CT Lesion Model-Based Structural Allografts: Custom Fabrication and Clinical Experience

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Keywords

X-ray computed tomography · X-ray CT · Individualised medicine · Customised transplant · Bone transplantation · Allograft

Summary

Background: Patients requiring knee and hip revision arthroplasty often present with difficult anatomical situations that limit options for surgery. Customised mega-implants may be one of few remaining treatment options. However, extensive damage to residual bone stock may also be present, and in such cases even customised prosthetics may be difficult to implant. Small quantities of lost bone can be replaced with standard allografts or autologous bone. Larger defects may require structural macro-allografts, sometimes in combination with implants (allograft-prosthesis composites). **Methods:** Herein, we describe a process for manufacturing lesion-specific large structural allografts according to a 3D, full-scale, lithographically generated defect model. These macro-allografts deliver the volume and the mechanical stability necessary for certain complex revisions. They are patient- and implant-matched, negate some requirements for additional implants and biomaterials and save time in the operating theatre by eliminating the requirement for intra-operative sizing and shaping of standard allografts. **Conclusion:** While a robust data set from long-term follow-up of patients receiving customised macro-allografts is not yet available, initial clinical experience and results suggest that lesion-matched macro-allografts can be an important component of revision joint surgery.

Schlüsselwörter

Röntgen-Computertomographie · Röntgen-CT · Individualisierte Medizin · Transplantat-Sonderanfertigungen · Knochentransplantation · Allogenes Transplantat

Zusammenfassung

Hintergrund: Der Revisionsarthroplastik im Hüft- und Kniegelenk liegt häufig eine komplexe anatomische Defektsituation zugrunde, welche die Möglichkeiten der chirurgischen Behandlung einschränkt. Spezielle und teilweise aufwändig produzierte Sonderanfertigungen von Endoprothesen sind dann oft eine der wenigen Behandlungsmöglichkeiten. Ausgedehnte Knochendefekte können die Implantation hochspezifischer Prothesen zusätzlich erschweren. Während kleinere Defekte mit Standardprodukten (Knochengranulate/-chips) oder autologem Knochenmaterial gefüllt werden können, konkurrieren für die Wiederherstellung größerer Knochendefekte strukturelle Knochengewebe-transplantate (auch in Kombination mit Implantaten) mit Metallaugmentationen. **Methoden:** In dem nachfolgenden Artikel wird der Prozess des Designs und der Herstellung von strukturellen Knochengewebe-transplantaten basierend auf der computertomographischen Erfassung des Knochendefekts beschrieben. Solche Transplantate ermöglichen den Ersatz der verlorenen Knochenbasis sowie die Wiederherstellung der mechanischen Stabilität in schwierigen Revisionssituationen. Als Sonderanfertigungen sind diese Transplantate optimal an die Anatomie des Patienten und an eventuell ko-transplantiertes Prothesenmaterial angepasst. Dank dieser Punkte kann die Dauer der Operation deutlich verkürzt werden, da ein intraoperatives Anpassen von Standardprodukten sowie eine Entnahme autologen Materials entfällt. **Schlussfolgerung:** Erste klinische Erfahrungen zeigen, dass defektbasierte Sonderanfertigungen von Makrotransplantaten einen wichtigen Platz unter den Behandlungsmöglichkeiten bei Revisionsarthroplastiken besetzen können. Die Ergebnisse der bisher beobachteten Langzeitverläufe sind vielversprechend, bedürfen aber einer Verifizierung durch weitere klinische Daten.

Introduction

The number of primary hip and knee replacement operations continues to increase as the indications broaden and the average life expectancy of patients and their demand for activity increase [1]. Between 2003 and 2008 there was a concomitant increase in revision arthroplasty. During this time, the number of knee revisions increased by a factor of 2.24 and that of hip revisions by a factor of 3.4 (fig. 1a,b).

Moreover, multiple (third and even fourth) revisions of implanted prosthetic joints are becoming routine surgical assignments. These cases may be associated with major bone defects as a consequence of previous surgery and/or extensive age and/or disease-related degeneration [2, 3]. Specialised endoprosthetic components can be used to treat many types of defects. However, when bone loss becomes extensive, alternative treatments such as custom implants, allograft augmentation, or combinations of custom implants and allografts (allograft-prosthesis composites) may become necessary [1, 4–6]. As a consequence, surgeons and manufacturers of implants and transplants are facing new challenges.

The custom manufacture of total hip (THA) and total knee arthroplasty (TKA) implants is becoming commonplace. Endoprosthesis manufacturers already provide patient-specific implant services. However, the cost-benefit ratio of customised implants is still under discussion. Significant differences in clinical outcomes between standard and custom implants have been shown to be either non-existent or are only found in specific clinical settings or within individual clinics [7, 8].

However, recent data suggest that custom implants improve outcome in young patients after a 15-year follow-up [9]. Furthermore, custom-made cement-less components in THA for patients with skeletal dysplasia had lower revision and complication rates with comparable function and higher mid-term survival [10].

Bone allografts are generally indicated in, but not limited to situations including bone replacement during endoprosthetic surgery, post-traumatic bone defects, bone tumour surgery, osteotomy or as allograft-prosthesis composites.

While the demand for standard allogeneic bone grafts is high, custom manufacture of structural bone allografts is not well established. Possible reasons include the limited availability of donated tissue and the time-consuming manufacturing process. In contrast to medical device companies, among those tissue banks with the necessary approvals most do not yet have the necessary infrastructure or expertise to offer reliable custom transplant manufacturing services.

Nevertheless, the combination of lesion model-based soft tissue and bone allograft components with standard and/or individualised revision prosthetic products offers patient-specific therapeutic options in situations that are otherwise often associated with unsatisfactory clinical outcomes. In both revision THA and revision TKA structural allografts are a valuable alternative to standard treatment options such as in-

Fig. 1. General data on primary and revision total joint replacement in hip and knee. **a** Number of operations in 2003 and 2008. The number of total hip arthroplasty (RTHA) and total knee arthroplasty (RTKA) revision operations increased by a factor of 3.4 and 2.24 respectively. **b** 5-year course of hip and knee primary and revision surgeries. **c** Age distribution of patients that had revision total hip or knee arthroplasty in 2008. **d** Classification of patients that had RTHA or RTKA in 2008 according to the classification system of the American Society of Anesthesiologists. (Source: BQS Institut für Qualität und Patientensicherheit).

creased resection or component shift, cement or cement and screw reconstruction, metal prosthetic augmentation or impaction grafting [11–13]. For revision TKA, it has been shown, that early results of structural allografts are similar to those of standard metal augmentation [14].

Further studies have been performed to test allograft-prosthesis composites in the reconstruction of the humerus after tumour resection, for the reconstruction of the proximal tibia [15,16] and for total elbow arthroplasty [17–19]. Among the advantages in using structural allografts are the availability of capsular soft tissue attachments with which to reconstruct the salvaged host soft tissues (as demonstrated in the second case study, see below). Potential disadvantages include a higher risk of infection, re-fracture and non-union [20], but the combination of structural allograft and prosthesis may enable each component to provide specific advantages. The allograft can supply soft tissue tendinous and capsular attachment possibilities whilst use of a prosthetic joint can negate articular degeneration and sub-chondral collapse [20]. In a study analysing function and survival in a comparison of allograft-prosthesis composites and mega-protheses in proximal femoral reconstruction [21], significant differences could not be demonstrated. In this indication, allograft-implant combinations appear to be a viable alternative to mega-implants.

The use of structural allografts is indicated in situations where the bone stock present is not sufficient for reliable implantation of endoprostheses or in settings where the im-

Fig. 2. Process flow chart with swim lanes for clinic, implant manufacturer and allograft manufacturer.

provement of bone stock is necessary for likely revisions [22]. In these situations allografts allow reconstruction for sizeable defects [23, 24]. Moreover, for patients with a life expectancy exceeding 10 years, a structural bone graft may be preferable since restoration of bone stock is desirable [25].

Babis and co-workers [3] presented statistics about the long-term function of allograft-prosthesis composites. At 2, 5 and 10 years post operation the percentage of intact, functional implant/transplant combinations was 93, 78 and 69 respectively. This is comparable with other reported data (65–86%) at 10 years [3]. The study identified pre-operative bone loss, the number of previous hip revisions exceeding two and

the length of the allograft used as statistically significant modulators of outcome.

The decision to treat a patient with a custom implant and an individual macro-allograft confronts the surgeon, the implant manufacturer and the allograft manufacturer with significant logistical challenges that can only be met when the individual players collaborate closely from the outset. Such a collaboration is also required to deliver the high level of inter-component precision that is a prerequisite for a successful outcome. Matching the allograft to the bone is described as one of the problems associated with the use structural macro-allografts [3]. This can be solved by custom

Fig. 3. Revision total hip arthroplasty: 62-year-old male patient with artificial left hip after multiple revisions. **a** Post-operative radiograph of a previous acetabular component revision. **b** Acetabular component loosening 15 months after revision. **c** Virtual 3D planning model for the surgery. **d** Lateral view of the physical model with the custom implant attached. **e** Medial view of the physical model with the custom implant attached. The large acetabular defect is visible. **f** Photographs from the early stage of allograft template fabrication. **g** Allograft template nested in the physical model of the defect. The socket later to hold the acetabular component of the implant is visible. **h** Projection lines show the delineation of the two parts later to be produced from two donor bone blocks of the proximal tibia. **i** Initial preparation of a proximal donor tibia. **j-k** The individual allograft components interlock with a dovetail (**j** early shaping, **k** final allograft). **l** The allograft positioned in the physical defect model, confirming fit prior to sterilisation. **m** Intra-operative check of allograft to implant fit, **n** Post-operative X-ray.

preparation and manufacturing. This article describes a procedure for specifying and manufacturing lesion-specific allografts for complex primary and revision arthroplasty within the German regulatory environment. Six patients have been treated at the Robert Koch Clinic (Apolda, Germany) using structural macro-allografts, custom manufactured at DIZG gGmbH (Berlin, Germany). Two of these cases are reported in detail.

Material and Methods

This section provides a general overview of the complete custom allograft process from diagnosis to transplantation. A diagrammatic representation of the process is provided in figure 2.

Informed consent was obtained from all patients prior to treatment.

Diagnosis and Planning

Patients requiring a joint implant revision and for whom such surgery is

Fig. 4. Total knee arthroplasty: 77-year-old female patient with proximal femur nail left, traumatic osteoarthritis of the left knee and necrosis of the patellar ligament. **a** Pre-operative radiograph of the left leg. **b** CT-scan: posterior view of the left knee. **c** CT-scan: lateral view of the left knee. **d** Representative lesion model and allograft template. **e** Mensuration of donor tissue in the initial stage of custom allograft production. **f** Lateral view of the manufactured custom macro-allograft. **g** Posterior view of the manufactured custom macro-allograft. **h** Tibial nail for implant fixation next to the custom macro-allograft. **i** Surgical situation after resection of the remnants of the patellar ligament and the patella. **j** Surgical situation post transplantation of the custom allograft held in place by screws, a Kirschner-wire and the tibial component of the implant. **k–m** Post-operative (8 months) X-rays (**k**, **l** posterior and lateral view of the position of the implant, **m** sunrise view of the transplanted patella revealing its lateral position).

not contra-indicated may be candidates for a combination treatment with a custom implant and an individual allograft when standard, evidence-based treatment options have been depleted.

Once the requirement for a custom implant has been identified, a careful review of anamnesis, imaging as well as clinical and laboratory results is conducted in order to establish whether a custom allograft is also necessary and appropriate. At this early point, although the allograft cannot be specified, it is advisable for the surgeon to contact the allograft manufacturer with a general description of the case so that the allograft manufacturer can start to review released tissues regarding their suitability for manufacturing the necessary component.

Imaging and Lesion Model Construction

X-ray CT data from a single imaging session with constant scale and gantry angle are a pre-requisite for the production of matched implants and grafts. Detailed instructions for this procedure are available from most implant manufacturers. Data for the cases presented in this article were collected on a Somatom Emotion 16 (case 1) and a Somatom Emotion 6 (case 2), both Siemens AG (Munich, Germany). The surgeon supplies such a CT data set to the implant manufacturer where it is used to generate a stereolithographic data file from which a fast-prototype full-scale model is fabricated on a computer-controlled milling machine (fig. 3d,e; 4d). This model is the basis for all further collaboration between clinic,

implant manufacturer and allograft manufacturer and allows the surgeon to precisely plan the placement of graft, implant, plates and screws [26–31].

Planning for Allograft Manufacture

Once the implant design has been finalised, the lesion model is passed on to the allograft manufacturer. The allograft manufacturing technicians continuously review tissue released to manufacturing in order to identify candidate material from which a suitable macro-graft can be manufactured. At this stage, discussions between the allograft manufacturer and surgeon focus on the required characteristics of the allograft. The necessary load-bearing properties and any requirements for anchorage are identified. The allograft manufacturer can then define the nature of the required allograft component so that the surgeon may place an order for a custom graft.

Ordering a Custom Allograft (Germany)

Human tissue transplants are regulated in Germany as medicinal products. There are three recognised active ingredients for bone transplants: Cancellous bone, cortical bone and demineralized bone matrix. Individual marketing authorisations are defined by the active ingredient and the preservation method. Custom macro-allografts are generally manufactured from non-demineralised bone according to the approval for the predominant active ingredient. They may only be manufactured upon written request from a surgeon for a named patient and must be manufactured with the sterilisation, preservation, aseptic processing and packaging methods named in the marketing authorisation for the given active ingredient. However, such a graft must not be in compliance with registered package sizes. Once the surgeon places such an order for the macro-graft, the manufacturer can begin fabrication.

Manufacture of a Custom Structural Macro-Graft

Custom allograft fabrication begins with evaluating donor tissues released to manufacture for suitable structures that meet size and stability requirements. To this end a polyurethane (PU) graft template (fig. 3f,g) is initially generated according to the physical lesion model. The PU model is then used in a selection process for identifying available tissue components that match size and quality criteria. Proximal tibial, proximal and distal femoral components are usually the basis of macro-allografts. Once suitable donor material is identified, the PU model also serves as a template for the final allograft. At this point, a proposal from the allograft manufacturer is sent to the clinic. This proposal details the construction plans for the macro-graft and describes the material selected for manufacture. Once the clinic approves the proposal, manufacturing can begin.

Pre-Sterilisation Manufacture

The tissue for the allograft is initially processed in a clean, controlled but non-classified (CNC) environment. The material necessary for the graft is dissected and separated. Cancellous bone is delipidised by purging with warm water $\leq 37^\circ\text{C}$. Cleaned bone components are then approximately shaped with a band saw and then more precisely shaped with rotary power tools in an iterative process of shaping the component and checking it either against the PU template or for fit in the lesion defect model. Once a satisfactory fit is achieved, the allograft undergoes a final pre-sterilisation process of aqueous rinsing for 16 h.

Sterilisation and Packaging

Allografts are sterilised by a validated method involving the treatment of the tissues with a solution of 1% peracetic acid (Wofasteril (AM); Kesla Hygiene AG, Bitterfeld-Wolfen, Germany) / 24% Ethanol (Berkel AHK Alkoholhandel GmbH and Co. KG, Berlin, Germany) in aqua ad iniectabilia for 4 h with vigorous shaking at a pressure below 200 mbar [32–37].

After sterilisation the custom allografts are aseptically packaged in double sterile bags (Steriking; Wipack B. V. Medical, Sittard, the Netherlands). The custom allografts are stored in a frozen state at -40°C and are finally sent on dry ice to the recipient via courier.

Transplantation Preparation

Prior to transplantation, a final consultation is necessary to check that all components fit together in the model. In this context, the most recent images from the patient are also reviewed. It is also necessary to check that the patient is in an appropriate condition for the operation. The likelihood that prolonged general anaesthesia will be necessary and that post-operative complications may arise should be taken into consideration. Patients should therefore have normal blood coagulation parameters as well as adequate cardiac function and are free from infection and likely to be post-operatively compliant, especially in physiotherapy.

Results

During the last 6 years, a total of 6 (2 male and 4 female) patients have been treated with custom manufactured macro-allografts at the Clinic for Accident, Hand und Reconstructive Surgery of the Robert Koch Krankenhaus in Apolda, Germany. During this time, no adverse reactions or events in relation to the macro-allograft prosthesis composite treatment were recorded.

The average time between planning CT and transplantation was 134 ± 90 days.

Patient Example 1

In a 62-year-old male with essential arterial hypertension, insulin-dependent diabetes mellitus type II and obesity, an initial left-side stage V coxarthrosis [38] producing severe pain and limiting mobility was diagnosed in 2008. A primary THA was carried out in April 2008. Stem loosening was diagnosed in February 2009, and the femoral component was revised in March 2009. Acetabular component loosening was identified in March 2010. The latter was associated with a fracture of the contra-lateral os sacrum. The acetabular component underwent revision in May 2010 (fig. 3a) with subsequent loosening being diagnosed in October 2011 (fig. 3b). An acute local infection with *Propionibacterium acnes* and *Staphylococcus aureus* was diagnosed in November 2011. Complete explantation of the endoprosthesis and replacement with a temporary spacer component was conducted in March 2012.

At this point, initial planning of a 4th revision began. A requirement for a custom-manufactured allograft-prosthesis composite was identified (fig. 3m). Specifically, the infected acetabulum with a type 6 defect [39] and an associated Paprosky [40] type IV stem defect required a THA with filling of the pelvic defect with a custom manufactured allograft and implantation of customised total hip endoprosthesis.

The computer-generated defect data used to develop a defect-correcting therapeutic strategy are illustrated in figure 3c. Figures 3d and 3e show the lesion model and custom implant fabricated for this treatment. The allograft template manufac-

tured from polyurethane is depicted in figure 3f. The desired fit and form of the allograft component with respect to the defect and the implant design can be seen in figure 3g. The size of the allograft component required for this treatment mandated that the component be manufactured from 2 donor tissue blocks. Since the graft would be load-bearing, these two components must interlock in such a way as to prevent their dislocation in the defect. A projection line for the division of the allograft component into 2 interlocking parts can be seen in figure 3h. The initial machining of one epiphyseal tibial component is depicted in figure 3i. The results of the iterative shaping and fit-checking process are shown in figures 3j (early comparison of graft and template), 3k (final) and 3l (final in lesion model). The results of a final intra-operative check of the fit of the allograft component to the implant can be seen in figure 3m.

Each of the 2 components of the structural allograft was manufactured from a proximal tibial epiphysis from a 36-year-old male donor.

The transplant operation was carried out in August 2012. It was successful and free from implant and transplant-related complications. Figure 3n shows the post-operative radiograph demonstrating the position of the total custom hip endoprosthesis.

The early post-operative course was normal apart from slightly elevated inflammatory parameters in the first 14 days post operation. The patient could be released from hospital on schedule and at the time of writing (6 weeks post operation) is mobile with crutches. Limb utility has been restored. A misalignment of the centre of rotation and differences in limb length have been corrected.

Patient Example 2

A 77-year-old female with hypertonia, obesity and a left-sided proximal femur nail presented with traumatic osteoarthritis in the left knee with cystic patellar degeneration, associated necrosis of the patellar ligament and misalignment. The patient also complained of constant pain and required daily analgesic medication (5–6 on the visual analogue scale (VAS)). A maximum walking distance of 500 m and a knee society score of 58 points were also recorded at this time.

A requirement for a custom total knee endoprosthesis and associated structural allograft was identified. The macro-allograft requirements were: compensation of a major anterior proximal tibial defect, complete replacement of the patellar ligament including patella and provision of a significant distal component of the quadriceps tendon for soft tissue anchorage.

The pre-operative situation is depicted in figures 4a (X-ray), 4b (CT) and 4c (CT). The resulting lesion model (left) and graft template (right) are shown in figure 4d. In this case, the primary challenges in tissue matching were associated with the soft tissue components. Figure 4e depict the process of tissue matching during the manufacture of the required graft, figures 4f and 4g show the final macro-allograft.

This allograft component could be manufactured from a single tibial epiphysis of a 27-year-old male donor.

The intra-operative situation is represented in figures 4h (pre-transplantation, custom tibial implant and matched structural allograft), 4i (intra-operative, tibial defect) and 4j (post transplantation and implantation, detailing fixation of the allograft component with screws and a tensioned circumferential wire).

The initial post-operative course in this patient was complicated by a local infection with *Staphylococcus epidermidis* that responded to antibiotic treatment.

Radiographic check-ups demonstrated that the integrity and position of the allograft components was retained throughout the follow-up period. The radiographs in figures 4k, 4l and 4m illustrate the situation 8 months post operation. The ideal position of the tibial allograft component can be seen clearly in figure 4l, and the optimal lateral placement of the patella is evident in figure 4m.

At 18 months post operation, this patient was pain-free (0 on the VAS), could walk distances of 2 km outdoors with a walking stick, was domestically mobile without restrictions or a requirement for walking aids and could flex the knee without pain more than 90 degrees against gravity (knee society score 140).

Discussion

Our experience suggests that custom macro-allografts to be used in revision surgery in combination with custom endoprosthetic implants can be manufactured with an acceptable quality, within an acceptable time frame and according to the stringent requirements of the German regulatory environment. The mean time between initial CT scan and transplantation was 134 days. The allograft component was available within 100 days of ordering. Whilst this can be acceptable for planned elective revision surgery, it contrasts with the 4-week time frame required to manufacture and release standard allogeneic transplants. A significant block of the approximately 100 days required for release of custom-manufactured macro-allografts is associated with the 'screening' of incoming tissue for suitability for manufacture of specific macro-graft components.

Transplant-related complications, reactions and adverse events have been absent so far.

However, this experience is currently limited to the treatment of 6 patients in a single clinic; so it is not yet possible to quantitatively assess clinical outcomes and benefits. In contrast, bone augmentation with standard allografts in endoprosthetic revision surgery is an established method [41].

Even though extensive re-modelling of structural macro-allografts is not to be expected [42], such grafts offer important possibilities with regard to the integration of the graft in host bone. A zone of re-modelling at the interface of well perfused host bone and allograft delivers important stability to

the graft/implant combination [42]. In one study of proximal femoral allograft-prosthesis composites, union of the host bone and the allograft was achieved in 81.9% (59/72) of the cases [3].

While there is currently an absence of level 1, or 2 evidence about whether the use of custom structural allografts has an effect on the lifespan of endoprosthetic implants, the use of such transplants offers ground for expectation of re-stocking the bone material available for future revisions and can therefore be considered as a prudent measure in terms of long-term results as long as there are no associated significant medical disadvantages.

There are clear short-term advantages associated with the use of custom allografts rather than standard products. When successfully manufactured according to precise anatomical lesion models, the former negate all requirements for intra-operative modification of the component. In addition to ensuring that the operation can proceed as planned without having to improvise for unforeseen fixation requirements and thereby avoiding extra direct costs, this correlates with a reduced requirement for operating theatre time and therefore also reduces indirect costs.

These advantages are in part a consequence of a high level of pre-operative planning and the use of modern tools and technologies including 3D medical modelling and planning software and as such represent a partial shift in terms of planning and responsibility from the surgeon to the manufacturer and from the peri-operative to the pre-operative phase. The necessity for thorough planning by all parties makes regular and effective communication between all parties a prerequisite.

Despite the advantages of the application of custom-manufactured transplants based on CT data, there are some caveats to consider:

- i) Inconsistencies between the physical model generated from CT data and the actual anatomical situation in the patient (possibly due to continuing degeneration in the joint, or possibly due to artefacts in the CT dataset being transcribed into the lesion model) may lead to the manufacture of an allograft component that does not fit perfectly. It will therefore usually be expedient to utilise the time available and perform a pre-operative CT scan to ensure the CT data used to produce the physical defect model matches the current defect situation.
- ii) Furthermore, even if the CT data and the physical model are accurate and both implant and transplant produce a perfect fit in pre-operative checks, it may nevertheless prove impossible to carry out the operation as planned if all spatial and navigational requirements for placement of components are not given due pre-operative consideration. This is particularly important in cases where large bone grafts require to be placed in difficult to reach anatomical positions.
- iii) Occurrence of graft resorption cannot generally be ruled out when large avital allograft components are trans-

planted. It is not surprising that in most series a degree of resorption is considered to be evident in radiographic images. However, as long as resorption is limited and marginal and since re-vascularisation of such grafts is usually not extensive, the graft is unlikely to collapse due to loss of mechanical strength during remodelling.

Three retrieval studies in the knee and hip revealed neither re-vascularisation nor resorption [42–44]. However, a meta-analysis by Babis and co-workers [3] evaluated 7 studies analysing the application of allograft-prosthesis composites and calculated the mean level of resorption to be $24.1\% \pm 14.7\%$. Even though this fraction covers all levels of detected resorption (mild, medium, severe), this issue should not be neglected.

There is a theoretical risk of disease transmission associated with the use of allografts. All allograft transplants manufactured in Germany are required by law to undergo a validated sterilisation procedure. Tissue transplants manufactured by DIZG undergo a peracetic acid-based sterilisation process validated in co-operation with the Charité Hospital and the Robert Koch Institute (both Berlin, Germany). This process was shown to effectively eliminate model viral and bacterial populations representative of the array of known relevant pathogenic microorganisms [33]. Although established methods of sterilising tissue transplants can have a negative effect on graft remodelling [45], the advantages of sterilisation in terms of safety can legitimately be considered to outweigh potential disadvantages with respect to remodelling in the case of structural macro-allografts. To some extent, a restricted remodelling capacity can be advantageous since loss of mechanical strength in the critical post-operative phase will be limited as a consequence. A non-remodelled graft generally provides adequate mechanical load bearing capacity [42].

Perspectives

The application of CNC milling technology might improve the precision and production rate of custom allografts. With software that could interpret CT data, recognise anatomical landmarks and envisage intra-operative requirements for placement and navigation, a computer could generate the data required for CNC milling or fast-prototype fabrication of the graft and delegate the fabrication task to an appropriate machine. The data generated for graft fabrication could also be used to scan donor tissue released to manufacturing in order to identify tissue components suitable for manufacturing the graft. Non-destructive test methods might also conceivably be used to analyse candidate tissue components for their suitability in terms of required biomechanical properties.

Nevertheless, although such automation might enable substantial process refinement, the anatomical knowledge and manufacturing experience of a skilled tissue preparation engineer and the facility for direct and unfiltered communication between this engineer and the orthopaedic surgeon are extremely valuable and should not be disregarded.

Conclusions

The use of structural macro-allografts is an alternative to endoprosthetic mega-implants in difficult revision THA or TKA. The process requires elaborate planning and extensive communication, but comes with the benefits of a ready-to-use transplant that fits perfectly and enables the re-stocking of bone material for future surgery. Additional benefits include reduction of operating theatre time, reduction of blood loss and, when compared with use of autologous bone for augmentation, absence of harvest site morbidity. Our manufacturing process for custom allograft is still associated with a requirement for skilled and precise manual labour. The efficiency of the process could be improved by the application of state-of-the-art computer-controlled milling technology.

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