result in pain, swelling, and mechanical symptoms, with the potential to cause clinically significant disability.[1] Surgeons generally turn to surgical intervention when conservative measures fail and symptoms persist. Although several surgical options are available, physicians base treatment algorithms primarily on lesion size and location.[2] Surgeons widely use osteochondral allograft (OCA) for symptomatic focal chondral defects of the knee and often select this procedure for patients who are young and athletic. OCA transplant offers immediate structural support and articular surface integrity, restores hyaline cartilage, and may be more suitable for lesions with poor containment or subchondral bone involvement.[3-7]

Study results have shown that OCA transplant has good long-term outcomes, with subjective improvement seen in 75% of patients and an overall 85% graft survival rate 10 years postoperatively.[3,8,9] However, large, irregular, or ovoid cartilage lesions can not only increase operative complexity but also be associated with inferior patient outcomes.[10] Surgeons can manage these large, irregular chondral defects with different grafting techniques, including a single, oblong allograft plug or multiple overlapping cylindrical allografts. Graft mismatch producing even minor areas of articular incongruity (proud or sunken areas) can alter cartilage contact pressures significantly and lead to failure of graft integration.[11] Thus, articular congruity between native and graft cartilage plays an integral role in procedural technique during OCA transplant. A paucity of literature exists in which investigators specifically evaluate which graft method (oblong or overlapping) produces a more native articular environment. Therefore, the purpose of this study was to compare topographical mismatch and step-off of cartilage and subchondral surfaces between a single, large oblong graft and multiple overlapping grafts. We hypothesized that the overlapping graft configuration would produce better subchondral and cartilage surface congruity with surrounding native tissue, as well as less articular step-off when compared with a large oblong graft. We reached this hypothesis because of the theoretical ability for 2 overlapping grafts, compared with a single, large oblong graft, to provide a more similar radius of curvature (ROC) to the recipient.

MATERIALS AND METHODS

A tissue bank (AlloSource, Denver, Colorado) donated 12 cadaveric medial hemicondyle specimens with intact articular cartilage from 12 individual donors, which we used for this study. We based the sample size on those of previous studies we have published in which we used similar methodology.[12-14] We use the same group of 12 hemicondyles to analyze both types of OCA grafts (overlapping and oblong). All included hemicondyles were free of preexisting osteochondral disease, including osteoarthritis or chondromalacia. An overview of the methodology is as follows: we will obtain computed tomography (CT) scans for the cadaveric specimen and will use them to create 3D models of the articular surface and subchondral bone. We then will create 2 different types of defects and grafts (oblong and overlapping) virtually on these models, and we will perform topography matching analysis for multiple combinations of these defect-graft models. We explain these steps in detail within the following sections. The institutional review board at the participating institution, Rush University Medical Center, granted this study exemption because of the use of deidentified cadaveric specimens.

Three-dimensional Computed Tomography Computer Model Creation of the Distal Femoral Articular and Subchondral Surfaces

We used a computed tomography (CT) unit (BrightSpeed; GE Healthcare, Wauwatosa, Wisconsin) to scan 0.625-mm, continuous sections of the distal femoral hemicondyles in the coronal, axial, and sagittal planes (120 kV, 100 mA, 1.0-mm/second duration, 20-cm field of view, 512 × 512 matrices). We then created separate, 3-dimensional (3D) CT models of the articular cartilage surface and subchondral surface of each hemicondyle and exported them into polygon and point-cloud models (at a density of 2.3 points/mm^2) by using a 3D-reconstruction software program (Mimics; Materialise Inc., Leuven, Belgium). We used custom-written programs coded in Microsoft Visual C++ with Microsoft Foundation Class programming environment (Microsoft Corp.; Redmond, Washington) to create both oblong and overlapping allograft matching, as described separately in the following sections.

Computer Defect and Graft Model Creation

Oblong Defect and Graft Models

We created oblong articular cartilage defect and graft models with an oval shape (17.0 × 30.0 mm) in the medial distal femoral condyle (Figure 1). We selected this size because it is a common clinically observed defect: a medium-sized defect centering on a primary weight-bearing area. Furthermore, we specifically chose the 17.0 × 30.0-mm size because it corresponds to a commonly used, commercially available template for a medium-sized oblong graft. For each distal femoral condyle, we determined the centroid of the oval shape to be the most distal point of the articular cartilage surface, a primary weight-bearing focus of the condyle, and a common location of an osteochondral defect (Figure 2).[12-14] We then created subchondral bone defect and graft models on the same location as the articular cartilage defect and graft models. When we projected the oval shape of articular cartilage onto the subchondral bone surface, we defined the polygon and point-cloud data within the area as the data set of the defect and graft models.

Overlapping Defect and Graft Models

We harvested 2 circular osteochondral grafts (anterior and posterior, 17.0 mm in diameter) virtually from the medial femoral condyle. We obtained the grafts from any possible location along a center line of the femoral condyle separated by 5.0 mm to avoid convergence of the subchondral plugs at convex areas of the femoral condyle.[14]

We created overlapping defect and graft models at the same location as for the oblong defect. The shape of the overlapping grafts defect was the same at both hemicircular ends of the oblong defect model, having 2 circles 17.0 mm in diameter with 4.0 mm overlap (Figures 1 and 2). The area of the overlapping grafts defect was approximately 5% smaller than that of the oblong defect.

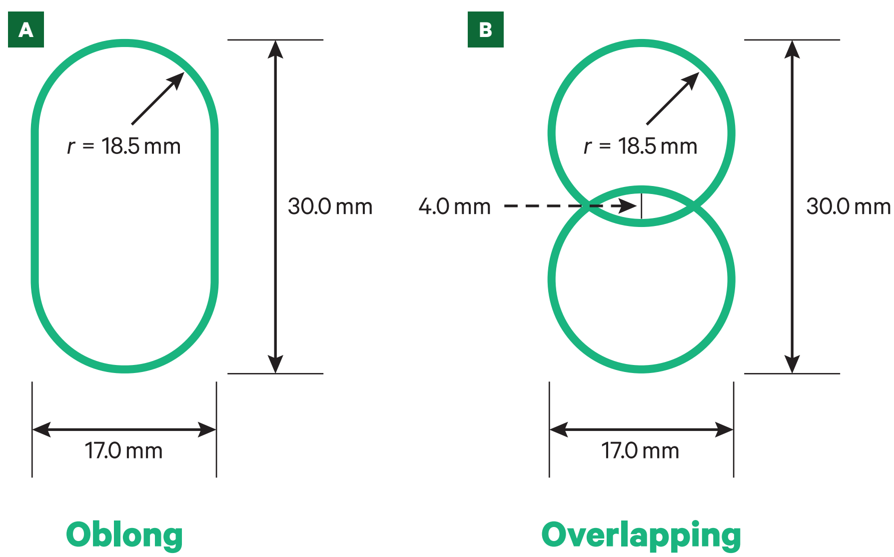

Figure 1. Oblong and Overlapping Defect and Graft Models. We created oblong and overlapping defect and graft models with a radius of 8.5 mm in the medial distal femoral condyle. **A,** For the oblong graft models, we created an oval shape, 17.0 × 30.0 mm. **B,** For the overlapping graft models, we created 2 circles, 17.0 mm in diameter, with 4.0 mm overlapping (dashed arrow).

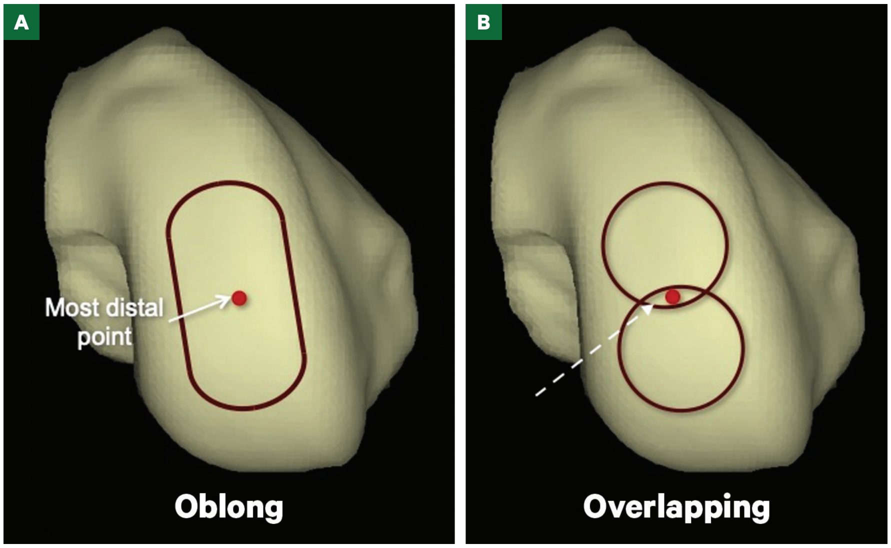

Figure 2. Determination of Centroid and Most Distal Point. **A,** For oblong models, the centroid of the oval shape is the most distal point of the articular cartilage surface in each distal femoral condyle (arrow and dot). **B,** For overlapping graft models, the overlapping circles are positioned such that the most distal and centroid point is in the center of the overlapping portion of the circles (dashed arrow and dot).

Three-dimensional Articular and Subchondral Surface Topography Matching

Oblong Defect and Graft Models

We compared the articular cartilage surface of the oblong defect model with the cartilage surface of the oblong graft model in each combination. Including all groups, we simulated 132 recipient-donor combinations: 12 defect models and 11 graft models. We placed the oblong graft model virtually on the oblong defect model and then adjusted orientation of the graft model to match the most anterior and posterior points of the graft model with those of the defect model. We calculated each point-plane distance between the articular cartilage surfaces of the defect and graft models so that we positioned the graft model optimally to minimize surface mismatch with the defect model.[13-15] Then we measured the shortest distance from the point in question on the defect model to the corresponding point in space on the graft model as the mismatch between the 2 models. A perfect congruent match would equal a mismatch of 0 mm for given data points on the simulated articular surface. We calculated a mean value of the mismatch for each combination. We simultaneously calculated articular cartilage step-off as the point-plane distance at the periphery between the defect and graft models. We calculated the shortest point-plane distance between the subchondral bone surfaces of the defect and graft models as the mismatch of the subchondral bone. We performed these calculations on all combinations of simulated graft models and recipient models.

Overlapping Defect and Graft Models

We compared 3D surface topography between the defect and graft articular surfaces for 132 defect-graft comparative combinations: 12 defect models and 11 graft models. We placed the anterior articular surface graft model virtually on the anterior articular cartilage defect surface so that the centroid of both models merged. We then performed defect-graft 3D articular cartilage surface topography matching by using the previously reported procedures.[13-15] We calculated and recorded the distribution of least mean square distances between the defect and graft surfaces. Then we rotated the defect model 360° around the axis perpendicular to the articular cartilage surface in 1° increments and calculated the least distance at each rotating angle. We calculated the least distance at each position and defined the best match as the minimum least distance value. We then applied the same procedure to the posterior graft. We defined a mean value of the anterior and posterior least distances as the best-match value of the cartilage graft model. We repeated these procedures for all graft positions throughout the distal femoral condyle and defined the graft with the minimum value as the best-match graft. We calculated the step-off values at the graft-recipient distal femoral condyle articular cartilage surface junctions. We calculated the subchondral bone surface matching in a similar manner by using the best-matched anterior and posterior grafts.

Statistical Analysis

We performed all quantitative statistical analysis by using software (Stata v13; StataCorp LLC, College Station, Texas; and Excel; Microsoft Corp., Redmond, Washington). We used paired *t* tests to compare mismatch and step-off differences between the oblong and overlapping grafts groups. We used a Fisher exact test to compare the number of minimally clinically adequate allografts (at thresholds of 0.5 and 1.0 mm) between the overlapping and oblong groups.[14,16,17] Finally, we performed an F test to analyze differences in variance between each group. We set significance at $P < .05$.

RESULTS

We included 12 femoral condyles in the final analysis. We tested each donor defect with a graft from each of the remaining condyles, resulting in 132 (12 defect models × 11 graft models) tests for both the oblong and overlapping grafts groups. Table 1 shows the least mean square distances for cartilage and subchondral topographical mismatch and cartilage step-off for the overlapping and oblong groups. The overlapping group had significantly less cartilage ($P < .001$) and subchondral ($P < .001$) topographical mismatch, as well as articular cartilage step-off ($P < .001$), when compared with the oblong group (Figure 3).

We analyzed the distributions of least mean square distances of cartilage and subchondral topographical mismatch and cartilage step-off. When compared with the oblong group, the overlapping group illustrated significantly less variance in cartilage topography matching ($P < .001$), subchondral topography matching ($P < .001$), and cartilage step-off ($P < .001$) (Figures 4 and 5).

We analyzed overlapping and oblong grafts on the basis of 2 clinically relevant thresholds of mismatch and step-off: least mean squares of 0.5 mm and 1.0 mm. At a threshold of 1.0 mm, overlapping and oblong grafts demonstrated significant differences in the percentage of grafts meeting clinically acceptable step-off ($P < .001$), cartilage topographical matching ($P < .001$), and subchondral topographical matching ($P < .001$) (Table 2). The risk of oblong grafts having a clinically unacceptable difference defined at 1.0 mm in mismatch of cartilage surface incongruity was 10% ($P < .001$). In addition, at a clinically acceptable threshold of less than 0.5-mm mismatch and step-off, overlapping grafts were more likely to be under this threshold for both surface topography matching ($P < .001$) and step-off ($P < .001$) (Table 3). Here, the risk of oblong grafts having a clinically unacceptable difference of cartilage surface mismatch of greater than 0.5 mm was 44% ($P < .001$). All subchondral mismatches were greater than 0.5 mm in both groups. Because no overlapping grafts had a clinically unacceptable cartilage surface topography or step-off exceeding either the 0.5- or 1.0-mm threshold, we could not calculate a risk ratio between oblong and overlapping grafts.

Table 1. Least Mean Square Distances for Cartilage and Subchondral Topographical Mismatch and Cartilage Step-off for Oblong and Overlapping Grafts

Variable	Cartilage Mismatch	Subchondral Bone Mismatch	Cartilage Step-off
Overlapping	0.27 (0.02)	0.80 (0.19)	0.32 (0.04)
Oblong	0.62 (0.43)	1.49 (1.10)	0.77 (0.23)
P Value	< .001	< .001	< .001

Data are presented as mean (SD) and in millimeters.

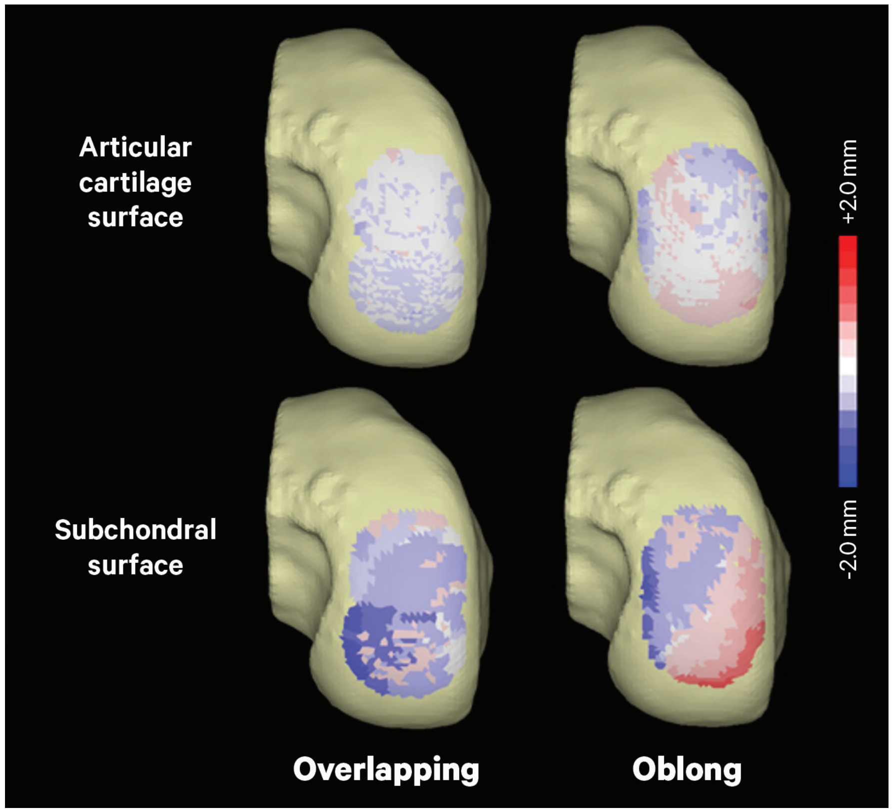

Figure 3. Example of Articular Cartilage and Subchondral Bone Topographic Matching on a Medial Femoral Hemicondyle With Overlapping and Oblong Defect-graft Models. Blue denotes negative mismatch (sunken graft); red denotes positive mismatch (proud graft).

DISCUSSION

In this study, we sought to compare surface topography matching and step-off in a computer-simulated model of matching oblong and overlapping OCA grafts to osteochondral defects of cadaveric medial femoral condyles. We found that overlapping grafts provided surface topography matching statistically significantly superior to that of oblong grafts for both articular cartilage and subchondral bone. In addition, overlapping grafts provided smaller cartilage step-off distances than did oblong grafts. Furthermore, we found that overlapping grafts provided more consistent and clinically reliable results, whereas oblong grafts demonstrated greater variance between surface topography matching and articular step-off data.

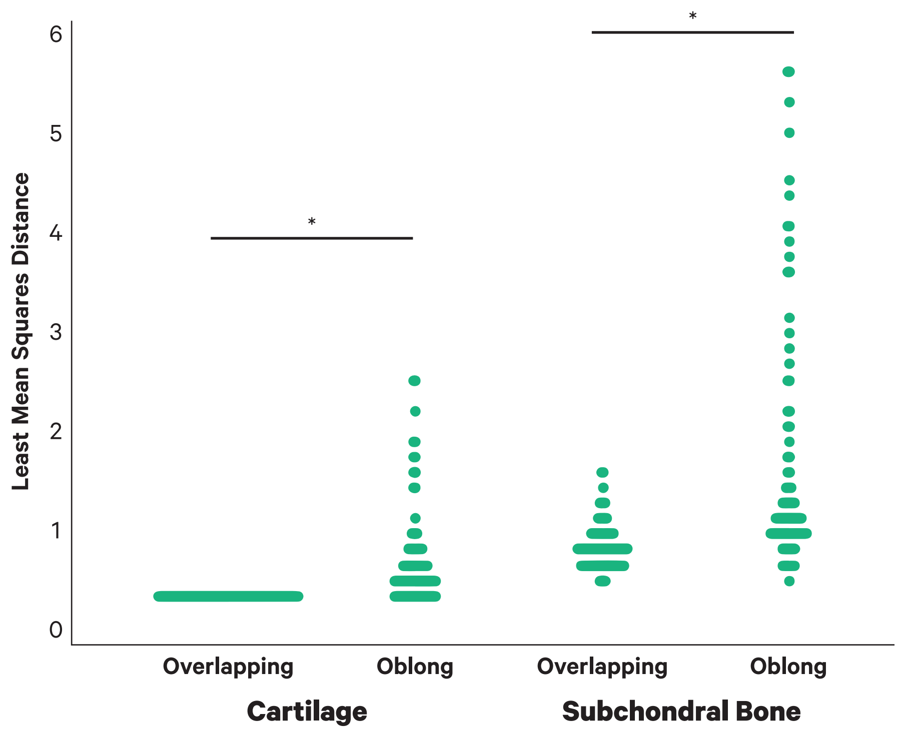

Figure 4. Least Mean Square Distances for Cartilage and Subchondral Bone Topographical Mismatch in Overlapping and Oblong Grafts.
*denotes $P < .001$.

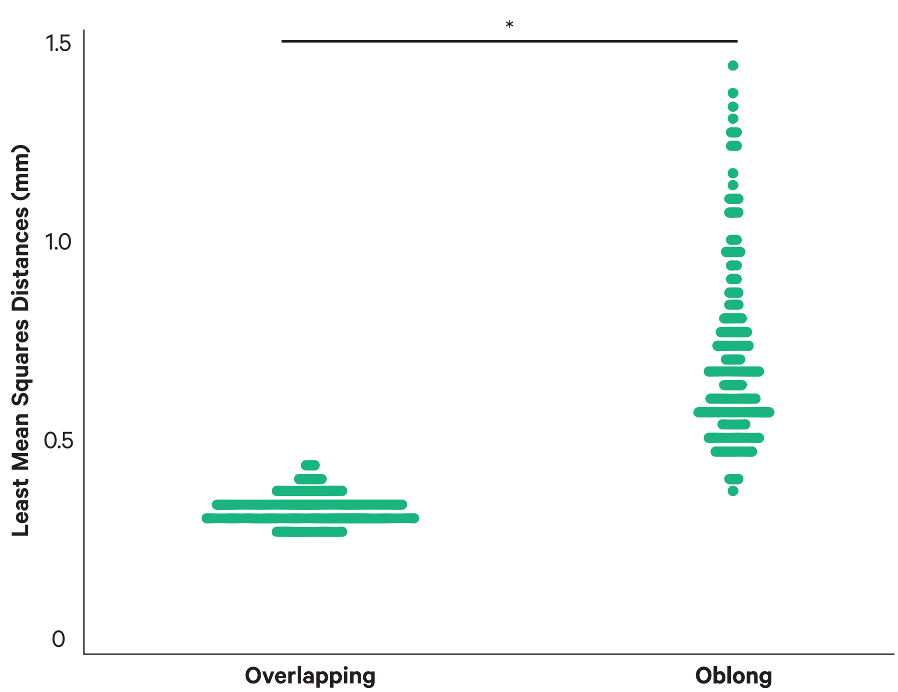

Figure 5. Least Mean Square Distances for Articular Cartilage Step-off in Overlapping and Oblong Grafts.
*denotes $P < .001$.

A mismatched OCA graft can have significant subsequent effects on the biomechanics of the knee joint. In an early study, Koh et al[11] found that peak contact pressures increase significantly when there is surface incongruity (0.5- and 1.0-mm differences) between the graft cartilage and the surrounding recipient cartilage in swine knees. They found significant increases in contact pressure with both sunken ($P < .01$) and proud ($P < .01$) grafts compared with intact cartilage at both 0.5 and 1.0 mm. In another study, Du et al[17] investigated how a large (> 20 mm) proud graft influences tibiofemoral contact forces in a cadaveric model. They found that increasing the proudness of a medial OCA graft in 20° of flexion by 0.5, 1.0, and 1.5 mm resulted in an increase in contact pressures of 80 N (36%), 155 N (70%), and 193 N (87%), respectively. The researchers observed a similar trend, although to a lesser degree, in the lateral compartment (0.5 mm, +44 N; 1.0 mm, +90 N; 1.5 mm, +118 N). In a finite element analysis of contact pressures before and after OCA implantation, D'Lima et al[18] found that although an OCA restores contact pressure to near-anatomic levels, a graft that is as little as 0.25 mm proud can produce increases in peak contact stresses, with a graft that is 0.5 mm proud nearly doubling the contact pressure of the native joint (6.7 vs 3.4 MPa).

Despite study results suggesting that even 0.25 mm of surface incongruity may result in altered contact pressures, the clinical consequences remain unclear. On the basis of current literature, we chose to use 2 thresholds of mismatch and step-off differences, 0.5 and 1.0 mm, to determine whether the topographic matching was clinically acceptable. In a previous study, we reported minimal differences in surface topography when using lateral femoral grafts for medial femoral defects, with "minimal" defined as less than 0.5 mm.[12,14] In contrast, Du et al[19] reported that 97.8% of lateral-to-lateral and 92.5% of

Table 2. Differences Between Overlapping and Oblong Grafts in Providing Clinically Acceptable Significant Step-off or Mismatch at Least Mean Square Distances Less Than 1.0 mm

Variable	Step-Off	Matching		
		Cartilage	Subchondral Bone	Both
Overlapping, No. (%)	132 (100)	132 (100)	115 (87)	115 (87)
Oblong, No. (%)	114 (86)	119 (90)	56 (42)	56 (42)
P Value	< .001	< .001	< .001	< .001

Table 3. Differences Between Overlapping and Oblong Grafts in Providing Clinically Acceptable Significant Step-off or Mismatch at Least Mean Square Distances Less Than 0.5 mm

Variable	Step-Off	Matching		
		Cartilage	Subchondral Bone	Both
Overlapping, No. (%)	132 (100)	132 (100)	0	0
Oblong, No. (%)	16 (12)	74 (56)	0	0
P Value	< .001	< .001	—	—

lateral-to-medial combinations would result in a clinically acceptable surface mismatch, with clinical acceptability defined as < 1.0 mm. There is no consensus on a clinically allowable amount of graft incongruity because of the scant amount of clinical literature on the effects of a proud or sunken graft. Therefore, on the basis of these studies, biomechanical studies, and the clinical experience of the senior authors, we evaluated oblong and overlapping grafts at 0.5- and 1.0-mm thresholds for determining clinically acceptable mismatch. In this study, cartilage surface incongruity ranged from 0.22 to 0.34 mm and from 0.29 to 2.48 mm for overlapping and oblong grafts, respectively. Thus, all overlapping grafts were clinically acceptable at both thresholds, whereas 90% of the oblong defect-graft pairs met the 1.0-mm threshold, and only 56% met the 0.5-mm threshold.

Investigators in previous studies have demonstrated that the ROC of the distal femoral condyles linearly increases from the posterior to the anterior aspect of the femoral condyle.[19] Thus, a large cartilage defect such as those used in this study involve a range of ROCs. However, despite this linear relationship, study results have shown that ROCs vary greatly across femoral condyle donors, which can complicate finding an ideal defect-graft match.[20] Because of the large range of ROCs within a defect, it is understandable that it would be more challenging to fit a single, large graft appropriately from a donor who may have differing ROCs from the recipient instead of 2 smaller grafts that can be harvested from 2 different areas with differing ROCs. The 2 grafts together can minimize the overall difference in ROCs, thereby minimizing average cartilage surface incongruity. These findings suggest that properly matching a femoral defect to an adequate femoral graft, which could involve matching based on the ROC, requires a thorough process. We randomly selected the hemicondyles used in this study from a large research bank and made no effort to match these samples on the basis of size or ROC. However, oblong grafts may provide improved and clinically adequate surface topography matching if the defect is matched to a hemicondyle on the basis of various factors such as size and ROC. Researchers in future studies should investigate and define a matching process that could render oblong grafts more viable in terms of surface topography matching.

Large osteochondral defects result in a substantially more complex surgical procedure. Therefore, understanding the advantages and disadvantages for each graft technique is essential.

A main advantage to using an oblong graft is eliminating the number of interfaces that need to incorporate, possibly decreasing synovial fluid penetration that may lead to loosening and cyst formation. However, literature on overlapping graft failure and incorporation remains limited. In contrast, using the oblong allograft is a more technically demanding procedure with minimal spare allograft tissue because of the amount of tissue needed to perform the transplant. The current study's results suggest that another disadvantage to using an oblong graft is that it may result in inferior surface topography matching compared with that of an overlapping approach. However, harvesting and implanting multiple plugs in an overlapping approach may lead to cyst formation, as mentioned. Although this study's results suggest that multiple overlapping grafts provide improved surface topography matching, this result may be difficult for surgeons to achieve consistently. In the operating room, obtaining a good fit has as much to do with diligent measuring, cutting, and impaction as it does with the native topography of the graft. This study provides evidence that a perfectly executed overlapping graft is more likely to result in adequate surface topography matching, but how this translates to the operating room remains unclear.

There is a paucity of clinical outcome literature on graft approaches for large, irregular defects. Study results have shown lower graft survival rates in this clinical scenario (64.1%-66.7% at minimum 2 years), especially when compared with those for smaller, uniform defects (87.5% at 5 years).[10,21,22] Despite this lack of data, investigators in previous clinical studies have recommended the use of overlapping grafts for large defects and have shown improvement of statistical significance in postoperative, patient-reported outcomes.[10] However, there is scant literature available on the clinical outcomes of using an oblong graft, making it almost impossible to compare clinical outcomes directly for these 2 approaches. Although this study's results support the use of multiple smaller grafts instead of a single, large oblong graft for large, irregular defects, it is unclear how improved surface matching correlates with clinical outcomes and failure rates. This information is useful for any orthopedic surgeon who performs complex OCA procedures. Future clinical studies are needed to investigate the effect of cartilage surface incongruity on clinical outcomes.

Although the results of the present study provide insight into grafts for large osteochondral defects, there are several important limitations to consider when interpreting these results. The most substantial limitation is that we performed all analyses virtually, on computer models of cadaveric femoral hemicondyles. Whether surgeons can reproduce the same results in vivo remains unclear. However, computer simulations are common, and physicians have used them previously to test various defect and graft matching within the knee and shoulder; thus, we believe our computer-simulated findings are useful in understanding and potentially influencing graft choices. In addition, our measurements were limited to surface topography mismatch and step-off analyses. Other differences between the grafts may exist outside of the tested variables of this study. Furthermore, we used threshold cutoffs of 0.5 and 1.0 mm to define clinically acceptable surface mismatch and articular step-off, which we based on the senior authors' surgical experience and previously published literature.[14,16,17] However, it remains unclear whether a higher or lower cutoff would be more clinically relevant. Lastly, in this study, we do not address any biomechanical or clinical outcome differences between oblong and overlapping grafts. Thus, one should use the findings of this study in conjunction with existing biomechanical and clinical literature on graft selection.

CONCLUSIONS

Overlapping allografts provided reliably superior cartilage and subchondral topographical matching and decreased cartilage step-off compared with results with oblong allografts in a 3D point-cloud model. These findings suggest that overlapping grafts may be superior in treating large, osteochondral defects involving the femoral condyles. ✤

References and financial disclosures are available online at www.rush.edu/orthopedicsjournal.