Despite technical improvements in limb salvage procedures, amputation continues to be prevalent. In 2005, an estimated 1.6 million individuals in the United States were living with limb loss; by 2050, this number is expected to increase to 3.6 million. Prostheses are meant to enhance mobility, functionality, independence, safety, and quality of life for amputees. After World War II, dramatic developments in prosthesis technology occurred, mainly based on the incorporation of electromyography sensors, motors, and microprocessors. Unfortunately, the primary limb–prosthesis interface (ie, the socket) has not kept pace with these advances. The socket connection leads to the residual limb undergoing excessive stresses and pistoning (vertical movements within the socket), resulting in skin irritation and ulcers, often considered the major reasons amputees reject prostheses.

The idea of directly connecting a limb prosthesis to the skeleton was conceived at least 50 years ago. However, real clinical success was not achieved until 1990, when Swedish professor Per-Ingvar Brånemark inserted dental fixture–like implants in the femurs of a young woman with bilateral transfemoral amputation. The patient could ambulate with crutches with the transcutaneous prosthesis and continued using it for 23 years. The success of the first clinical trial created great interest among bone researchers, clinicians, and engineers in Europe. In Sweden, a series of clinical trials with dental fixture–like implants were performed by Dr Rickard Brånemark. Patients with different types of limb loss, including transfemoral, transradial, transhumeral, and thumb amputations, were treated and had positive outcomes. In 1998, the Integrum AB Company was founded in Gothenburg and began producing standard and custom-designed Osseoanchored Prostheses for the Rehabilitation of Amputees (OPRA). In 1999, another bone-anchored prosthesis connecting system based on press-fit osseointegration, later named the Integral-Leg-Prosthesis (ILP), underwent clinical trials in Germany. The project was led by Dr Horst Aschoff. The implant design is derived from the noncemented femoral stem that is widely used in hip replacement surgeries. The implant devices and surgical techniques have undergone several major modifications. With the latest

**abstract**

The direct attachment of the osseointegrated prosthesis to the skeleton avoids the inherent problems of socket suspension. It also permits physiological weight bearing, improved range of motion in the proximal joint, and osseoperceptive sensor feedback, enabling better control of the artificial limb by amputees. This article describes the osseointegration program in Sweden based on the use of bone-anchored prostheses for transfemoral amputation rehabilitation. The authors discuss in detail the patient-centered evaluation, surgical technique, and postoperative rehabilitation protocol. The outcomes of a prospective study of transfemoral amputees using the bone-anchored prostheses are presented. [Orthopedics. 2018; 41(2):75-80.]

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Trending in Orthopedics

implant system, an improved success rate has been reported for the OPRA devices.9

The concept and technique of a transcutaneous endo–exo prosthesis, championed by Drs Brånemark and Aschoff, spread rapidly throughout Europe and then to Australia and Mexico.10 In 1999, the first prospective study with a standard implant design, surgical technique, and postoperative rehabilitation protocol began in Sweden with a cohort of 51 patients. The cumulative success rate of 92% at 2 years,11 an acceptable complication rate, and reports of dramatic improvements in quality of life11-14 led to the OPRA device being approved by the US Food and Drug Administration for rehabilitation of above-the-knee amputations in 2015. This led to renewed interest in amputation surgery and efforts to develop transcutaneous implant systems in the US orthopedic community. Among these efforts, the Compress transcutaneous device (Integrum, Mölndal, Sweden) is moving from bench to bedside. The system is derived from the Compress distal femur replacement device (Zimmer Biomet, Warsaw, Indiana), which induces osseointegration by axial compression load to the distal bone end and likely has a theoretical advantage of avoiding distal bone resorption due to stress shielding.15

This article describes the Swedish experience with bone-anchored prosthesis surgery for transfemoral amputees based on the application of the OPRA implant system. The technique is complicated, and the results are dependent on adequate training and precise technique. The authors’ experience may help orthopedic surgeons to avoid surgical mistakes and improve clinical outcomes. Complicated and controversial issues such as management of the skin–bone–implant interface, surgical indications, and postoperative rehabilitation are discussed.

Materials and Methods

Patient-Centered Evaluation

The evaluation of patients who require a transcutaneous osseointegration prosthesis involves teamwork and intimate collaboration among the orthopedic surgeon, radiologist, prosthetist, and physiotherapist. Prior to their first visit with the osseointegration team, patients complete the EuroQol-5 Dimension and Short Form-36 Health Survey, documenting their health status. The Questionnaire for Persons with a Transfemoral Amputation is used to evaluate prosthesis use and mobility. During the visit, a thorough history, including the reason for amputation, post-amputation complications, time and duration of radiotherapy for patients with tumors, phantom limb pain and neuroma pain, and other musculoskeletal diseases (eg, osteoarthritis and osteoporosis), should be obtained. A detailed physical examination, including measurement of the length and shape of the stump, evaluation of skin conditions (eg, the presence of scars and the position of skin grafts), muscle strength and/or contracture of the hip joint, and palpation of painful neuroma, should be performed. Patients are profiled according to risk factors, including age, sex, body mass index, residual femur geometry, presence of disuse osteopenia, history of radiotherapy, diabetes control, smoking status, and medications.

On the basis of the orthopedic and the oral and craniofacial osseointegration experience, the bone-healing potential is the most important factor for successful treatment. The intimate contact between bone and the device is crucial for implant stability and is the primary barrier to the penetration of bacteria, which are unavoidably colonized in the skin–bone–implant interface.16 The authors consider a previous history of radiotherapy17 and heavy smoking18 negative prognostic factors for treatment. Evidence is lacking regarding the detrimental effect of diabetes19 on the survival of osseointegration implants, and surgery may be indicated for patients with adequate glycemic control. Aging and age-related osteopenia adversely affect the initial stability and delay osseointegration.20 However, the authors’ experience indicates that because of decreased muscle strength and balance, older patients are even more dependent on a prosthetic device to maintain an independent lifestyle and are more satisfied with the outcome of a bone-anchored prosthesis. One case in the authors’ series involved an elderly patient with a dysfunctional prosthesis who rejected extraction of the non-osseointegrated implant because he felt that it still worked much better than the socket one.

Next, patient goals need to be considered. Although the OPRA system provides increased naturally proprioceptive feedback and prosthetic control to the users, the current implant devices cannot resist the stresses induced by sports. Mechanical failure of the prosthetic components is not uncommon for active or heavy users of the device. The system is contraindicated for patients who expect to participate in vigorous sports activities including running and jumping. Patients should also know that phantom limb pain cannot be solved by the osseointegration system, although relief of neuroma pain sometimes occurs due to avoidance of socket compression. The psychological status and compliance of patients are particularly noteworthy. Premature excessive mechanical overloading may lead to fibrous integration, which results in chronic weight-bearing pain and ultimately septic implant loosening. Also, patients who have disuse osteopenia need an extended rehabilitation program to obtain adequate bone stock in order to match the elastic modulus of the implant. A lack of patience and compliance with the tedious rehabilitation program may lead to the treatment being abandoned.

Computed tomography scans and plain radiographs should be obtained. Distal femoral cortical thickness and residual bone length and geometry are important in determining the implant and postoperative rehabilitation. With the OPRA system, at least 2 mm of cortical bone around the device is required for matching the...
elastic modulus of the implant. To avoid over-reaming of the medullary canal, the authors emphasize preoperative determination of implant size based on computed tomography scans. If exostosis around the distal femur end is present, its location and size should be known and used. Bone tissue usually provides a better anchor place for myotenodesis of the residual muscle than periosteum. Transfemoral amputations above the lesser trochanter level are challenging. In these cases, the authors recommend bone graft augmentation with prolonged rehabilitation. Patients should be informed of the higher failure rate and prolonged rehabilitation period.

**Surgical Technique**

The current commercially available bone-anchored prosthesis systems have 3 major components: the bone-anchoring part for osseointegration; the transcutaneous part for connection to the outer prosthesis; and the connector(s) for bridging the bone-anchoring part and the transcutaneous part. The intraosseous part of the device is designed with outer threads for osseointegrating with the inner surface of the cortical bone. The distal part contains a socket, which holds the skin-penetrating (transcutaneous) male part for abutment by press-fitting and securing it with an abutment screw.

Osseointegration operations are usually performed in 2 stages. Single-stage surgeries can be performed in selected patients with optimal bone quality and good compliance. This is in accordance with the experience of Al Muderis et al\(^\text{11}\) with ILP devices. The authors agree that a single-stage surgical protocol reduces perioperative risks as well as bleeding, pain, hospital stay, and likely the rehabilitation period. However, the long-term outcome is not known. On the basis of the experience with dental osseointegration, the authors do not recommend a single-stage surgery for patients who receive bone graft augmentation and who present with disuse osteopenia or inadequate bone stock in the bone–skin–implant interface.\(^\text{22}\)

**Stage 1 Surgery**

Unlike the application of internal fixation materials in orthopedic surgery, osseointegration is a biological process rather than a mechanical concept. For treatment to be successful, osseointegration with living bone must be obtained. At the stage 1 (S1) surgery, periosteum of the distal bone end should not be stripped. To avoid thermal damage to osteoprogenitor cells, the bone medullary canal should be gently reamed and threaded. Bone marrow content is saved after each reaming and tapping step because it contains a much higher number of mesenchymal stem cells than peripheral cortical bone. The surface of the intraosseous part of the device is covered with bone marrow before insertion into the medullary canal. The authors usually insert the intraosseous part of the device approximately 2 cm deeper than the distal bone end to gain a reserve bone volume for potential distal bone resorption. Close contact of the device threads to the inner cortex is necessary, and good primary rotational stability usually indicates the possibility of early weight bearing. However, for patients with severe osteopenia, the authors do not recommend over-reaming the bone canal. A thin bone cortex is difficult to match with the mechanical modulus of the titanium implant. Weight-bearing pain and cortical bone resorption due to stress shielding are more likely to occur. If primary stability cannot be obtained during S1 surgery, secondary stability can be expected after a healing period of approximately 12 weeks. However, a strictly controlled rehabilitation program is mandatory.

A “living” and “integrated” bone–skin–implant interface is a prerequisite to avoiding complications of skin opening. Another key step in S1 surgery is to create a well-osseointegrated bone end. For standard operations with diaphyseal fixation, bone debris from the reaming and tapping procedures is saved and sometimes additional cancellous bone graft from the iliac crest is used to fill the gap between the intraosseous component and the distal inner bone cortex to ensure an optimal distal bone closure. The bone graft is compacted densely with a special instrument and kept in place around the healing components with compression graft screws. If the quality of the distal bone end is inferior due to disuse osteopenia or a defect, a cylindrical bone graft is harvested from the iliac crest using a trephine burr and is then transplanted between the distal inner cortex and the intraosseous component with a compression graft screw. Once all components are in place, the periosteum is closed, followed by suture closure of the muscle, subcutaneous tissue, and skin. The major part of the S1 surgery is done intramedullarily; thus, pain is not severe after surgery. Patients can be discharged approximately 2 days postoperatively and can start using their socket prosthesis shortly after discharge. As with all orthopedic cases, pain from the iliac crest donor site is common.

**The Healing Period**

There has been no evidence-based study to determine the optimal healing period between S1 and stage 2 (S2) surgeries for orthopedic osseointegration. In a prospective study from Gothenburg evaluating the cumulative success rate and complications of the OPRA device in transfemoral applications, a healing time of 6 months was used.\(^\text{11}\) This was largely based on Per-Ingvar Brånenmark’s osseointegration theory for dental implants in the 1970s. Because patients are allowed to use their original socket prosthesis shortly after surgery, there is no demand to shorten the healing period as observed by the osseointegration team. However, experience from other centers using the ILP devices indicates that a 6-week healing period is probably long enough to allow stable osseointegration. The authors’ recent experience shows that a shorter period between S1 and S2 surgeries can reduce weight-bearing pain during rehabilitation, which is probably due to bone resorption and torsional stresses that occur if the implant is inserted without early weight bearing. The authors currently
opt for a 6- to 8-week healing period after standard operations with implants in the diaphysis and a 12-week healing period for patients without primary stability and patients who receive bone grafts during the S1 surgery.

Stage 2 Surgery

Unlike the relatively stable situation in oral and craniofacial applications, in the extremities, the osseointegration implant system is under much greater and unpredictable stresses during movement. Muscle contraction and relaxation during activity result in the skin edges undergoing frequent traction and twisting stresses against the transcutaneous abutments. The technique for the S2 surgery was developed in the 1990s. Initially, the importance of direct attachment of the dermal flap to bone was not known, and attempts were made to attach the muscles and subcutaneous fat directly to the abutment. However, the soft tissue could not be “integrated” to the implants. The “gap” between the soft tissues and the abutment caused frequent inflammation and infection around the skin openings, which led to several later revision surgeries and frequent antibiotic treatments. The experience with the osseointegrated Baha hearing aid (Cochlear Ltd, Mölnlycke, Sweden), which emphasized the strict removal of all hair follicles in the skin in a 3-cm radius from the abutment opening and adequate soft tissue reduction at the end of the stump, was adapted later.  

This technique effectively reduces the risk of soft tissue problems.

During the S2 surgery, the transcutaneous components are removed. A careful check of the bone–device interface should be performed. Nonvital bone graft needs to be removed because skin flap attachment to it does not last and it is susceptible to bacterial penetration. The muscle endings are sutured to the periosteum at least 1 cm proximal to the distal bone end. The authors advocate the attachment of the functional muscle groups to bone or exostosis with osseous sutures. The subcutaneous fat is removed at least 3 cm from the skin opening to guarantee a thin, hair follicle–free, immobile skin around the abutment. Direct healing of skin to bone without any mobile soft tissue interface is crucial to reduce future soft tissue problems. The male abutment is then inserted through the stoma into the press-fitting part of the device with compression applied by the abutment screws. Suction drains are routinely used for 3 to 4 days postoperatively to maintain negative pressure under the skin flaps. Patients can be discharged 1 week postoperatively.

The functional muscles, including the adductors, rectus femoris, hamstrings, and sartorius/gracilis (if still preserved from earlier amputation), take their origin above the hip joint. The importance of adductor myotenodesis in gait kinetics for amputees has been described previously. The authors noticed that the rectus femoris and hamstrings change from being knee joint controllers to effective hip extensors and flexors, hence enabling better control of the prosthesis.

Postoperative Rehabilitation Protocol

Patients begin rehabilitation approximately 2 weeks after S2 surgery by performing gentle exercises (ie, range of motion exercises without full voluntary muscle contraction) to prevent development of hip joint contractures. At 4 to 6 weeks after S2 surgery, when the skin penetration area and the soft tissue are adequately healed, more active training begins. The initial training includes axial weight bearing and weight shifting with standing on a short training prosthesis. Patients can measure the amount of weight put on the short training prosthesis using a bathroom scale. In addition, patients are given a general exercise program emphasizing more active training of hip range of motion and muscle strength. The aim of the general exercise program is to stimulate bone strength by loading the bone–implant unit in additional directions other than axial.

For patients with good bone quality and optimal primary stability, weight bearing on the short training prosthesis starts at 20 kg and is performed twice a day for 30 minutes. Patients are instructed to increase weight bearing by 10 kg each week until weight shifting to full body weight is achieved painlessly. Most patients report some pain during weight-bearing training. Pain at level 2 to 3 on the visual analog scale is considered safe. However, pain above level 5 on the visual analog scale should be avoided, with weight-bearing exercises decreased to a more pain-free level. For all patients, the protocol includes 5 to 6 weeks of training with the short training prosthesis before prosthetic gait training on the definitive prosthesis starts. Thus, prosthetic gait training starts at approximately 12 weeks after S2 surgery. During the first 2 prosthetic training weeks, the authors instruct patients to use the prosthesis a maximum of 2 hours per day, only indoors, and with the support of 2 crutches with very limited weight bearing on the prosthetic foot. The time that the prosthesis is worn and the prosthetic activity and weight bearing are gradually increased in the following weeks. Patients achieve full-day prosthetic use after 4 to 6 weeks. During the first 3 months of prosthetic use, walking should be done with double support (crutches or canes). Based on radiographs and the clinical status approximately 6 months after S2 surgery, a decision is made by the team regarding walking without a walking aid support both indoors and outdoors. Again, pain above level 5 on the visual analog scale should be avoided, and individual progress should be slowed so as not to risk overloading the ongoing integration of the bone–device interface. To summarize, patients following the normal-speed protocol are treated for approximately 6 months after the S2 operation. For patients with poor skeletal condition or inadequate primary stability, an individually designed, prolonged training protocol is used that can last more than 12 months after the S2 surgery.
RESULTS

Clinical Outcomes

Between 1999 and 2007, a total of 51 patients with 55 transfemoral amputations, including 6 bilateral transfemoral amputations, were consecutively enrolled in a prospective, single-center nonrandomized study and followed for 2 years. All operations were performed at Sahlgrenska University Hospital, Gothenburg, Sweden. Removal of the implant was regarded as the endpoint signaling failure. The main reasons for amputation were trauma and a malignant tumor. The patients were followed at 3, 6, 12, and 24 months after the S2 procedure. All complications were recorded. Two validated, self-reported questionnaires, the Questionnaire for Persons with a Transfemoral Amputation13 and the Short-Form 36 Health Survey,25 were used to assess functional outcome and health-related quality of life. Both were completed before the S1 procedure and at 12 and 24 months after the S2 procedure.

Three patients were removed from the study for reasons unrelated to the implant (1 unrelated death, 1 severe dysfunction of the contralateral knee, and 1 loss to follow-up). Implants were removed from 3 patients during the study period because of inadequate osseointegration and from 1 patient shortly after the study ended because of deep infection. Therefore, the cumulative survival rate was 92% after 2 years (95% confidence interval, 80% to 97%). At 24 months, 40 (89%) of 45 patients reported daily prosthesis use, compared with 57% (29 of 51) before the implant was inserted. One patient had severe pain and did not use the prosthesis at all, and 4 patients (2 with bilateral transfemoral amputations) reported not using the prosthesis daily. The mean prosthetic use score improved from 47 (range, 0 to 100) prior to the S1 procedure to 79 (range, 0 to 100) 2 years after the S2 procedure (P<.0001). All Questionnaire for Persons with a Transfemoral Amputation scores improved (P<.0001), indicating improved prosthetic mobility, fewer problems, and an improved global situation. The overall situation as an amputee was reported to be improved among 31 (69%) of the patients receiving the S1 operation. The Short Form-36 Health Survey physical function scores showed that general quality of life also improved (P<.0001).

Complications

Superficial infection was the most frequent complication, occurring 41 times in 28 patients (infection rate, 54.9%). Most were treated effectively with oral antibiotics. Nine mechanical complications with the abutment and/or the abutment screw, resulting in fracture or bending of the abutment and/or the abutment screw, were reported in 4 patients. Six of these occurred in the same patient. All patients returned to normal function after the damaged components were replaced. There were no mechanical complications related to the intramedullary components.

CONCLUSION

After more than 25 years of effort by the pioneers developing the transcathetaneous bone-anchored prosthesis devices, the concept of orthopedic osseointegration is gaining acceptance in the orthopedic community. The outcomes with OPRA and ILP devices have confirmed the tremendous advantages of bone-anchored prostheses over socket prostheses. The skeleton exerts function in weight bearing again, and the stability of the osseointegrated connection causes the wearer to perceive a more realistic and appropriate kinesthesia. Because no forces are transmitted through soft tissue, the residual skeletal muscles in the stump are free to exercise their new function in moving the hip joint. With the rapid advances in technology and clinical experience, the authors believe that the indications for osseointegration treatment will broaden in the near future. The concept that bacteria do not penetrate the skin–bone–implant interface with well-osseointegrated implants needs to be clarified by laboratory evidence.

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