Introduction

Chondral and osteochondral lesions in the articular surface of the knee are injuries frequently encountered in clinical practice. Because of the inadequate healing response of cartilage, defects of a critical size may lead to osteoarthritis if untreated. Most commonly used treatment options for defects include microfracture, autologous chondrocyte implantation (ACI), and autologous osteochondral transplantation, also known as mosaic arthroplasty.

In a prospective randomized clinical study, Gudas et al. found significantly better clinical outcomes and histology using autologous osteochondral transplantation compared with microfracture. The study found excellent or good post-operative results in 96% of the patients treated with autologous osteochondral transplantation compared with 52% of the patients treated by microfracture. Horas et al. concluded, from a study of 40 patients, that autologous osteochondral transplantation resulted in a faster recovery than ACI. This
result is in contrast to a study conducted by Bentley et al.,22 who found excellent or good results in 88% of the ACI patients compared with 69% for autologous osteochondral transplantation patients. Dozin et al.,23 on the other hand, found no difference between both techniques in a randomized trial. Recent reviews of randomized and controlled trials24,25 to compare the effectiveness of different cartilage repair methods concluded that, at this point, there is insufficient evidence concerning the relative effectiveness of ACI or autologous osteochondral transplantation.

Various studies have demonstrated the importance of creating a congruent, continuous joint surface using autologous osteochondral transplantation to optimize outcomes.26-28 Donor sites accessibility and the variation in the radius of the femoral condylar curvature29 make re-creation of a congruent joint surface challenging when using multiple small grafts. Sanders et al.30 found in 2-week postoperative MRI evaluations of 21 autologous osteochondral transplantation patients that only one patient had surface congruency, whereas 16 patients had mild, 2 patients moderate, and 1 patient marked surface incongruency over the defect. This raises the question of whether improved intraoperative methods that help the surgeon to achieve higher accuracy in harvesting and delivery of grafts might improve the outcome of autologous osteochondral transplantation procedures. Kouhalis et al.31 compared the outcome of optoelectronically navigated procedures versus freehand autologous osteochondral transplantation procedures in three cadaveric knees and found improved accuracy in the navigated procedures for the perpendicularity of graft removal and placement, as well as for the depth of graft placement. A limitation of this study was the use of in vitro specimens: the authors could not evaluate whether this improved accuracy influenced the clinical outcome.

Although the use of optoelectronic technology for image-guided knee applications has had gratifying results, this technology has some drawbacks: additional technical equipment (optoelectronic camera, PC) is required in the operating theater and an intraoperative registration process is required to find the correspondence between the image data and the patient. To overcome these drawbacks, recent research in the area of image-guided surgeries has used patient-specific templates.31-34 The idea is to build custom surgical templates based on a three-dimensional reconstruction of the patient’s specific anatomical structures. In the trial presented here, we investigated the application of two image-guided systems for autologous osteochondral transplantation, one system using optoelectronic tracking and the other system using patient-specific templates, and compared the short-term clinical outcome for both systems with the conventional freehand method. The purpose of the pilot study presented here was to investigate whether image-guided methods can help improve the outcome of autologous osteochondral transplantation procedures.

**Methods**

Fifteen mature sheep were randomly assigned to one of three treatment groups. For each sheep, one treatment and one control knee was randomly assigned. All sheep underwent an initial computer tomography (CT) arthrogram (LightSpeed Plus, GE Healthcare, Waukesha, WI) in helical mode, with a slice thickness of 0.625 mm at 140 kVP, followed by a procedure to create a traumatically induced cartilage defect in the medial condyle of both knees (cartilage defect surgery). During a second procedure 4 months later, one of three repair procedures was performed (cartilage repair surgery). Three months after the repair surgery, the sheep were euthanized. Both the treatment knee and the control knee were harvested and the outcomes were evaluated. This study was performed with approval from the University Animal Care Committee at Queen's University and the University of Guelph.

The cartilage defect surgery was performed through a 2-cm infrapatellar arthrotomy using spring-loaded impactor to create chronic chondral defects on anterior central weightbearing region of the medial femoral condyles in both knees of each sheep as per previous reports.35 After routine closure of the arthrotomy, sheep were recovered and allowed exercise in large pens. These 4.5 to 7 mm diameter injuries increased in size over 3 months, resulting in an irregularly shaped chondral lesion that was debrided to a minimum 7 mm diameter full thickness chondral defect in a second surgery 4 months later (7 mm is reported as the minimum defect dimension that sheep are incapable of repairing without intervention). Reconstruction was performed with one of the three following techniques: (a) conventional freehand technique, (b) optically guided technique, and (c) template-guided technique. All surgeries were carried out by the same surgeon who was experienced in autologous osteochondral transplantations. The autologous osteochondral transplantation system from Smith and Nephew Endoscopy (Mosaicplasty, Andover, MA) was used for all surgeries. For all procedures, a medial parapatellar arthrotomy was performed and the patella was luxated laterally to expose the donor sites in the medial and lateral trochlear ridges as well as the medial femoral condyle recipient site.

**Conventional Surgical Technique**

The conventional osteochondral grafting technique was performed as described by Hangody and Kárpáti.37 During the surgery, 4.5 mm osteochondral grafts were harvested from the axial aspect of the medial trochlear ridge for
transplantation into the medial condyle. The surgeon determined the location of donor and recipient site at the time of the surgery, optimizing the fit and congruency by eye.

**Optically Guided Technique**

The optically guided procedure consisted of preoperative planning and intraoperative guidance. Prior to the surgery, a CT arthrogram scan for the treatment knee was obtained. All scans were performed after the injection of an iodinated contrast material and were obtained with a LightSpeed Plus (GE Healthcare, Waukesha, WI) in helical mode, with a slice thickness of 0.625 mm at 140 kV. Three-dimensional (3D) surface models for bone and cartilage were created using the commercial software package Amira (Visage Imaging Inc., Carlsbad, CA).

Custom-made surgical planning software for osteochondral grafting was developed. The 3D surface models as well as the CT dataset were loaded into the software and displayed (Fig. 1a). The operator created a surgical plan consisting of a set of osteochondral grafts (“plugs”) positioned over the defect site. The 3D position and orientation of each plug, as well as its shape (diameter, height, and surface slope), were chosen by the operator to best reconstruct the desired articular surface at the defect site (Fig. 1b).

For each plug, a harvest location was chosen to best match the shape of the plug. The plugs could be rotated axially so that the sloped surface at the harvest site could be made to match the sloped surface at the defect site. The operator validated the surgical plan by superimposing the plugs on the 3D models and by superimposing the plugs on three orthogonal slices of the CT dataset (Fig. 1a).

A Polaris optoelectronic tracker (Northern Digital, Waterloo, Canada) was installed in the operating theatre (Fig. 2a) and a tracking sensor was rigidly attached to the femur (Fig. 2c). Tracking sensors were attached to conventional harvest chisels and drill guides. A special retractable attachment was required for the harvest chisel because the heavy impacts made to the chisel would dislodge a conventionally attached sensor (Fig. 2d).

A registration was made between the sheep femur and the 3D bone model of the femur using a combined pair-point and surface matching algorithm. Using visual feedback from the computer-guidance system, the surgeon used a tracked pointing device to locate the planned harvest site of a plug and, using a sterile pen, marked an axial rotation reference on the cartilage surface of this plug. This mark allowed the surgeon to keep track of the rotation of the plug between harvesting and delivery. Using visual and numerical feedback on the display, the surgeon positioned and oriented the harvesting chisel on the cartilage according to the preoperative plan (Fig. 2b). The surgeon then drove the chisel into the cartilage and bone until the guidance display indicated that the correct depth was reached. Then the graft was harvested.
After each graft was harvested the surgeon positioned and aligned, in a similar manner, the tracked drill guide over the planned recipient site and the recipient hole was drilled. The depth of the hole was navigated using the conventional depth indicator at the drill bit. The harvested plug was inserted into the drill guide in such a way that the rotation mark of the plug was aligned with the calibrated upward direction of the drill guide. Using the visual feedback of the guidance system, the drill guide was then axially rotated until the planned rotational position of the graft was reached and the graft was carefully inserted into the recipient hole. This procedure was repeated for each planned graft.

**Template-Guided Technique**

The template-guided procedure consisted of preoperative planning, template construction, and intraoperative guidance. The surgery was planned identically to the optically guided procedure.

A set of individualized templates was built for each knee, containing one “marking guide,” one “harvesting guide,” and one “delivery guide” for each planned plug. The underside of each template was shaped to exactly match part of the surface of the knee (Fig. 3), using the information from the prerepair CT arthrogram. By this means, the planned position of the template could be correctly reproduced intraoperatively by adjusting the position of the template until an exact fit with the cartilage surface was achieved. Each template was built out of thermo-plastic acrylonitrile butadiene styrene (ABS) on a rapid prototyping machine (dimension SST; Statasys Inc., Eden Prairie, MN).

The marking guide was designed to fit into the femoral patella groove and contained, for each plug, a hole at the planned harvest site of the plug. Each hole had on its circumference a small indicator bump; the surgeon would draw a radial line on the cartilage surface at the location of the indicator. The line allowed the axial rotation of the plug to be tracked.

The harvesting guide was designed to fit into the femoral patella groove and contained, for each plug, a guidance cylinder for the harvesting chisel (Fig. 3a). The height of each cylinder was chosen to stop the chisel after the chisel had been inserted to the planned depth (Fig. 3c).

Each delivery guide fit to the medial femoral condyle at the location of the defect and contained a single guidance
Kunz et al.

157
cylinder. The conventional drill guide fit into the guidance
cylinder to guide the drill bit during drilling and to guide the
plug during delivery.

Rotation marks at the guidance holes (Fig. 3b) ensured
that the harvested plug was delivered with the correct rota-
tional alignment with respect to the plug axis.

After the conventional incision was made, the mark-
ing guide was positioned on the knee and a rotation refer-
ence mark was made for each plug. The harvesting guide
was placed on the knee and fixated with two 2-mm
Kirscher wires. Using the guidance cylinders, all plugs
were harvested and stored in numbered containers
(Fig. 4a). For each plug, the length of the plug was veri-
fied using a conventional ruler. The harvesting guide was
removed.

For each plug in sequence, one delivery guide was placed
on the knee (Fig. 4b). The delivery hole was drilled. The
depth marking on the Mosaicplasty drill bit was used to
determine the depth of the hole. Then the plug was inserted
into the drill sleeve and the rotation mark on the plug
aligned with a corresponding rotation mark at the guidance
cylinder. Finally, the plug was pushed through the drill
sleeve into the delivery hole and the delivery guide for that
plug was removed.

Postoperative Assessments

All sheep were recovered from anesthesia and had restricted
exercise in small pens for 3 weeks followed by unrestricted
movement in larger pens for the 3-month recovery period. At
the end of the study, the sheep were euthanized with an over-
dose of pentobarbital and the hind limbs harvested for assess-
ments. CT arthograms were repeated in the reconstructed
joints. The joints were then dissected carefully and photodocu-
mented. The following criteria were recorded from each joint:

Shape of articular surface reconstruction. Immediately after
the surgery, the surgeon documented the result in surgical
notes, describing the congruency of each plug to the sur-
rounding surface at four points on the circumference of
the plug.

Weight, pain, and lameness. After the surgery, each sheep
was followed daily for 3 months. Weight, pain, and lame-
ness were documented. Pain was graded on a scale of 1 to 3
as a combination of lameness, respiration, attitude, and
appetite. Lameness was graded on a scale of 1 to 5, with 1
being “weight bearing but slight limp” and 5 being “not
weight bearing, leg lifted or cannot get up.”

Macroscopic International Cartilage Repair Society (ICRS)
score after healing. All sheep were euthanized 3 months
postoperatively and both knees were harvested and dissected. The joints were photographed and examined macroscopically using the ICRS Macroscopic Score. The scoring was done by one observer who was blinded to the treatment method used for repair.

**Shape of articular surface after healing.** Three-dimensional models for bone and for cartilage were created from CT images before injury and 3 months postreconstruction using the commercial software package Mimics (Materialise, Leuven, Belgium). Using the Iterative Closest Point algorithm, the posthealing bone model was registered to the predefect bone model. The resulting transformation was applied to align the posthealing cartilage model with the pristine articular surface of the predefect scan. The root mean square (RMS) error between both surfaces over the defect was calculated.

**Subchondral bone cyst formation after healing.** After harvesting the treatment knee, a MicroCT (GE LOCUS Explore) with a voxel size of 0.095 mm³ was performed. Using the Mimics software, the cysts in the medial condyle were segmented and the volume of these cysts determined.

**Histological measures after healing.** Immediately after harvesting, imaging, and macroscopic evaluation of the knees, the following tissue samples were obtained for histological evaluation: synovial membrane intercondylar area, medial aspect; osteochondral blocks from the medial femoral condyle; the tibia plateau; and the medial trochlea. All samples were stored in formalin, decalcified in formic acid, and embedded in paraffin blocks from which 6-µm-thick sections cut. Sections were stained with hematoxylin and eosin (H&E) and safranin-O/fast green. Sections from the repair site were examined by two independent reviewers using the ICRS II histological scoring system consisting of 14 parameters. This system is an integrated evaluation of tissue and cell morphology with emphasis on restoration of normal cartilage and subchondral bone plate architecture as well as integration of the grafts and intergraft repair tissue with the surrounding host tissue.

**Statistical Analyses**

Statistical analysis was performed using the software package Analyse-It (Analyse-It Software Ltd., Leeds, UK). A non-paired Student t test was used to evaluate significant differences between all three groups for parametric tests. For nonparametric score results, differences were evaluated by the Mann-Whitney U test. For all tests, $P < 0.05$ was considered statistically significant.

**Results**

For all 15 sheep, the cartilage defect and cartilage repair surgery was successfully performed. There was one case of superficial wound infection in the conventional group after the reconstructive surgery, which was treated successfully with antibiotics. For one sheep in the optically guided group, a mechanical lameness due to an intermittently luxated patella was diagnosed 1 week following the cartilage repair surgery. Figure 5 shows photographs for three knees (one from each group) during different steps of our study and evaluation.

**Shape of Articular Surface Reconstruction**

Figure 6 shows the percentage of recessed and proud plug surface for all three groups, as determined from the intraoperative notes immediately after surgery. The percentage of proud surface was significantly smaller ($P < 0.02$) for the template-guided group (1.4 ± 3.1%) compared with the conventional group (31.2 ± 22.4%). The difference between the optically guided group (7.8 ± 7.8%) and the conventional group was not significant ($P = 0.06$), but the borderline $P$ value suggested a trend toward smaller values for the optically guided group. The percentage of recessed surface had no significant differences between conventional (0.0 ± 0.0%), optically guided (27.1 ± 23.1%), and template-guided (6.2 ± 13.9%) groups.
Weight, Pain, and Lameness

There was no significant difference in weight, pain, or lameness between the conventional group and the computer-assisted groups. But within the computer-assisted groups, the average duration of pain was significantly greater ($P < 0.04$) for the template-guided group ($6.2 \pm 2.6$ days) compared with the optically guided group ($2.4 \pm 2.3$ days). The conventional group pain duration was $4.0 \pm 4.1$ days.

The intensity of the pain for the template-guided group ($2.6 \pm 1.4$) was significantly greater ($P < 0.035$) than that of the optically guided group ($1.0 \pm 0.8$). The conventional group pain intensity was $2.0 \pm 2.1$.

Macroscopic ICRS Score after Healing

No significant difference was found between any groups in the 3-month postrepair macroscopic evaluation (Table 1).

Shape of Articular Surface after Healing

The articular surface over the defect in the posthealing CT scan was compared to the corresponding (pristine) articular surface in the predefect scan. We found an RMS error of $0.33 \pm 0.10$ mm for the conventional group, $0.44 \pm 0.14$ mm.
Table 1. Three-Month Postoperative Macroscopic Scores (Mean ± Standard Deviation)

|                         | Conventional | Optically Guided | Template Guided |
|-------------------------|--------------|------------------|-----------------|
| ICRS repair score       | 6.0 ± 2.7    | 5.0 ± 1.8        | 8.0 ± 1.8       |
| Treatment effect whole joint quantitative assessment score | 1.5 ± 7.1    | 9.0 ± 5.8        | 11.0 ± 6.2      |

ICRS = International Cartilage Repair Society.

Figure 7. Results for cysts volume in medial condyle 3 months post-surgery. Values are displayed as average and 95% confidence interval.

for the optically guided group, and $0.29 \pm 0.25$ mm for the template-guided group. No significant differences between the three groups were found.

Subchondral Bone Cyst Formation after Healing

Figure 7 shows the cyst volumes in the medial condyle 3 months posthealing. The cyst volume for the template-guided group ($51 \pm 47$ mm$^3$) was significantly smaller ($P < 0.02$) than that of the conventional group ($173 \pm 76$ mm$^3$). No significant difference was found with the optically guided group ($98 \pm 144$ mm$^3$).

Histological Measures after Healing

Figure 8 shows the histology scores for three areas (the medial condyle, the tibial plateau, and the surrounding tissue) and for the three groups. Error bars show the 95% confidence interval. For the medial condyle, the treatment effect was significant better ($P < 0.02$) in the optically guided group than in the conventional group. Also, the treatment effect in the template-guided group was significant better ($P < 0.01$) than in the conventional group. For
the tibial condyle, the treatment effect was significantly better ($P < 0.035$) in the template-guided group than in the conventional group. No significant differences were found for the histology score of the surrounding tissue for all three groups. A significant linear correlation was found (linearity fit $P < 0.004$) between the ICRS II treatment effect for the medial condyle and the intraoperative estimated percentage of proud reconstructed articular surface for all 15 sheep (Fig. 9).

**Discussion**

The primary finding was that both image-guided techniques had a significantly better treatment effect than did the conventional surgical technique.

The template-guided technique resulted in significantly better surface congruency than the conventional technique. We also saw a trend toward better surface congruency using the optically guided method compared with the conventional technique. Interestingly, our results did not show a correlation between the articular surface congruency immediately after the operation and the macroscopic appearance of the cartilage at 3 months postoperatively. Similarly, no correlation was found between the articular surface congruency immediately after the operation and the surface congruency measured on the CT scan taken 3 months postoperatively. The lack of correlation suggests that in this time the proud plugs subsided and recessed plugs filled in. This is consistent with observations from other studies.

A secondary finding is the significant correlation between the articular surface congruency immediately after the operation and the histology of the cartilage 3 months postoperatively. The results showed that proud plugs are associated with poorer healing in the short term. The poorer healing could be the effect of peak pressure on these grafts. Koh *et al.* observed in an *in vitro* study striking increase in peak pressures when the plug was proud. This increased pressure may cause overload in the tissue and may damage the cartilage. The reason that we observed this poorer healing of the cartilage only in the histology and not in the macroscopic appearance could be that our follow-up period of only 3 months was too short to alter the macroscopic appearance of the cartilage.

Our results did not show a correlation between recessed plugs and short-term cartilage healing. This is in agreement with a study conducted with rabbits, in which marginally recessed plugs did not adversely affect outcomes. Also, during a sheep study, it was observed that plugs recessed up to 1 mm had a good survival rate. However, our healing results are limited to a short-term period; the longer term effects of recessed plugs were not studied.

The surgeon found that it was difficult to hold the position and orientation of the tool according to the optoelectronically guided computer display during impacts. This was likely because the hardness of the sheep bone required more manipulation to harvest osteochondral plugs than would be necessary in normal human bone. On the other hand, the template-guided technique provided mechanical support to the surgical tools because the template was stabilized in the registered position using wires. This might explain the better surface reconstruction for the template-guided group. We speculate that the problem of holding the optically guided chisel will not arise in human patients unless the subchondral bone was sclerotic. We did not find any significant differences in ICRS II score in the surrounding cartilage between the template-guided and conventional techniques, which suggests that the placement and fixation of the templates did not have a negative effect on the tissue in the first 3 months postoperatively.

The 3-month post-reconstruction micro-CT images revealed a significantly larger cyst volume in the conventional group than in the template-guided group. Subchondral cysts can result in serious complications, such as a collapse of the graft into the recipient hole. Cyst creation during healing might be larger for the conventional technique because of the significantly higher percentage of proud plugs found in the conventional technique. This is consistent with results from Pearce *et al.*, who observed in a study significantly more cyst creation with plugs placed proud with respect to the articular surface than with flush placed plugs. Those authors suggested that micromotion of the plugs could lead to synovial fluid penetrating normal subchondral bone, which in turn might predispose the

---

**Figure 9.** Linear correlation between the percentage of reconstructed articular surface that was proud and the ICRS II treatment effect for the medial condyle for all 15 sheep. ICRS = International Cartilage Repair Society.
development of subchondral cysts. Tytherleigh-Strong et al. also discussed the possibility of synovial fluid penetration into the gap between the graft and the surrounding, normal subchondral bone to create subchondral cysts. The template-guided technique may provide a more tightly fitting plug, reducing the penetration of synovial fluid, because the drill guide is held more rigidly inside the template during the preparation of the recipient site. With the conventional and optoelectronically guided techniques, the tools are hand-held, without external support, and can result in a hole that is less cylindrical.

We found no significant difference in measures of pain, lameness, weight, and macroscopic scores after healing between the optically guided and conventional techniques. This suggests that the invasive attachment of the sensors to the femur was well tolerated. However, we found a significant increase of the length and intensity of postoperative pain in the template-guided group compared with the optically guided group. This difference might be explained by the reduced invasiveness of the optically guided technique: although the arthotomies in both groups were the same, the insertion of the template required more soft tissue retraction, which could have caused more caputitis and synovitis.

Conclusions

The small number of sheep limited the statistical power of the measures obtained from the study. Nonetheless, statistical significance was found for a number of important measures. This is, to our knowledge, the first in vivo study to investigate the clinical outcome of image-guided autologous osteochondral transplantation in comparison to the conventional surgical method. The planning for the image-guided techniques required that an operator use a computer interface to place virtual plugs on a model of the patient’s bone and cartilage. The planning process took 30 to 45 minutes per procedure and required that the surgeon estimate, on the computer screen, the desired 3D articular cartilage surface over the defect. To improve the planning process, we developed, subsequent to this study, fully automatic planning methods.

In conclusion, this in vivo animal study has shown that image-guided techniques produce better morphological and healing outcomes for autologous osteochondral transplantation compared with conventional surgical techniques. Further studies are necessary to confirm that this short-term improvement will translates to a better long-term clinical outcome. However, we believe that the results of this study show a great promise that computer-assisted mosaic arthroplasty can improve the clinical outcome not only in an animal model but also in patients.

Acknowledgments and Funding

The authors are grateful to Karen Lowerison and Nicole Kudo for their help with data collection, Paul St John for his technical support, and Emily Bishop, David Wright, John Li, Tamara Redwood, and Jerome Grondin-Lazzazzera for their valuable help with segmenting the data. This research was supported by Grant STPGP 336779 from the Natural Sciences and Engineering Council of Canada.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethical Approval

This study was performed with approval from the University Animal Care Committee at Queen’s University and the University of Guelph.

References

1. Curl WW, Krome J, Gordon ES, Rushing J, Smith BP, Poehling GG. Cartilage injuries: a review of 31,516 knee arthroscopies. Arthroscopy. 1997;13(4):456-60.
2. Hjelle K, Solheim E, Strand T, Muri R, Britberg M. Articular cartilage defects in 1,000 knee arthroscopies. Arthroscopy. 2002;18(7):730-4.
3. Hunter W. Of the structure and disease of articulating cartilages 1743. Clin Orthop Relat Res. 1995;(317):3-6.
4. Hunziker EB. Articular cartilage repair: problems and perspectives. Biorheology. 2000;37(1-2):163-4.
5. Gelber AC, Hochberg MC, Mead LA, Wang NY, Wigley FM, Klag MJ. Joint injury in young adults and risk for subsequent knee and hip osteoarthritis. Ann Intern Med. 2000;133(5):321-8.
6. Steadman JR, Briggs KK, Rodrigo JJ, Kocher MS, Gill TJ, Rodkey WG. Outcomes of microfracture for traumatic chondral defects of the knee: average 11-year follow-up. Arthroscopy. 2003;19(5):477-84.
7. Asik M, Ciftci F, Sen C, Erdil M, Atalar A. The microfracture technique for the treatment of full-thickness articular cartilage lesions of the knee: midterm results. Arthroscopy. 2008;24(11):1214-20.
8. Gill TJ, McCulloch PC, Glasson SS, Blanchet T, Morris EA. Chondral defect repair after the microfracture procedure: a non-human primate model. Am J Sports Med. 2005;33(5):680-5.
9. Kreuz PC, Erggelet C, Steinwachs MR, Knause SJ, Lahm A, Niemeyer P, et al. Is microfracture of chondral defects in the knee associated with different results in patients aged 40 years or younger? Arthroscopy. 2006;22(11):1180-6.
10. Mithoefer K, Williams RJ 3rd, Warren RF, Potter HG, Spock CR, Jones EC, et al. The microfracture technique for the treatment of articular cartilage lesions in the
knee. A prospective cohort study. J Bone Joint Surg Am. 2005;87(9):1911-20.

11. Britberg M, Lindahl A, Nilsson A, Ohlsson C, Isaksson O, Peterson L. Treatment of deep cartilage defects in the knee with autologous chondrocyte transplantation. N Engl J Med. 1994;331(14):889-95.

12. Peterson L, Minas T, Britberg M, Nilsson A, Sigren-Jansson E, Lindahl A. Two- to 9-year outcome after autologous chondrocyte transplantation of the knee. Clin Orthop Relat Res. 2000;(374):212-34.

13. Peterson L, Britberg M, Kiviranta I, Akerlund EL, Lindahl A. Autologous chondrocyte transplantation: biomechanics and long-term durability. Am J Sports Med. 2002;30(1):2-12.

14. Fu FH, Zurakowski D, Browne JE, Mandelbaum B, Erggelet C, Moseley JB Jr, et al. Autologous chondrocyte implantation versus debridement for treatment of full-thickness chondral defects of the knee: an observational cohort study with 3-year follow-up. Am J Sports Med. 2005;33(11):1658-66.

15. Matsusue Y, Yamamura T, Hama H. Arthroscopic multiple osteochondral transplantation to the chondral defect in the knee associated with anterior cruciate ligament disruption. Arthroscopy. 1993;9(3):318-21.

16. Hangody L, Kárpáti Z. New possibilities in the management of severe circumscibed cartilage damage in the knee. Magy Traumatol Ortop Kezsz Plasztikai Seb. 1994;37(3):237-43.

17. Hangody L, Füles P. Autologous osteochondral mosaicplasty for the treatment of full-thickness defects of weight-bearing joints: ten years of experimental and clinical experience. J Bone Joint Surg Am. 2003;85(Suppl 2):25-32.

18. Jakob RP, Franz T, Gautier E, Mainil-Varlet P. Autologous osteochondral grafting in the knee: indication, results, and reflections. Clin Orthop Relat Res. 2002;(401):170-84.

19. Chow JC, Hantes ME, Houle JB, Zalavras CG. Arthroscopic autogenous osteochondral transplantation for treating knee cartilage defects: a 2- to 5-year follow-up study. Arthroscopy. 2004;20(7):681-90.

20. Gudas R, Kalesinskas RJ, Kimtys V, Stankevicius E, Toliusis V, Bernotavicius G, et al. A prospective randomized clinical study of mosaic osteochondral autologous transplantation versus microfracture for the treatment of osteochondral defects in the knee joint in young athletes. Arthroscopy. 2005;21(9):1066-75.

21. Horas U, Pelinkovic D, Herr G, Aigner T, Schnettler R. Autologous chondrocyte implantation and osteochondral cylinder transplantation in cartilage repair of the knee joint. A prospective, comparative trial. J Bone Joint Surg Am. 2003;85(2):185-92.

22. Bentley G, Biant LC, Carrington RW, Akmal M, Goldberg A, Williams AM, et al. A prospective, randomised comparison of autologous chondrocyte implantation versus mosaicplasty for osteochondral defects in the knee. J Bone Joint Surg Br. 2003;85(2):223-30.

23. Dozin B, Malpeli M, Cancedda R, Bruzzi P, Calcagno S, Molfetta L, et al. Comparative evaluation of autologous chondrocyte implantation and mosaicplasty: a multicentered randomized clinical trial. Clin J Sport Med. 2005;15(4):220-6.

24. Vasiliadis HS, Wasiak J, Salanti G. Autologous chondrocyte implantation for the treatment of cartilage lesions of the knee: a systematic review of randomized studies. Knee Surg Sports Traumatol Arthrosch. 2010;18(12):1645-55.

25. Vavken P, Samartzis D. Effectiveness of autologous chondrocyte implantation in cartilage repair of the knee: a systematic review of controlled trials. Osteoarthritis Cartilage. 2010;18(6):857-63.

26. Imhoff AB, Ottl GM, Burkart A, Traub S. Autologous osteochondral transplantation on various joints. Orthopade. 1999;28(1):33-44.

27. Koh JL, Wirsing K, Lautenschlager E, Zhang LO. The effect of graft height mismatch on contact pressure following osteochondral grafting: a biomechanical study. Am J Sports Med. 2004;32(2):317-20.

28. Pearce SG, Hurtig MB, Clarnette R, Kalra M, Cowan B, Miniacci A. An investigation of 2 techniques for optimizing joint surface congruency using multiple cylindrical osteochondral autografts. Arthroscopy. 2001;17(1):50-5.

29. Kosel J, Giouroudi I, Scheffer C, Dillon E, Erasmus P. Anatomical study of the radius and center of curvature of the distal femoral condyle. J Biomech Eng. 2010;132(9):091002.

30. Sanders TG, Mentzer KD, Miller MD, Morrison WB, Campbell SE, Penrod BJ. Autogenous osteochondral “plug” transfer for the treatment of focal chondral defects: postoperative MR appearance with clinical correlation. Skeletal Radiol. 2001;30(10):570-8.

31. Koulalis D, Di Benedetto P, Citak M, O’Loughlin P, Pearle AD, Kendoff DO. Comparative study of navigated versus free-hand osteochondral graft transplantation of the knee. Am J Sports Med. 2009;37(4):803-7.

32. Radermacher K, Portheine F, Anton M, Zimolong A, Kaspers G, Rau G, et al. Computer assisted orthopaedic surgery with image based individual templates. Clin Orthop Relat Res. 1998;(354):28-38.

33. Owen BD, Christensen GE, Reinhardt JM, Ryken TC. Rapid prototype patient-specific drill template for cervical pedicle screw placement. Comput Aided Surg. 2007;12(5):303-8.

34. Kunz M, Rudan JF, Xenoyannis GL, Ellis RE. Computer-assisted hip resurfacing using individualized drill templates. J Arthroplasty. 2010;25(4):600-6.

35. Hurtig M, Chubinskaya S, Dickey J, Rueger D. BMP-7 protects against progression of cartilage degeneration after impact injury. J Orthop Res. 2009;27(5):602-11.

36. ASTM International. Standard guide for in vivo assessment of implantable devices intended to repair or regenerate articular cartilage. Conshohocken, PA: ASTM International; 2005.

37. Hangody L, Kárpáti Z. A new surgical treatment of localized cartilaginous defects in the knee. Hung J Orthop Trauma. 1994;37:237-242.
38. Ma B, Ellis RE. Robust registration for computer-integrated orthopedic surgery: laboratory validation and clinical experience. Med Image Anal. 2003;7(3):237-50.

39. Brittberg M, Winalski CS. Evaluation of cartilage injuries and repair. J Bone Joint Surg Am. 2003;85(Suppl 2):58-69.

40. Besl P, McKay N. A method for registration of 3-d shapes. IEEE Trans Pattern Anal Machine Intelligence. 1992;14:239-256.

41. Mainil-Varlet P, Van Damme B, Nesic D, Knutsen G, Kandel R, Roberts S. A new histology scoring system for the assessment of the quality of human cartilage repair: ICRS II. Am J Sports Med. 2010;38(5):880-90.

42. Lefkoe TP, Walsh WR, Anastasatos J, Ehrlich MG, Barrach HJ. Remodeling of articular step-offs. Is osteoarthrosis dependent on defect size? Clin Orthop Relat Res. 1995;(314):253-65.

43. Huang FS, Simonian PT, Norman AG, Clark JM. Effects of small incongruities in a sheep model of osteochondral autografting. Am J Sports Med. 2004;32(8):1842-8.

44. Tytherleigh-Strong G, Hurtig M, Miniaci A. Intra-articular hyaluronan following autogenous osteochondral grafting of the knee. Arthroscopy. 2005;21(8):999-1005.