Orthopedic Application of Polycarbonate Urethanes: A Review

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Summary: Soft materials that aim to reproduce the tribological function of the natural joint are gaining popularity as an alternative concept to conventional hard bearing materials in the hip and knee. Polyurethane (PU) elastomers, in particularly polycarbonate urethane, are among the highest performing medical-grade polymers. They have mechanical and biological properties that make them suitable for use in orthopedic implants, as they demonstrate a unique combination of toughness, durability, flexibility, biocompatibility, and biostability. As presented in this paper, newly developed implants based on polycarbonate urethane perform more similarly to the natural joint in their mechanical response to load, and in their ability to utilize a thinner structure similar to that of cartilage, without jeopardizing the integrity or stability of the implant. Several wear studies of implants based on PU demonstrate a very low damage level to the implants' articulating surfaces following repeated loading, and provide good assurance that this material can generate a low and stable wear rate in the long term. Animal studies further provide understanding of the biological response to PU implants in the hip and knee. Short-term clinical results are now becoming available from several commercial products. These generally show good functioning of these implants in the body and no material-related complications.

Key Words: meniscus prosthesis—hip prosthesis—soft bearing—elastomer

(*Tech Orthop* 2017;00: 000–000)

Polyurethane (PU) elastomers are among the highest performing medical-grade polymers. They have mechanical and biological properties that make them suitable for use in a diverse range of implantable medical devices, as they demonstrate a unique combination of toughness, durability, flexibility, biocompatibility, and biostability.[1,2] PUs possess more complex chemical structures than many of the most widely produced polymers such as polyethylenes, polystyrenes or polypropylenes, which are synthesized from 1 or 2 monomer units. PUs typically comprise 3-reactive components: (i) a diisocyanate, (ii) a soft segment (which is an oligomeric macromonomer), and (iii) a chain extender. The 3 "degrees of freedom' available when planning PU syntheses provide a wide range of combinations that can potentially yield PU's with vastly differing physicochemical and mechanical properties, as well as varying biostability.[1,2] PU elastomers typically show a 2-phase structure in which hard segment micro-domains are dispersed in a matrix of soft segments. The hard segment micro-domains mainly comprise the diisocyanate and the chain extender. Consequently, PU's are often referred to as "segmented block copolymers." The microphase separation of segmented PU's is driven by the thermodynamic incompatibility of the hard and soft segments. The soft segments form amorphous, rubbery domains, whereas, the hard segments form semicrystalline domains that are stabilized by hydrogen bonding between urethane and urea groups. The predominant linkage in the soft segment identifies the type of PU, for example, poly-(esterurethanes) incorporate ester linkages, poly-(etherurethanes) incorporate ether moieties, and polycarbonate urethanes (PCUs) incorporate carbonate linkages.

The first generation of biomedical PUs, poly-(ester urethanes), were found to be unsuitable for long-term implantation due to the rapid hydrolytic degradation of the aliphatic polyester soft segment. Poly-(ether urethanes) were identified as a suitable replacement due to their excellent hydrolytic stability. However, unanticipated failure rates of devices containing softer grade PUs led to the discovery that poly-(etherurethanes) were subject to oxidative degradation including environmental stress cracking and metal ion oxidation.[3–5] Failure of PU-based pacemaker leads and breast implant coatings in the late 1980s brought the long-term stability of these implants under scrutiny. More recently, PCUs were designed to remove the susceptible ester and ether linkages in the soft segment. These polymers were developed specifically and purposely to address the problem of cracking or degrading when implanted for a long period of time during which other types of PUs would degrade or crack.[6] The materials are commercially available from DSM (Exton, PA). Polycarbonate urethanes have shown great promise as long-term biostable elastomers that exhibit excellent resistance to hydrolysis, environmental stress cracking, and metal ion oxidation. The inclusion of silicone into the backbone to create silicone copolymer chemistries (PCU-S or CarboSil) has also been found to improve biostability of PCUs under some conditions. The following sections detail the knowledge base that has become available on the first commercially available orthopedic devices that were designed to utilize PU as a compliant bearing surface, and how they may potentially provide substantial advantages over traditional bearing materials.

HIP REPLACEMENT: THE TRIBOFIT ACETABULAR BUFFER

Throughout all the advancements and significant improvements that have been made to hip replacement over the past 50 years, the orthopedic community continues to face complications related to wear, fatigue, squeaking, and osteolysis. These problems, associated with most current implant materials, contribute to early loosening of the implant and to premature failures. In 2006 PCU was applied for the first time

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You may inquire whether the author(s) will agree to phone conferences and/or visits regarding these techniques.

in a commercial cushion-bearing system as an acetabular socket called the TriboFit Acetabular Buffer (Active Implants, LLC Memphis, TN) (Fig. 1). This hip system which pairs the PCU Acetabular Buffer with a CoCr femoral head has been available on the European market for 10 years. During this time, it has undergone extensive testing in the laboratory and clinic. The following sections will introduce the system, preclinical testing, and experience gained during clinical use.

Design Rationale

The TriboFit acetabular buffer implant has significantly different design goals as compared with conventional polyethylene, ceramic, and metal bearings. The softer compliant PCU was designed to function in a way that resembles the natural hip on the acetabular side of the hip joint. The PCU acetabular implant is 3 mm thick, thus it requires very little bone removal and enables the use of larger head sizes. It has a novel "snap-fit" locking mechanism that provides ease of insertion and positive locking stability. In cases where it is needed, an acetabular metal shell backing is also available for use with the PCU as a "snap-fit" liner. This novel design provides versatility to be used as a standalone acetabular cartilage replacement or as a standard acetabular component which replaces the polyethylene bearing surface. Although it is too early in clinical evaluations to determine if 1 approach is better than the other over the long term, it is certain that a PCU bearing used as a standalone cartilage implant has the advantage of less bone removal.

Wear Evaluation

Several wear studies were performed in recent years to evaluate the wear rate of the PCU acetabular Buffer. Fisher and Jennings[7] tested a configuration of the Buffer which simulated implantation directly against bone. The PCU buffers were placed in saw-bone replicas of the acetabulum that were reamed and grooved as mentioned before. The implants were loaded according to ISO standard 14242 for 5 million cycles (Mc) in a new born calf serum diluted to 25%. The wear rate gradient was measured between 2 and 5 Mc, after the Buffers had reached a steady creep state and wear rate. The average wear rate measured in this interval was 2.8 mm^3/Mc.

St John and Gupta[8] compared the wear characteristics of a ultrahigh molecular weight polyethylene (UHMWPE), cross-linked UHMWPE, and PCU Buffers of a similar geometry, against cobalt alloy femoral components. Over the course of 5 million load cycles, the PCU Buffers were seen to have the lowest wear rate, with an average material loss of 19.1 mm^3/Mc. The cross-linked UHMWPE components had a loss rate of 25 mm^3/Mc, and the UHMWPE components had a much higher rate of material loss of 100 mm^3/Mc. The finding of about a 70% reduction in wear due to cross-linking reconfirms that cross-linking of UHMWPE is beneficial in reducing wear, but the material loss for the PCU samples seems to have been at least 24% lower than for the cross-linked UHMWPE. This finding can be explained by tribological studies which have shown that PCU, if used in the hemispherical configuration against a hard bearing surface such as a femoral head, promotes micro-elasto-hydrodynamic lubrication (analogous to hydroplaning), that enhances its wear performance compared with hard-on-hard bearings.[9]

The longest controlled laboratory wear study of the commercially available PCU Buffer was conducted on a Buffer implanted against a metal shell.[10,11] An ISO-based simulation was performed for the duration of 20 Mc. The PCU Buffer showed excellent wear characteristics in terms of its low and steady volumetric wear rate (5.8 to 7.7 mm^3/Mc) and low particle generation rate (2 to 3×10^6 particles/Mc). The latter is 5 to 6 orders of magnitude lower than that reported for cross-linked UHMWPE and 6 to 8 orders of magnitude lower than that of metal-on-metal (MOM) bearings. Microscopic analysis (atomic force microscopy and profilometry) of the implants' articulating surface after the simulation demonstrated a low damage level even after 20 Mc. Another important finding in this study was that only 3.4% of the PCU wear particles isolated from the lubricant laid in the 0.2 to 10 μm size range, with the majority of particle mass being associated with larger sizes. This particle size range has been shown to stimulate macrophages to produce high levels of the cytokine TNF-α, and the major part of UHMWPE wear particles usually lie in this range.[12] Another potential advantage of PCU with this respect is that, while highly cross-linked UHMWPE and UHMWPE materials share similar values of biological activity,[13] a recent study has shown that PCU is less inflammatory to periprosthetic tissue and bone compared with these materials.[14] Thus, based on the combination of larger wear particles, less reactivity of the material itself, and lower particle generation rate, the authors hypothesized that the osteolytic risk of the PCU Buffer may be lower than that of hard bearings.

Large Animal Studies

The in vivo biocompatibility and biostability of the TriboFit Hip System has been tested for the duration of 24 months in a sheep model. Sheep have often been used in studies involving hip arthroplasty. The bony acetabulum of the sheep is made up of the 3 bones of the pelvis, as it is in humans, and the anatomy of the soft tissue around the ovine hip is also very similar to that of humans.[15] In addition, instrumented endoprostheses have shown a similar load orientation.[16] However, the walls of the ovine socket are thin, making it very difficult to expose cancellous bone at the rim of the acetabulum. This means that the ovine acetabulum anatomy is an ideal model to test the efficacy of an implant against sclerotic bone at the rim.

Four sheep were implanted with Buffer alone, and 4 sheep were implanted with a Buffer and hydroxyapatite (HA)-coated shell configuration. One sheep from each study group was euthanized and examined 6 and 12 months after implantation. The remaining sheep in each group were euthanized and examined 24 months after implantation.

Physical examination of the sheep 6, 12, or 24 month's postimplantation revealed the animals to be performing well with no gait or functional issues apparent. Specifically, the range of motion appeared unrestricted, and no dislocations or subluxations were noted. At a gross macroscopic level it would appear that there are no untoward effects of the componentry.

Evaluations at necropsy 6, 12, and 24 months postintervention demonstrated that the gentle reaming and removal of articular cartilage followed by "grooving" the surface were sufficient to maintain the Buffer alone in good position, and provided rigid fixation of the acetabular component. Similarly, the undersizing of the reamed acetabulum and impaction of the shell into the acetabulum created a tight interface fixation of the hemispherical HA-coated Co-Cr shell with the acetabular bone. Lucencies visible around the shell at the time of implantation had filled, presumably with new bone infiltrating the HA surface coating.

The surfaces of the retrieved Buffer specimens from both groups appeared intact with no gross evidence of surface abrasion. Some edge wear along the dorsal and cranial aspects of the

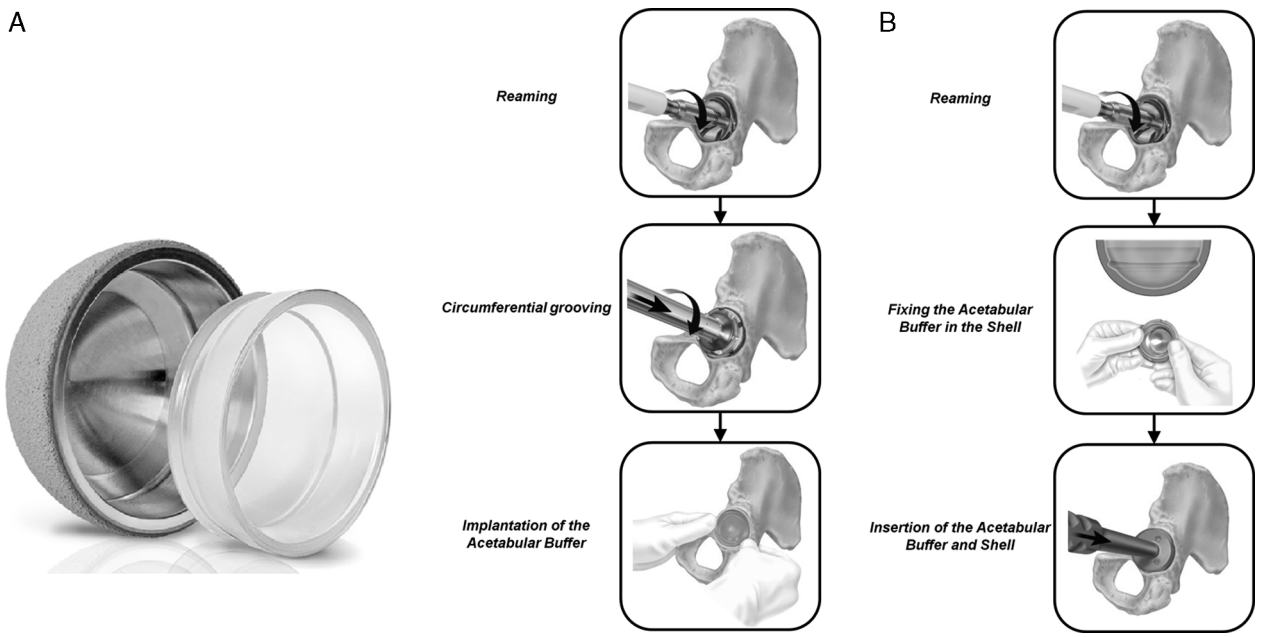

FIGURE 1. Side view of the TriboFit PCU Buffer, and a hydroxyapatite coated metal shell. The Buffer can be implanted directly against bone (A), or by fixation to the metal shell backing, by snap-fit mechanism based on a ring shaped flange (B). PCU indicates polycarbonate urethane. full color online

24-month explants developed in response to abrasion from the stem during locomotion but this finding was not considered unusual or significant. In one of the Buffer-on-bone explants, some backside wear was indicated. Nevertheless, the implant remained in place for the full duration of 24 months, and the sheep did not show any signs of lameness before necropsy. Histologic examination of the surrounding tissues verified no noticeable untoward biological response to the implant components, and very few traces, if at all, of wear particles.

Surgical Technique

The TriboFit system was designed for all standard surgical approaches. If the Buffer implant is to be used as a standalone cartilage replacement it requires full bony containment so preparation and insertion techniques are significant factors. All soft tissue should be removed, but it is not necessary to remove all remnants of articular cartilage. Light reaming can be done to ensure a hemispherical shaped socket, but it does not require reaching down to a bleeding bony bed (Fig. 1A, top). Trial gauges are available for sizing. Once the size has been determined, a special groove reamer similar to the original Charnley grooved reamer is used to cut a locking channel into the acetabular wall (Fig. 1A, middle). The Buffer implant should then be snapped into place with finger pressure (Fig. 1A, bottom). It is imperative to ensure full containment of the implant within the acetabular cavity to eliminate the risk of edge loading and deformation of the material that increases the risk of wear.

Implantation with a metal shell component follows the standard surgical technique as with any cementless hemispherical metal shell component. Progressive socket reaming should be carried out with standard implant orientation of 45 to 50 degrees of abduction and 15 to 20 degrees of anteversion with the metal shell being press-fit between 1 and 2 mm (Fig. 1B, top). Once proper reaming and sizing is carried out, the Buffer implant is snapped into place and can then be inserted as a monoblock acetabular component (Fig. 1B, middle). Implantation and component insertion is carried out as with any standard cementless conventional acetabular component (Fig. 1B, bottom).

Clinical Experience

The first implantation of the TriboFit Acetabular Buffer was done in 2006. As of August 2013, the TriboFit Acetabular Buffer has been implanted in >1200 patients, with the longest implantation reaching 7 years. As of 2017, the TriboFit Acetabular Buffer has been implanted in more than 1,800 patients, with the longest implantation reaching 10 years.

Two case studies describing the early retrieval analysis results of patients, 10.5 and 12 months postimplantation were published by Wippermann et al[17] and Siebert et al[18] in 2008. Both patients experienced hip pain ~8 months postimplantation. The retrieved implants were analyzed for wear using scanning electron microscopy and micro-computed tomography technique, and the average wear rate was found to be 1.5 mm^3/y,[17] and 15 mm^3/y.[18] The average particles size was measured in one of the cases and was found to be 0.9 μm according to laser diffraction analysis and 2.9 μm (range, 0.5 to 90 μm, plus 1 at 200 μm) according to scanning electron microscopy analysis.[17] These average particle sizes are smaller than that reported in the laboratory.[10] A possible explanation for this discrepancy may be that only particles from the synovial fluid were characterized in the clinical study, and as smaller particle sizes tend to suspend in the fluid better than larger particles, the results could lean toward the lower range of sizes.

In 2011, Giannini et al,[19] reported a prospective controlled randomized study of the Buffer, which compared clinical outcomes of 60 osteoporotic patients with femoral neck fracture, treated either by the PCU Buffer or by bipolar hemiarthroplasty. The Harris Hip Score (HHS) was used to measure subjective outcomes 3 and 12 months postoperatively and adverse events were recorded along the follow-up period.

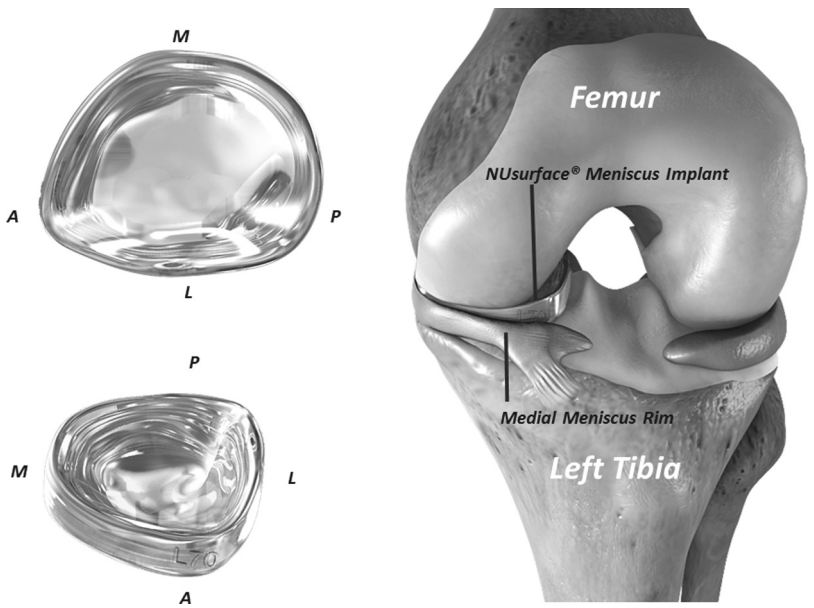

FIGURE 2. An illustration of the knee joint and the location of the NUsurface Meniscus Implant and side views of the device, which consists of PCU, reinforced internally with UHMWPE fibers. The circumferential orientation of the fibers assists in controlling deformation of the PCU material, and improving its pressure distribution performance. PCU indicates polycarbonate urethane. full color online

No statistical difference was found between the groups. The average HHS at 3 and 12 months was 71.6 and 75.5 in the hemiarthroplasy group, and 74.5 and 80.7 in the PCU Buffer group, respectively. In the reported study, no major complication occurred and the authors state that the surgical technique is fast and simple.

In another recent study, serum cobalt (Co) and chromium (Cr) levels were measured in a small group of 15 patients treated with the TriboFit Buffer (group A) and in 15 patients treated with MOM (metal on metal) total hip arthroplasty (group B).[20] The metal ions level was significantly higher in patients treated with MOM implants ($P < 0.05$). Specifically, Co (1.3 μg/L) and Cr (2.9 μg/L) median levels were found to be 5.4 and 4.8 times higher, respectively, from Co (0.24 μg/L) and Cr (0.6 μg/L) levels in patients treated with PCU Buffer. The radiographic results were excellent, and there were no signs of osteolysis or loosening of the Buffer. In both groups, the postoperative HHS and Oxford Hip Score (OHS) improved as compared with the preoperative scores. Even though patients in group A showed significantly higher preoperative scores ($P = 0.014$), at follow-up, neither group showed a statistically significant difference in results (HHS: $P = 0.148$; OHS: $P = 0.683$).

The latest clinical data from the 2016 UK National Joint Registry report are particularly encouraging. Of the 184 TriboFit Buffers which were implanted at 5 centers in the United Kingdom and followed up to 5 years, none had required revision surgery to at the date of publication. Tribofit is possibly the only uncemented aceatabular cup with a 0% revision rate after 5 years.[21]

MENISCUS REPLACEMENT

The menisci play an important role in functionality of the knee joint. Clinical studies have shown that the loss of the meniscus leads to degenerative arthritis due to changes in cartilage load distribution.[22] In these cases, there is clearly a need to protect the articular cartilage by either repairing or replacing the meniscus.

Meniscus replacement still represents an unsolved problem in orthopedics. Meniscal allografts have been shown to heal to the capsule and relieve pain.[23] However, besides problems related to availability, size matching, cost and risk of disease transmission, allograft menisci undergo remodeling after implantation, causing shrinkage, and reduced mechanical strength.[24,25] Other substitutes made from synthetic and natural biodegradable polymers have been described.[26–29] These prostheses form temporary scaffolds that degrade in the body and are replaced gradually by newly formed tissue. Potential shortcomings of this approach include the lack of durability associated with most biodegradable materials under in vivo knee loading conditions,[27] as well as the variability in the body response to the implant, limited age of the target population, and the quality of the tissue formed.

Nowadays, conservative care strategies (medication, knee bracing, activity modification, intrajoint injections of hyaluronic acid), and even a primary, secondary, or multiple meniscectomies, comprise the mainstream treatment for a typical 50-year-old patient with postmeniscectomy pain. At a later age, clinicians often choose to practice the more invasive treatment options to treat joint pain by performing high tibial osteotomy, unicompartmental, or total knee arthroplasties. On the basis of the above, there is a clear treatment gap for the middle-aged patient population creating a need for a treatment option which can delay more aggressive treatments by relieving pain associated with meniscal dysfunction and the associated joint overload.

This section will present an overview of a nonanchored PCU medial meniscus implant (NUsurface Meniscus Implant, Active Implants Corp.).

Design Rationale

The meniscus implant was designed as a composite construct made of PCU, which is reinforced circumferentially with UHMWPE fibers (Fig. 2). This composite structure aims to reproduce the functional properties and relationship between

structural components of the natural meniscus which consists of a solid matrix reinforced with a highly orientated collagen fiber network.[30] Functionally, the pliable matrix material is expected to distribute joint loads and reduce contact pressure by permitting local material deformation whereas the reinforcement material is designed to restrain matrix flow and bear a high portion of hoop stresses.

In contrast to the acetabular Buffer implant which is used in a total joint arthroplasty, the meniscus implant only consists of 1 component, and as a hemiarthroplasty implant, it articulates against existing articular surface. A 3-dimensional form of the meniscus was developed to match the geometry of existing cartilaginous surfaces and joint tolerances by using >130 human knee magnetic resonance imaging (MRI)-scans.[31] Another important design consideration was ease of insertion and leaving all options open for future joint replacement, by not drilling into the bone. The semilunar geometry of the natural meniscus, which is firmly fixed to the tibia in its horns, was modified into a semiconfined femur-conforming discoid geometry by adding an artificial "bridge" feature along the lateral side of the implant body. The "bridge" lies along the gap between the original medial insertion points of the meniscus and is designed to not come into contact with the cruciate ligaments.

Biomechanics

The load transfer capability of the implant was evaluated in vitro using human cadaveric knees.[32,33] The implant was inserted into the medial compartment of cadaveric knees following the removal of the natural meniscus, and knee was loaded under compression representative of the maximum physiological load during gait. The pressure distribution under the implant was measured utilizing flexible sensors (Tekscan Inc., Boston, MA) and compared with that of the natural meniscus before meniscectomy. Contact pressure distributions measured on the tibial plateau underneath the PCU implant were found to be in very good agreement with those measured under the intact natural meniscus of the specific knee, thus proving that the composite PCU implant fulfills the role of joint load distributor (Fig. 3).

Optimization of the implant design, namely determining the ratio of fibers incorporated in the PCU and their configuration, was done by employing a finite elements model of the medial knee with the PCU implant. The model was developed based on MRI scans of a cadaveric specimen, and analyses were conducted under peak gait loads. Internal strains and stresses which developed in both the PCU matrix and PE fibers were calculated.[34] The tibial plateau contact pressures, measured in cadaveric knees in vitro (mentioned previously in this section, Linder-Ganz and colleagues) were used to validate the finite elements model. Important findings of this study were that peak stresses in the PCU were all lower than the maximal allowed stress for this material (15 MPa). Similarly, the peak tensile stress calculated in the fibers was significantly lower than the material's yield stress (3.1 GPa).

Other biomechanical tests of the implant included strain rate testing, creep, relaxation, and hysteresis measurements of the device under simulated joint conditions.[35] Six months of static soaking in simulated physiological fluid, and dynamic fatigue loading for 2 Mc were used to simulate long-term effects of the physiological environment.

Creep and stress relaxation response of the implant were typical of a viscoelastic material. Soaking in simulated physiological fluid and dynamic fatigue simulation were both found to mildly increase the stiffness of the implant. The changes following static soaking stabilized after 28 days, while those measured following fatigue loading became steady after $\sim$300,000 load cycles. Preconditioning was found to occur during the first and second loading-unloading cycles in the hysteresis test, but subsequent loading and unloading pathways were found to repeat for the remaining loading cycles.[35]

In the long term, as seen after 2 million load cycles, the implant's width and length increased slightly (0.9% and 1.1%, respectively) and thickness reduced (-1%) compared with its initial state ($P \leq 0.05$). Moderate creep of the PCU bulk under gait conditions could be considered as an advantage in an implant which is expected to articulate between existing biological surfaces. The implant can adjust itself to variations in

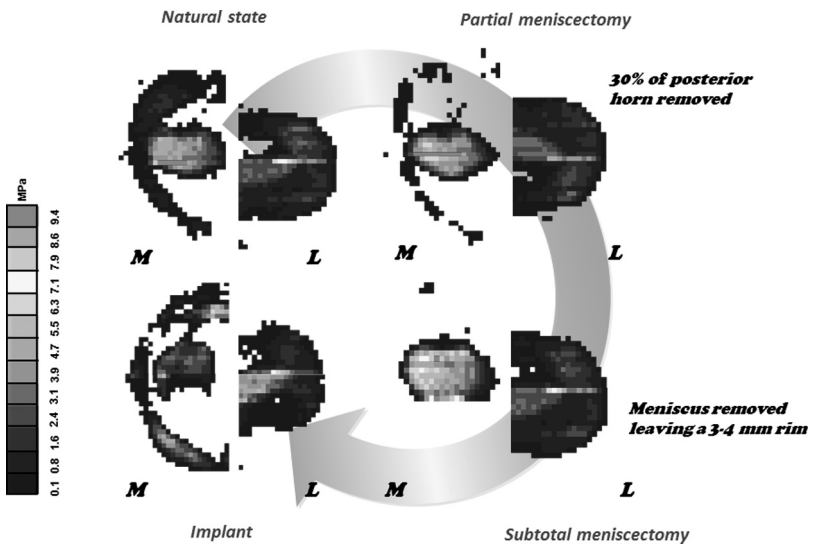

FIGURE 3. Pressure distribution maps as measured on medial (M) and lateral (L) tibial plateau when varying the condition of the medial meniscus: natural state (upper left), partial meniscectomy of the medial meniscus (upper right), subtotal meniscectomy of the medial meniscus (lower right), and following implantation of the NUsurface Meniscus Implant (lower left). full color online

the joint morphology of a specific patient, increase conformity, and improve pressure distribution.

Dynamic Stability

The stability of the implant under dynamic loading conditions was investigated in a human cadaver-based, robotic knee dynamic simulator.[36] Eight cadaveric knees were placed on a robotic manipulator (Rotopod R2000, Parallel Robotics System, Hampton, NH) in a way that retains as much soft tissue as possible. Motion and loading conditions were simulated dynamically by replicating the loads and knee flexion motion, for different sizes of the implant and for different surgical conditions or incorrect joint preparation conditions to test the sensitivity toward these parameters. In the majority of the cases, the implant was found to be stable. Implantation of an undersized implant and the presence of an anterior cruciate ligament tear increased the risk for subluxation/dislocation.

Other dynamic tests of the implant included a mixed-mode wear test, which was conducted according to ISO 14243. Axial load, together with flexion-extension, internal-external, and anterior-posterior movements were applied on the implant, using MRI-based Co-Cr replicas of tibia and femur. Five million mixed-mode cycles were applied on each specimen and wear was measured using gravimetry every million cycles. The average wear rate over 5 Mc was found to be <20 mg/Mc. The long-term wear rate is even lower, and close to zero since the "wear-in" rate measured in the first 3 Mc contributed most to the average value. This transient wear behavior may be linked to the fact that the meniscus implant articulates against existing joint surfaces, in contrast to a total joint replacement, where tolerances can be tailored in advance to assure full film lubrication. As the meniscus implant is compliant, it undergoes moderate and controlled creep over time,[35] and it is believed that such adaptation to the joint, typically after 2 to 3 million load cycles, improves the lubrication regime considerably thus reducing the wear rate. The implant's mechanical properties and functionality remained similar to those measured before the test.

Large Animal Study

A large animal study in sheep was used to evaluate the biological response exerted by the PCU implant when it articulates against cartilage, under load. It was hypothesized that the PCU meniscus could provide a protective effect on the underlying cartilage when subjected to repeated loading in the absence of the natural meniscus. The cartilage condition of sheep implanted with a PCU meniscus, following a total meniscectomy, was compared with the cartilage of the intact contralateral joint by using the Modified Mankin Score.[37]

Six ewes (1 to 2 y, 60 to 80 kg) were implanted with a PCU meniscus substitute following a full meniscectomy of the medial meniscus. Animals were killed after 3 (n = 3) and 6 (n = 3) months. Cartilage and surrounding soft tissues of both knees were assessed macroscopically and by hematoxylin and eosin and Safrinin-O staining using a semiquantitative modified Mankin grading scale,[38] with the contralateral knee serving as control.

In general, the sheep tolerated the operations well, stood upright immediately and bore weight on their operated hind limbs. Periodic physical examination indicated a full range of motion, no weight loss, and no signs of distress. The PCU implant was durable and remained well-secured throughout the trial period. Gross and microscopic examinations of the explanted PCU implant's surfaces did not reveal any changes in their structure. No inflammatory cellular infiltration was observed in the joint. Macroscopically, cartilage in direct contact with the implant was preserved well and did not show significant degeneration. In most sheep, the main change in soft tissue was fibrosis of the joint capsule and other regional structures. Histologic analysis showed that the total modified Mankin osteoarthritis scores were relatively low in both groups (< 45 of 140 possible.) At both 3 and 6 months, there was a trend toward an increase in the total scores, although these differences were not significant. Good preservation of articular cartilage was observed generally, particularly on the femoral condyles and tibial plateau. The histologic changes observed in this study were generally mild, as previous studies have shown significant loss of cartilage structure and properties following meniscectomy.[39,40] These findings imply that a compliant PCU implant can delay the progression of degenerative cartilage changes in the short term.

Surgical Technique

The implantation of the NUsurface Implant is typically done under general anesthesia and with a femoral nerve block in place. A tourniquet is applied high on the operative thigh followed by placement into a rigid thigh holder. The opposite nonsurgical leg is placed in a stirrup leg holder with the leg abducted and rotated out of position to have appropriate access to the entire medial side of the affected leg. The lower half of the bed is flexed and appropriate positioning of the lumbar spine is confirmed. The patient is given antibiotics before inflation of the tourniquet. Appropriate fluoroscopic access and multiplanar views are confirmed before prepping and draping. After prepping and draping a timeout is performed and vertical arthroscopic portals are initiated after the tourniquet is elevated.

Index arthroscopic visualization is critical to making the final assessment for implant inclusion. Settling upon the medial compartment it is very critical to have excellent exposure with significant stress on the knee to allow for appropriate visualization of the posterior horn of the meniscus. Meniscal remnant preparation is of critical importance. A variety of sharp side biters and up biters should be utilized to form a meticulous 2 to 3 mm vertical wall remnant (Fig. 4A). If the posterior meniscus root is incompetent, the patient should be disqualified from this procedure. Back biters and direct side biters can be utilized to work around the anterior horn of the medial meniscus. Anterior meniscus preparation can be completed through the vertical arthrotomy by extending the medial portal superiorly and inferiorly for ~10 to 12 cm. Once the anterior arthrotomy is completed, a portion of the fat pad and scarring from prior surgery may be resected and retractors can then be placed for appropriate visualization. The arthrotomy may need to be extended for appropriate access to the medial compartment. Final anterior meniscus preparation can be done anteriorly. Traction sutures can be placed on the anterior meniscus to allow for retraction when sizing the implant (Fig. 4A).

On the basis of the preoperative templating, the NUsurface trial of relevant size (7 in total) is opened. Sturdy trial clamps are available and should be used. The most challenging portion of the surgery is to insert the trial/implant. Typically an assistant can be very helpful. With the knee hyperflexed and the tibia externally rotated, the meniscus trial is held face on directly over the anterolateral aspect of the condyle. With the knee hyperflexed and the tibia externally rotated, and the meniscus implant held firmly against the anteromedial condyle, the knee is taken from a hyperflexed externally rotated valgus position into extension from the assistant while the

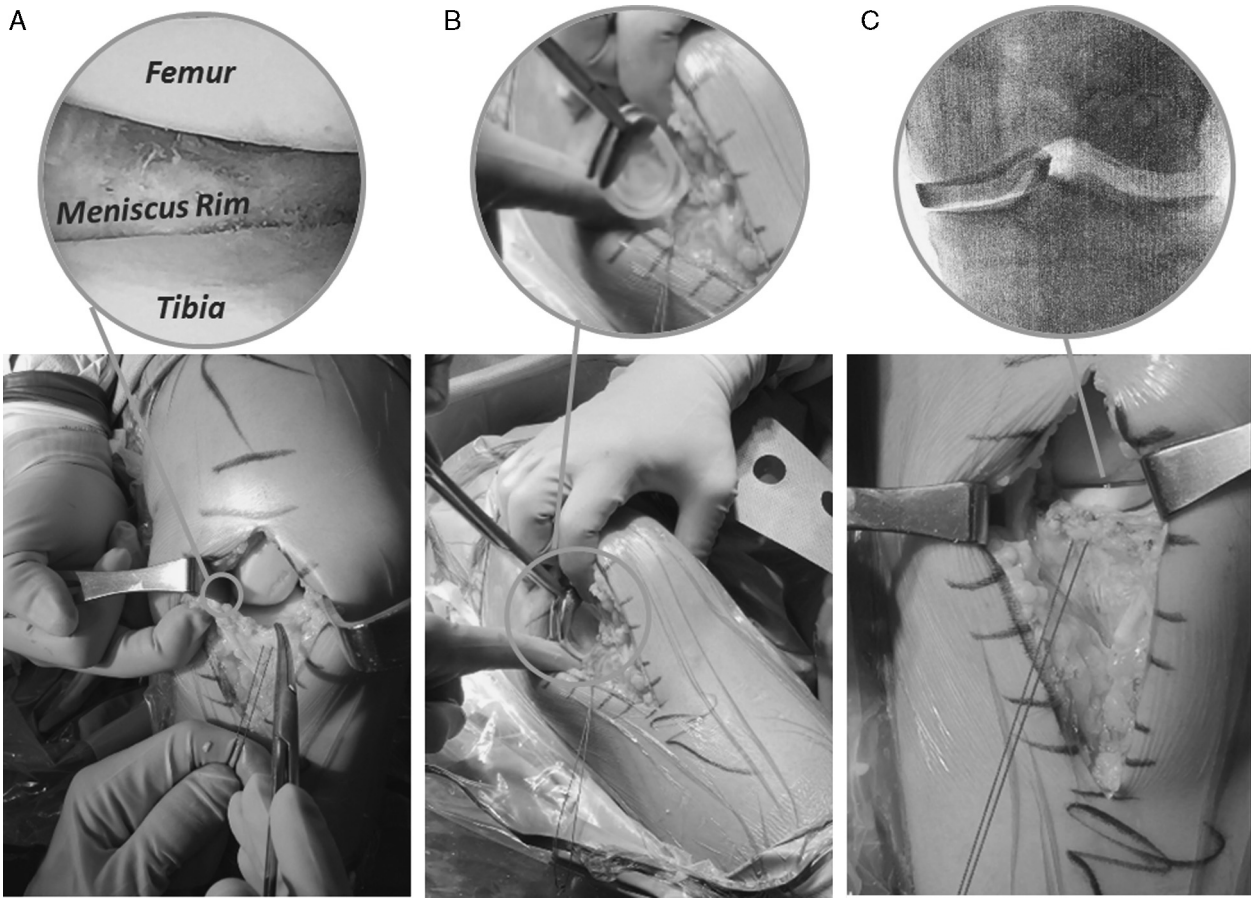

FIGURE 4. A, Photograph showing completed arthrotomy with sutures in place to prepare for trialing of the implant. B, Starting position for insertion of the trial/implant. C, Reduced trial with sizing confirmed by biplanar dynamic fluoroscopy. full color online

surgeon places a strong posterior force holding the meniscus implant clamp, allowing it to reduce using this coupled motion (Fig. 4B). Certainly every patient is different with variable anatomy. This reduction maneuver may need to be repeated with varying degrees of stress, flexion, and external rotation of the tibia.

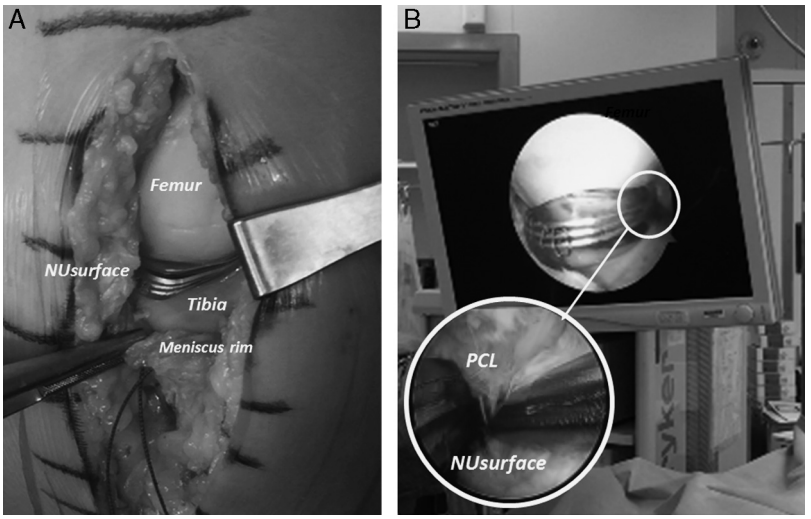

FIGURE 5. A, Open arthrotomy demonstrating final NUsurface implant with anterior meniscus retracted. B, Arthroscopic image and close-up view inspecting the NUsurface implant under dynamic conditions to assess mobility and rule out any boney or ligamentous impingement. PCL indicate posterior cruciate ligament. full color online

Once the trial implant is inserted, the knee is taken through a range of motion with direct visualization. This implant is designed to move like the native meniscus. Close attention is paid to conformity with the distal femoral condyle. Medial collateral ligament stability is checked as well. Biplanar active fluoroscopy is also very helpful to look at the behavior of the meniscus in relationship to the medial joint (Fig. 4C). Overall sizing determination is mostly dependent upon visual inspection of the meniscus relative to the femoral condyle. From a radiologic standpoint, it is preferred to have a slightly larger than smaller implant. It is recommended to trial the next appropriate size if in fact there is any question on the conformity.

At times removing the trial component can be challenging as well. In deep flexion the Kocher can be used with traction placed on the anterior meniscus to allow the NUsurface implant clamp to be applied to the anterior NUsurface trial. Deep flexion, external rotation, and valgus mechanisms will help to release and remove the meniscus implant. Copious antibiotic irrigation is utilized. The appropriate size implant is opened and confirmed by the operating surgeon and is placed into the knee in a similar manner as the trial. The knee is again taken through a range of motion to confirm conformity to the femoral condyle and stability. It is important to carefully inspect and remove any boney or soft impingement at this time. Further copious irrigation is utilized and wound closure is performed. The arthroscopic equipment is kept sterile. At the end of closure it is reinserted into the anterolateral portal to visualize and confirm from 1 last perspective appropriate positioning, sizing, and stability of the implant (Fig. 5). If there is any concern for posterior stability, a posterior medial portal can be utilized for accurate visualization if needed. The arthrotomy is closed in standard manner with a subcuticular closure and the implant is evaluated arthroscopically for visualization and assessment of the meniscus implant to confirm no boney or soft tissue impingement.

The knee is injected with Marcaine $\times 30$ mL. A bulky dressing wrap is applied after final closure. A knee immobilizer is placed with the knee in extension. The patient is discharged to home on the same day of surgery.

Clinical Experience

The NUsurface Meniscus Implant has not been approved by the Federal Drug Administration and is currently under clinical investigation in the United States. A series of 130 middle-aged patients in Europe and Israel have been treated so far with the NUsurface Meniscus Implant for medial knee pain, due to a medial meniscus tear and/or a previous meniscectomy. Patients with severe cartilage loss (grade-IV cartilage loss according to Outerbridge scale) or knee instability were excluded from the study. The primary clinical outcome was pain relief and improved function as measured by the Knee Osteoarthritis Outcome Score (KOOS) scale, with secondary outcomes measured by International Knee Documentation Committee (IKDC) and visual analogue score-pain scales. MRI scans were conducted periodically as well, to evaluate the condition of cartilage over time. Analysis of the data for a minimum of 24 months (average follow-up of 38.9 mo, range, 1 to 60 mo) indicates implantation of the NUsurface Meniscus Implant is effective in reducing pain, increasing function, and improving quality of life. Each of the Patient Reported Outcome measurements (KOOS, visual analogue score, IKDC, and EQ-5D) improved at each follow-up visit. The 24-month mean values for KOOS Pain and KOOS Overall (both primary endpoints) and IKDC (a secondary endpoint) were all statistically significantly higher/better ($P < 0.05$) than preoperative/baseline.

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