Computers in Biology and Medicine 176 (2024) 108553

Contents lists available at ScienceDirect

Computers in Biology and Medicine

journal homepage: www.elsevier.com/locate/compbiomed

BeST-Graft viewer, a new system to improve the bone allograft–recipient matching process

Marius Vila [a,*], Pau Xiberta [a], Marc Ruiz [a], Raquel Bermudo [b,c], Daniel Leivas [b], Oscar Fariñas [b,d], Anna Vilarrodona [b,c], Imma Boada [a]

[a] Graphics and Imaging Laboratory, Universitat de Girona, Girona, Catalonia
[b] Barcelona Tissue Bank (BTB), Banc de Sang i Teixits (BST), Barcelona, Catalonia
[c] Vall Hebron Institute of Research (VHIR), Barcelona, Catalonia
[d] Biomedical Research Institute (IIB-Sant Pau; SGR1113), Barcelona, Catalonia

ARTICLE INFO

Keywords:
Tissue establishment
Bone allograft matching
Medical imaging
3D virtual models
DICOM viewer

ABSTRACT

Introduction: Tissue establishments are responsible for processing, testing, preserving, storing, and distributing allografts from donors to be transplanted into recipients. In some situations, a matching process is required to determine the allograft that best fits the recipient. Allograft morphology is a key consideration for the matching process. The manual procedures applied to obtain these parameters make the process error-prone.
Material and Methods: A new system to manage bone allograft–recipient matching for tissue establishments is proposed. The system requires bone allografts to be digitalized and the resulting images to be stored in a DICOM file. The system provides functionalities to: (i) manage DICOM files (registered in the PACs) from both allografts and recipients; (ii) reconstruct 3D models from DICOM images; (iii) explore 3D models using 2D, 3D, and multiplanar reconstructions; (iv) take allograft and recipient measurements; and (v) visualize and interact with recipient and allograft data simultaneously. The system has been installed in the Barcelona Tissue Bank (Banc de Sang i Teixits), which has digitalized the bone allografts to test the system.
Results: A use case with a femur is presented to test all the viewer functionalities. In addition, the recipient–allograft workflow is evaluated to show the steps of the procedure where the viewer can be used.
Conclusions: The bone allograft–recipient matching procedure can be optimized using software tools with functionalities to visualize, interact, and take measurements.

1. Introduction

Current medical imaging devices can non-invasively obtain information from any part of the human body and represent it as a set of images. These images are fundamental for patient diagnosis and treatment follow-up requiring specific software systems such as radiological viewers [1,2] where image processing and visualization techniques are integrated and used to explore the images [3,4]. A common feature of these radiological viewers is their capability to examine and process images and obtain three-dimensional reconstructions of body parts from which different measurements can be obtained [5]. For instance, from a computer tomography of the lower limb, using proper functionalities it is possible to obtain a virtual reconstruction of the femur that can be then independently explored and analyzed to obtain different measurements. Exploiting these functionalities, a new system to automate and optimize the protocol of bone allograft–recipient matching is proposed.

Allografts, tissues or cells from a living or cadaveric human donor, are the key to many treatments in orthopedics (tumors, arthroplasty, trauma, osteochondral defects), cardiovascular or ocular surgery to name a few. Generally, allograft management (processing, testing, preserving, storing, allocating and distributing allografts from donors to be transplanted into recipients) is carried out by services of accredited health institutions, known as tissue establishments. Focusing on the allocation process, some requirements for the selection of the allograft that best fits a patient need to be satisfied. Particularly, in the allocation of an allograft for pathologies such as meniscal injuries, osteochondral defects, tumor resections, or cardiac valve replacements, among others, the allograft–recipient morphological correlation is decisive being necessary to know the graft dimensions/geometry and also the dimensions/geometry of the recipient. Numerous studies [6,7] have shown that a high anatomical correlation between the recipient and the graft is important for the success of the treatment and the reduction of integration problems. On the contrary, low correlation leads to poor alignment, fractures, joint degradation, and slow union, which can lead to failure [8]. Additionally, it has been found that grafts with anatomical similarity to the replaced tissue demonstrate similar mechanical and osteoconductive properties [9,10]. Therefore,

* Corresponding author.
E-mail address: marius.vila@udg.edu (M. Vila).

https://doi.org/10.1016/j.compbiomed.2024.108553
Received 13 December 2023; Received in revised form 23 April 2024; Accepted 30 April 2024
Available online 6 May 2024

obtaining the dimensions/geometry of the allograft and the recipient is fundamental. While the latter can be obtained from medical images of patients, graft dimensions/geometry are often derived from manual measurements that are inaccurate and error-prone [11,12]. To overcome these limitations, software solutions able to support allograft visualization and processing are required. Moreover, to cover the whole recipient–donor flow, these solutions need to be integrable into the tissue establishment information system. This integration requires different standards to be satisfied such as DICOM [13], which stands for Digital Imaging and Communications in Medicine. DICOM is the leading standard for image data management in medical applications used to capture, exchange, and archive image data in the Picture Archive Communication System (PACS) [14]. Taking into account all these considerations, the BeST-Graft Viewer is proposed, a software specifically designed and developed for the Barcelona Tissue Bank (Banc de Sang i Teixits) to support bone allograft–recipient matching process.

The aim of the paper is twofold: (i) Present the BeST-Graft Viewer design and development process; and (ii) Evaluate the performance and effectiveness of the BeST-Graft Viewer by comparing it with the classical workflow.

2. Related work

Previous to presenting state-of-the-art proposals related to non-manual allograft measurement strategies, a global overview of the allograft flow (from processing to distribution) to identify the key steps is provided.

2.1. The allograft flow

Although allograft flow depends on the specific tissue being transplanted, and the policies and procedures followed by the tissue establishment and healthcare institution, the applied process is quite similar. As shown in Fig. 1, the process starts at a tissue establishment with allograft processing (dissection, cutting, shaping and decontamination procedures), preservation to maintain their biological properties and integrity during storage until its allocation and distribution for transplant. When a patient, after medical history review, physical exams, laboratory tests, and imaging studies has been considered a candidate for an allograft transplant, the responsible healthcare team sends an allograft request to tissue establishment. Once this situation is given, the tissue establishment, in coordination with the healthcare team, selects the allograft that best matches the patient (allocation process). Different matching factors are considered such as tissue type, side, or size. Once the allocation is completed, the allograft is distributed for transplant, and after implantation, the recipient is closely monitored in a hospital setting and then, in regular follow-up visits.

2.2. Allograft measurement

In some cases, a key step in the allograft allocation process is obtaining measurements from the allograft and the recipient to match them and select the best allograft. Such measurements require specific strategies that can vary depending on the type of graft. However, the applied techniques can be grouped into two main categories: direct and indirect.

Direct strategies only require an expert to take direct measures of the allograft, which is economical, but imprecise and error-prone [15–18]. Indirect strategies require allografts to be digitalized (*i.e.*, scanned using a medical imaging technique such as a radiography, a computer tomography (CT), or a magnetic resonance (MR)), from which a DICOM file of the allograft is obtained. This DICOM file, if obtained via CT or MR scanning, contains a set of images from which, after applying a segmentation process, three representations of the allograft can be created and explored using medical image and visualization tools to take as many measures as necessary. Although this indirect approach becomes more complex and costly since it requires specific software tools, it is more precise and preferred by the tissue technicians who harvest, measure, and process the grafts and also the tissue bank employees who match the grafts based on measurements from the patient and the donor tissue [15]. Ideally, the recipient should be scanned with the same protocol to obtain allograft-equivalent images and make the comparison process between measurements easier. Note that, depending on the anatomical area, the segmentation of patient structures can be challenging.

To take measurements over the allograft virtual model, different strategies and software tools that have been proposed have centered on specific allografts. For instance, Paul et al. [18] focused on pelvic allografts and studied the limitations of selection methods that rely on radiograph superposition and distance comparison. Their study revealed the variability among observers in classifying allografts and emphasized the inaccuracies in hemipelvic allograft selection. Laurent et al. [19] compared two and three dimensional registration methods and demonstrated that the latter resulted in better matching results. Bousleiman et al. [15] demonstrated the superiority of automatic volume-based and surface-based methods over manual selection for choosing appropriate allografts from a bone storage bank. Particularly, they demonstrated the reduced computational time and improved contact surfaces at the donor–recipient junction in case of surface-based methods. Ritacco et al. [9,17] focused on osteoarticular allograft selection proposing a software to automate bone measurements for assessing distal femur sizes. Wu et al. [16] focused on limb-salvage surgery and how virtual bone bank, combined with computer-assisted navigation, enhances the safety and effectiveness of allograft selection and bone reconstruction procedures. Ritacco et al. [20] emphasized the potential benefits of using advanced virtual simulators, computer-assisted navigation, and patient-specific instruments in bone tumor resections and allograft preparations. These techniques have the potential to improve accuracy, minimize complications, and optimize the outcomes of these procedures. Qui et al. [12] developed a computer software that selected the graft from the distal femur that best matched the recipient by correlating the contour of the bone to be replaced. A similar study was conducted by Urtia et al. [10], in which grafts were digitized and the minimum distances between the bone and cartilage of the recipient and the graft were analyzed to select the condyle with the most similar characteristics to the defect to be replaced. Beeler et al. [7] focused on the accuracy of meniscus allograft selection considering MRI scans of bilateral and unilateral knee joints and comparing the 3D shape and dimensions of the original meniscus with the selected meniscus using different sizing methods. They conclude that the three-dimensional methods can significantly improve meniscus allograft selection, suggesting that conventional radiography may not be recommended for sizing. More recently, Flanagan et al. [21] reported a case study where computer navigation and 3D imaging were used in allograft transplantation surgery for the treatment of osteochondritis dissecans in the medial femoral condyle of the knee. The authors used computer navigation software to map and plan the surgical procedure, including the resection of the lesion and the placement of the allograft. 3D imaging was used to accurately align the allograft with the patient's knee joint. The surgical outcomes were successful, with postoperative radiographs showing implantation and union at follow-up appointments. The authors concluded that 3D imaging and computer navigation allows for precise preoperative planning and intraoperative guidance, facilitating accurate identification of anatomy, minimal resection margins, versatility in treating different lesion shapes, and optimal alignment of the allograft with the joint's articular surface angles. Dillon et al. [22] introduce an automated program designed for patient-specific alignment of fenestrations along endovascular grafts. The program utilizes a search algorithm to determine a suitable alignment between the patient's anatomy and a selected graft.

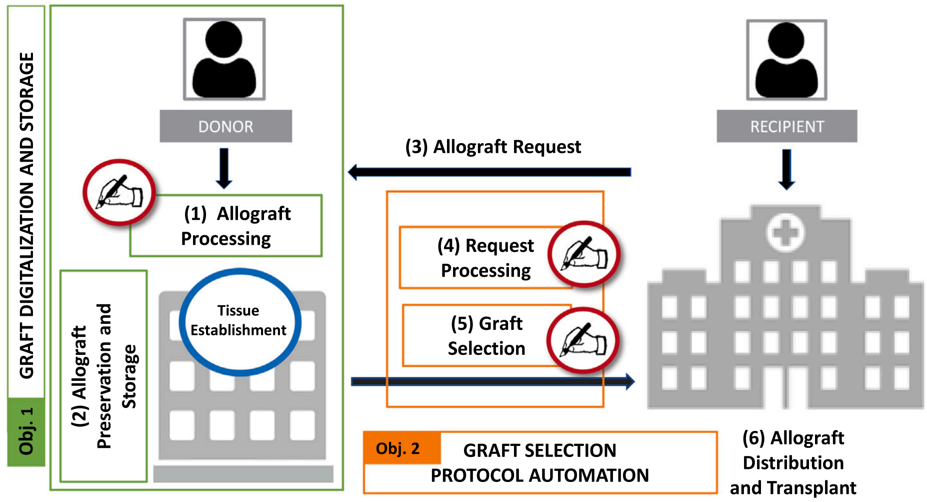

Fig. 1. Common allograft flow from processing to distribution in a tissue establishment, including allograft allocation. The numbers indicate the order of actions to be carried out and the hand icon indicates the actions that are performed manually.

Note that related proposals have focused on how to apply visualization and image processing techniques to enhance allograft selection for specific types. Inspired by the results of these techniques, we aim to go one step further with the design and development of a more global solution not specific to a type of allograft but applicable to all. Additionally, considering that the management associated with allograft transplantation is part of the healthcare system, we are also interested in ensuring that the proposed solution should be easily integrated into real-world settings.

3. Material and methods

3.1. The Barcelona Tissue Bank (Banc de Sang i Teixits)

The *Barcelona Tissue Bank (BTB)* is the tissue establishment of the Banc de Sang i Teixits (BST — Blood and Tissue Bank). BST is a public agency of the Catalan Department of Health whose mission is to guarantee the supply and proper use of human blood and tissues in Catalonia. The BTB has specialized personnel and facilities, including, among others, a multi-tissue recovery team composed by highly specialized professionals responsible for tissue retrieval from cadaveric donors; cleanrooms for tissue processing that follow the Good Manufacturing Practices quality regulations; specialized tissue processing personnel and equipment; and a medical advisory team that analyze and review all the processes to assess the suitability of the graft for transplantation. The current BTB protocol for allograft–recipient matching involves direct measurements of the allograft using a ruler or a vernier caliper. The measurements taken are pre-defined for each type of allograft, but they are always external lengthwise measurements and cannot include other types such as angles, areas, or inner measures. Furthermore, they may be affected by operator variability. Therefore, it is desired to replace these manual procedures with automated ones. To reach this objective, two goals have been defined: (i) the digitalization and storage of graft images in a database and (ii) the automation of the graft-recipient allocation protocol. These objectives, as well as the involved steps of the allograft–recipient allocation procedure, are illustrated in Fig. 1.

3.1.1. Grafts digitalization and storage

The first objective is to digitize the grafts (structural bone) from the BTB and store them in a specifically designed database. To reach this objective, all bone grafts are scanned using computed tomography. Scanned models are represented in DICOM file format. These files are processed to obtain relevant information for each graft, required for proper graft selection. Relevant information includes length, width, or diameter, to name a few. To extract these data from the files, specific tools have been implemented and integrated into a software system that we have denoted BeST-Graft Viewer. These functionalities cover steps (1) and (2) from Fig. 1.

3.1.2. Automation of the BTB's graft matching protocol

The bone graft-recipient matching protocol requires analyzing the scanned patient images and subsequently evaluating the different grafts available in stock to determine the one that best fits. The second objective is the design and development of different functionalities to extract all the required information from the patient and the graft database to automatically select and propose the best graft-recipient option. In this case, the involved steps are (3), (4), and (5) from Fig. 1. The functionalities required to support these steps have been integrated into the BeST-Graft Viewer.

3.2. The BeST-Graft Viewer

3.2.1. System requirements

After analyzing the applied graft-recipient selection protocol, the development team, in collaboration with the BTB experts, defined the functionalities that are provided by the proposed system. Particularly, it allows:

- *Opening and loading DICOM files*. Since DICOM is the standard for image data management in medical applications, used to capture, exchange, and archive image data in PACS, it is necessary for the system to support this format. This includes the ability to load allograft digitalizations as well as the DICOM files from the recipient.
- *Visualizing DICOM Images*. The system is able to visualize the DICOM images as 2D images as well as 3D volumes. It should also support multiplanar visualizations and allow the simultaneous visualization of allograft and recipient data.
- *Exploring and taking measurements on the images by using tools*. The system provides different tools to explore the 2D, 3D, multiplanar, and fused visualizations supporting zoom, pan, and other functionalities from classical radiological viewers. It also provides functionalities to measure distances, radii, etc. These measurements are the key to allograft selection processes and are stored in the DICOM files.
- *Segmenting structures of interest from a DICOM model*. The system supports the segmentation of organs, *i.e.*, the partition of DICOM images into multiple parts or regions, based on the characteristics of the pixels in the image.

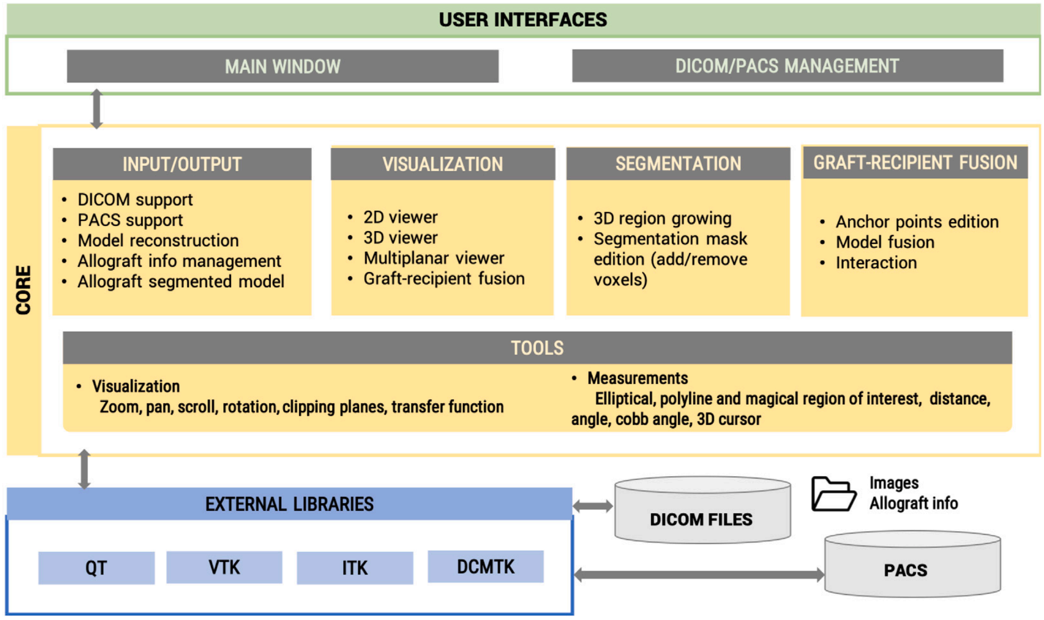

Fig. 2. BeST-Graft Viewer architecture block diagram.

- *Performing multimodal interaction*. The system supports the visualization of allograft and recipient data simultaneously allowing interaction with both models independently and simultaneously.
- *Communicating with PACS*. Since PACS is the standard to store DICOM data, the system supports the connection with the PACS not only to load and register DICOM data but also to register relevant information from the allograft required for the selection process.

In addition, the system is modular and extensible to allow the integration of new functionalities in a transparent way for the end user. It also supports different languages.

Note that the scope of our current development did not include osteochondral allografts or other *soft tissues* like menisci. The main application of a structural bone allograft is tumor surgery or prosthesis replacement, where a metallic prosthesis replaces the native articular surfaces. We consider that bony-only protocols cover the current needs for these grafts and the matching of osteochondral allografts, menisci, or other anatomical structures like acetabular or glenoid labrum will be included in the specifications of the next version of the viewer.

3.2.2. System architecture

To satisfy all these requirements, the three-level architecture illustrated in Fig. 2 and described below is proposed.

- **External libraries**. The first level of the BeST-Graft Viewer architecture contains the open-source libraries used by the system. In particular, Qt [23] is used as the development framework, and VTK [24] and ITK [25] for image representation, processing, visualization, interaction, and rendering. DCMTK [26] is used to communicate with the PACS and as the primary choice when reading DICOM files.
- **Core**. The second level of the BeST-Graft Viewer architecture has five main components named Input/Output, Visualization, Tools, Segmentation, and Graft-recipient fusion. The main functionalities of these modules are presented below.
  - The *Input/Output module* provides the functionalities required to support DICOM files allowing the user to connect to the PACS, either by obtaining or registering these DICOM files. This module is also responsible for reconstructing the volume model that represents the allograft or the patient information once the DICOM file has been accessed. The information related to allograft and patient measurements or other relevant data that needs to be registered into the DICOM file is also managed by this module.
  - The *Visualization module* integrates the techniques to support 2D, 3D, multiplanar, and fused visualizations from the DICOM files previously loaded into the system.
  - The *Tools module* provides visualization functionalities to interact with the information displayed on the screen at any given moment. These functionalities include zoom, pan, scroll, clipping planes (to select parts of a model), and transfer functions (to modify the colors used for the rendering or to apply pre-defined colors). This module also provides functionalities to take measurements such as the distance between two points in the volume, the area of a region of interest (ROI) with an elliptical or polygonal shape, the area of a ROI that automatically expands to include neighboring pixels with a similar intensity value to the initial point where the ROI was started (magical ROI), the angle formed by two lines that converge at a point, or the angle formed by two lines that converge at an undefined point (cobb angle). It also provides the 3D cursor functionality that allows identifying the same pixel in different views of the same model.
  - The *Segmentation module* provides the functionalities required to automatically segment parts of the volume model reconstructed from a DICOM file. Since only part of the volume models are relevant for allograft/recipient matching, the module provides functionalities to apply clipping planes to select the relevant part of the model, and tools to define the seed point required to apply the 3D region growing in the segmentation process. With this information, the module generates the segmentation mask, which can be manually edited if deemed necessary. Such edition process allows the user to add or remove pixels.
  - The *Registration module* allows the fusion of allograft and patient data in a single visualization. Such a feature is of special interest to monitor the allograft recipient matching. The current implementation of the module requires some user interaction to perform the fusion. Particularly, it is necessary for the user to mark two anchor points on the

recipient volume model and the same two points on the graft. These points will be the guide for the fusion. The result of the fusion can be adjusted by translating the graft along the axis defined by the anchor points and by rotating the graft around this same axis.

- **User Interfaces**. In the last level of the architecture, there are user interfaces where system functionalities are grouped. All interfaces follow a common design to ensure ease of use for users. In Fig. 3, the different types of interfaces are illustrated.
  Fig. 3(1) is the main interface used to visualize, explore, and take measurements on the models created from DICOM file images. In this interface, the different functionalities are grouped in a top menu, organized into five categories named File, Visualization, Tools, Window, and Help. Below, there is a menu with icons, grouped by functionality, to directly access menu options. Then, the main area of the interface provides different types of viewers to explore model information, including 2D, 3D, multiplanar and multimodal visualizations. In the example presented in Fig. 3(1), the axial, coronal, and sagittal views provided by 2D viewer are shown. Depending on the selected visualization, the information to be rendered is automatically updated. There are also functionalities to ease the exploration of the model, such as the scrolling option at the bottom of the viewer. Of special interest are clipping planes or the 3D cursor that allow the user to select parts of the model or see the same pixel in the different views, respectively.
  In addition, there are specific interfaces to query the DICOM files by accessing the PACS (see Fig. 3(2)). Note that different PACS can be accessed, and also that different filters can be applied to select the DICOM file. Once loaded, the user can consult DICOM data as illustrated in the image of Fig. 3(3).

4. Results and discussion

To present the results, first, a use case to illustrate the main functionalities of the system is given. Then, the allograft selection protocol presented in Fig. 1 is reviewed to illustrate the steps that have been automated using the proposed system.

4.1. Use case example

Our first objective is the digitalization of structural bone allografts from BTB. To carry out this process, allografts are wrapped with a plastic material filled with air and placed into a special box for digitalization (*i.e.*, obtaining DICOM images) with dry ice to preserve their properties. Once the DICOM file is obtained, it is necessary, for proper allograft processing, to virtually separate the allograft from the dry ice. This process is done via segmentation, as illustrated in Fig. 4, where (1) corresponds to the initial allograft input DICOM file; (2) corresponds to the segmentation process to obtain only the data from the allograft, which requires defining a seed point and setting parameters via a specific interface; and (3) shows 2D and 3D visualizations of the segmented allograft. The bounding box that appears around the 3D model of (1) corresponds to clipping planes functionality, which allows cutting parts of a model. The colors used to render the model are defined via a transfer function selected from the provided menu, where three predefined functions are available. In the case of 2D renderings, note that axial, coronal, and sagittal views, as well as multiplanar reconstructions, can be obtained. In all cases, the scrolling function allows navigating 2D images. In the case of multiplanar reconstruction, represented planes can also be interacted to move to new positions.

Once the allograft has been segmented, different measures can be taken using BeST-Graft Viewer's provided tools. In Fig. 5 some of these tools are illustrated, particularly the 3D cursor, which allows defining a point in a 2D view of the model and automatically placing the same point in the other views. Note that there is also a menu to define, remove, and edit measures.

In Fig. 6, functionalities of the viewer applied to the patient DICOM model are illustrated. Fig. 6(1) shows the visualization of DICOM images using the 2D and multiplanar visualization, and also the 3D rendering. Note again the transfer function feature, which provides some predefined functions that can be applied by simply selecting them. Fig. 6(2) corresponds to femur segmentation obtained using the same method as in the allograft case, and Fig. 6(3) illustrates measurement features. Of special interest are the 3D cursor and the possibility to see the taken measure in the multiplanar visualization.

Finally, the functionalities to explore the allograft and patient data simultaneously are shown in Fig. 7. Fig. 7(1) illustrates the patient and allograft 2D, multiplanar, and 3D visualizations. Note that the transfer function and other tools can be applied in each model independently. In Fig. 7(2), the patient allograft fusion model is represented. Although a single image is presented for the fusion, both models can be interacted with independence as illustrated in Fig. 7(2) top images, where allograft movements in different directions are shown. The directions of these movements are with respect to the axis defined by the user.

4.2. BTB global overview

To conclude this section, we would like to highlight the advantages of integrating the proposed viewer into the workflow of the Barcelona Tissue Bank. As illustrated in Fig. 8, all the manual actions that are currently performed (see Fig. 1) will be replaced by actions that can now be executed through the proposed software. The digitalization of implants has been a decisive point since it enables us to take more accurate measurements. In addition, the possibility of having virtual reconstructions of the allografts allows us to make measurements that would be challenging to achieve manually. Moreover, the application of hospital standards such as DICOM will facilitate viewer integration into the medical workflow. Regarding BTB's management, the proposed system also facilitates the recording of information using DICOM standards in which images and allograft data can be kept simultaneously. As a result, a more robust and efficient system is obtained. We also want to highlight the visualization options offered by the system, and especially the visualization of fused models in which the patient and allograft can be displayed in a single view. Such a feature allows inspecting the suitability of the selected allograft.

Despite the advantages that the viewer provides us, we are aware that there are many features that need to be improved. In particular, we consider that the entire measurement system should be optimized by identifying the key measurements for each type of graft and providing tools to ensure that they are always taken. This standardization of measurements would facilitate the automation of the identification of possible allografts given a recipient. Note that these measurements should also be possible on the patient model. As a first approach to tackle this problem, we are considering strategies that require user interaction. However, we are also considering automatic measurements by using image processing and artificial intelligence techniques to automatically identify the key parameters for each measure. In addition, we plan to extend viewer functionalities to support osteochondral allografts or other *soft tissues* like menisci.

5. Conclusions and future work

Identifying the best bone allograft for a recipient is not a trivial process. It requires, among others, a measurement process that guarantees that the allograft matches the anatomy of the recipient. In this article, a new system with visualization and image processing functionalities has been proposed that allows the analysis and interaction on virtual allografts created from DICOM files. The system allows reducing the procedures that are normally carried out manually, such as taking measurements, using semiautomatic procedures, which

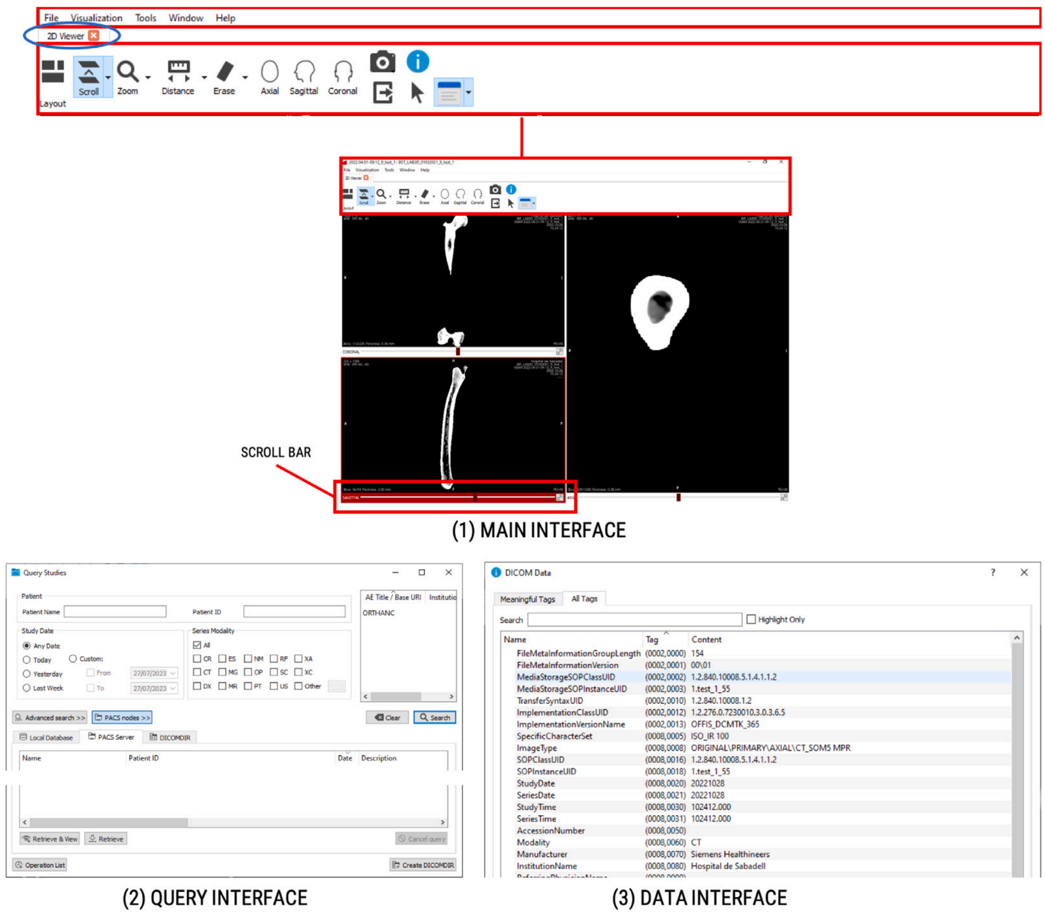

Fig. 3. User interfaces to visualize and interact with the DICOM model, to load a DICOM model, and to consult DICOM data.

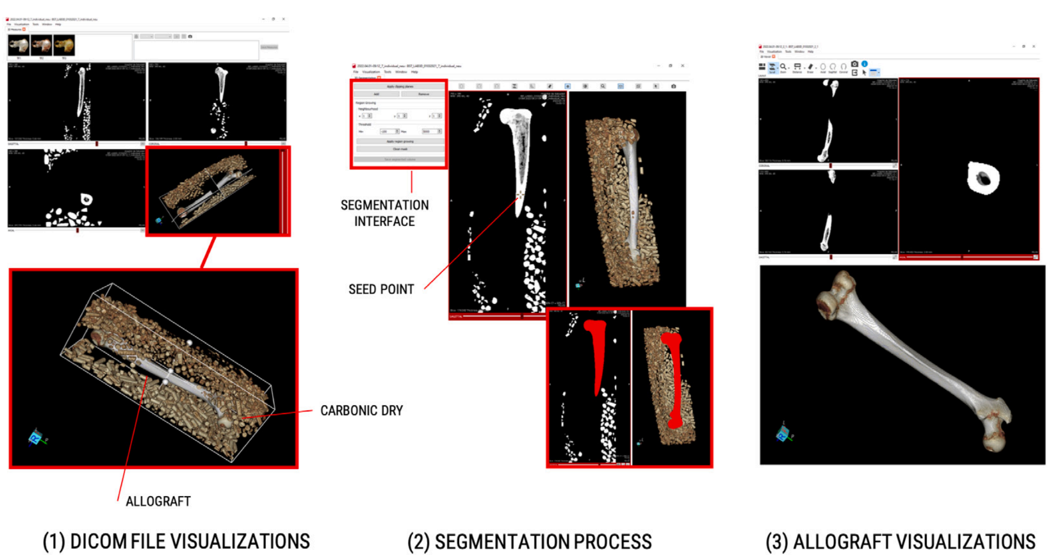

Fig. 4. Segmentation process using BeST-Graft Viewer functionalities to separate allograft from dry ice.

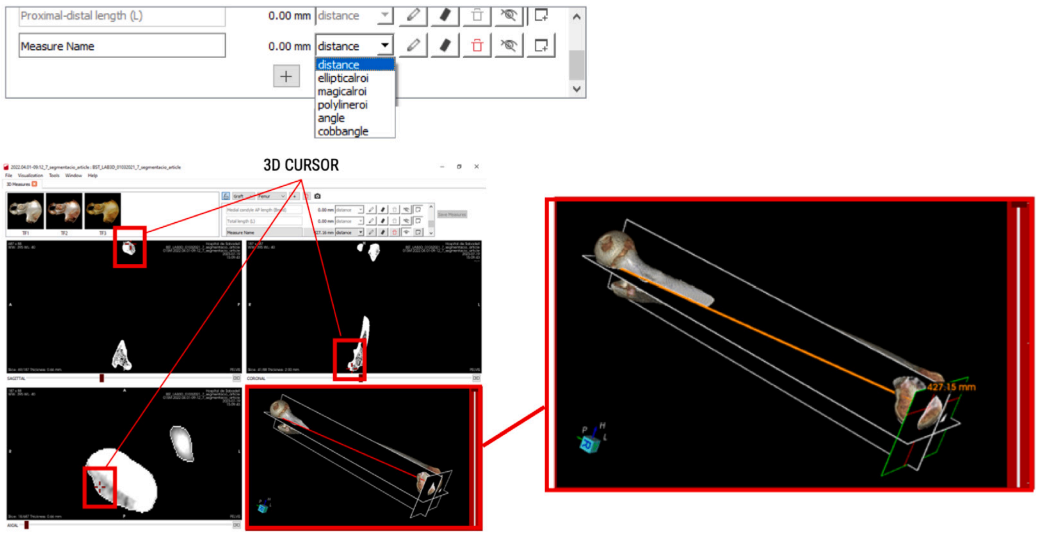

Fig. 5. Example of measurement tools provided by the viewer.

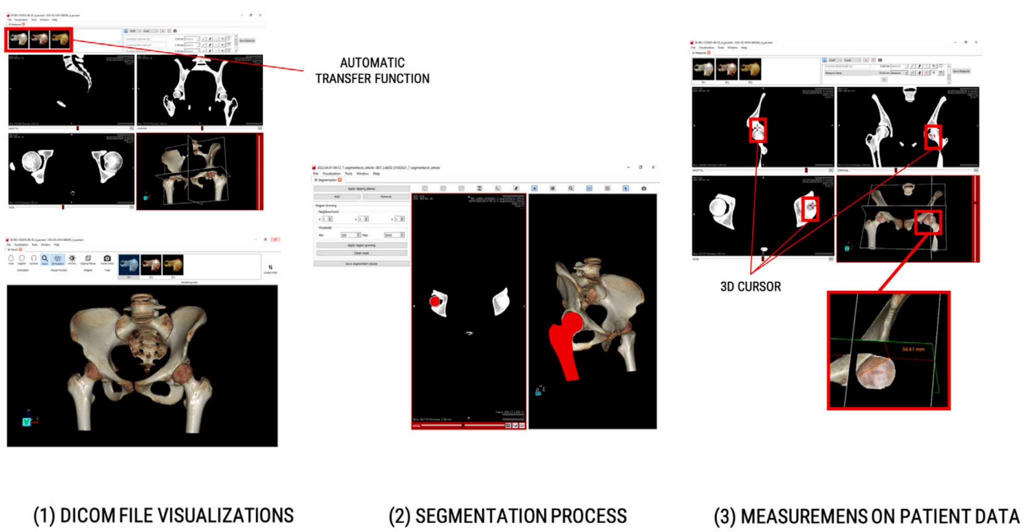

Fig. 6. BeST-Graft Viewer functionalities applied to the patient DICOM model.

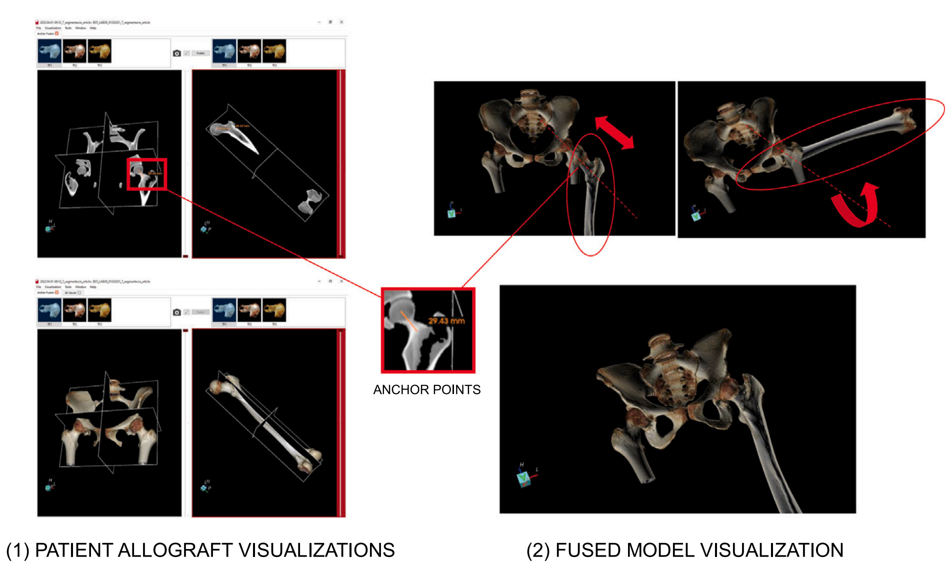

Fig. 7. BeST-Graft Viewer functionalities to support the simultaneous exploration of patient and allograft data as well as the fusion of both models.

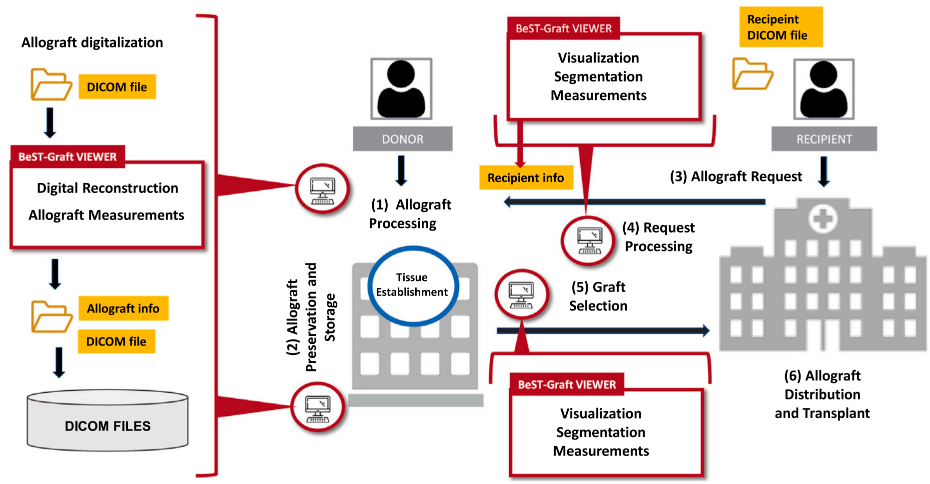

Fig. 8. The main processes of Barcelona Tissue Bank in the allograft–recipient selection process, indicating the steps in which BeST-Graft Viewer was used.

leads to more efficient and effective processes. The proposed system is the first version of a more advanced framework where automatic measurement strategies will be integrated. Particularly, the measurement functionalities will be extended to standardize the measurement process.

CRediT authorship contribution statement

Marius Vila: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Conceptualization. **Pau Xiberta:** Writing – review & editing, Software. **Marc Ruiz:** Writing – review & editing, Software. **Raquel Bermudo:** Writing – review & editing, Conceptualization. **Daniel Leivas:** Writing – review & editing, Conceptualization. **Oscar Fariñas:** Writing – review & editing, Conceptualization. **Anna Vilarrodona:** Writing – review & editing, Conceptualization. **Imma Boada:** Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Project PID2022–137647OB–I00 funded by MCIN/AEI/10.13039/501100011033 and by ERDF, EU. Open Access funding provided thanks to the CRUE-CSIC agreement with Elsevier.

References

[1] D. Haak, C. Page, T. Deserno, A survey of dicom viewer software to integrate clinical research and medical imaging, J. Digit. Imag. 29 (2016) 206–215, http://dx.doi.org/10.1007/s10278-015-9833-1.

[2] G. Valeri, F. Mazza, S. Maggi, D. Aramini, L. La Riccia, G. Mazzoni, A. Giovagnoni, Open source software in a practical approach for post processing of radiologic images, Radiol Med. 120 (2015) 309–323, http://dx.doi.org/10.1007/s11547-014-0437-5.

[3] A. Fedorov, R. Beichel, J. Kalpathy-Cramer, J. Finet, J. Fillion-Robin, S. Pujol, C. Bauer, D. Jennings, F. Fennessy, M. Sonka, J. Buatti, S. Aylward, J. Miller, S. Pieper, R. Kikinis, 3D slicer as an image computing platform for the quantitative imaging network, Magn. Reson. Imaging 30 (2012) 1323–1341, http://dx.doi.org/10.1016/j.mri.2012.05.001.

[4] O. Ratib, A. Rosset, Open-source software in medical imaging: Development of osirix, Int. J. Comput. Assisted Radiol. Surg. 1 (2006) 187–196, http://dx.doi.org/10.1007/s11548-006-0056-2.

[5] M. Ruiz, A. Julià, I. Boada, Starviewer and its comparison with other open-source dicom viewers using a novel hierarchical evaluation framework, Int. J. Med. Inform. 137 (2020) 104098, http://dx.doi.org/10.1016/j.ijmedinf.2020.104098.

[6] J. Yoon, T. Kim, J. Wang, H. Yun, H. Lim, J. Yang, Importance of independent measurement of width and length of lateral meniscus during preoperative sizing for meniscal allograft transplantation, Am. J. Sports Med. 39 (7) (2011) 1541–1547, http://dx.doi.org/10.1177/0363546511400712.

[7] S. Beeler, L. Jud, M. von Atzigen, R. Sutter, P. Fürnstahl, S. Fucentese, L. Vlachopoulos, Three-dimensional meniscus allograft sizing-a study of 280 healthy menisci, J. Orthop. Surg. Res. 15 (2020) 74, http://dx.doi.org/10.1186/s13018-020-01591-z.

[8] D. Muscolo, M. Ayerza, L. Aponte-Tinao, M. Ranalletta, Partial epiphyseal preservation and intercalary allograft reconstruction in high-grade metaphyseal osteosarcoma of the knee, J. Bone Joint Surg. 86 (2004) 2686–2693, http://dx.doi.org/10.2106/00004623-200412000-00015.

[9] L. Ritacco, G. Farfalli, F. Milano, M. Ayerza, D. Muscolo, L. Aponte-Tiano, Three-Dimensional Virtual Bone Bank System Workflow for Structural Bone Allograft Selection: A Technical Report, Hindawi Publishing Corporation, Sarcoma, 2013, http://dx.doi.org/10.1155/2013/524395.

[10] A. Urtia, G. Cvetanovich, B. Madden, N. Verma, N. Inoue, B. Cole, A. Yanke, Topographic matching of osteochondral allograft transplantation using lateral femoral condyle for the treatment of medical femoral condyle lesions: A computer-simulated model study, Arthroscopy: J. Arthrosc. Related Surg. 34 (2018) 3033–3042, http://dx.doi.org/10.1016/j.arthro.2018.05.039.

[11] D. Muscolo, M. Ayerza, L. Aponte-Tinao, M. Ranalletta, Use of distal femoral osteoarticular allografts in limb salvage surgery, surgical technique, J. Bone Joint Surg. 88 (2006) 305–321, http://dx.doi.org/10.2106/JBJS.F.00324.

[12] L. Qiu, Y. Zhang, Q. Zhang, L. Xu, X. Niu, L. Zhang, Allograft selection for distal femur through cutting contour registration, Cell Tissue Bank 17 (2016) 699–711, http://dx.doi.org/10.1007/s10561-016-9580-7.

[13] National Electrical Manufacturers Association, Nema ps3 / iso 12052, digital imaging and communications in medicine (dicom) standard, 2023, http://medical.nema.org/. (Accessed 18 July 2023).

[14] H. Huang, PACS and Imaging Informatics: Basic Principles and Applications, second ed., Wiley-Blackwell, 2010.

[15] H. Bousleiman, L. Paul, L. Nolte, M. Reyes, Comparative evaluation of pelvic allograft selection methods, Ann. Biomed. Eng. 41 (2013) 931–938, http://dx.doi.org/10.1007/s10439-013-0739-0.

[16] Z. Wu, J. Fu, Z. Wang, X. Li, J. Li, Y. Pei, G. Pei, D. Li, Z. Guo, H. Fan, Three-dimensional virtual bone bank system for selecting massive bone allograft in orthopaedic oncology, Int Orthop. 39 (2015) 1151–1158, http://dx.doi.org/10.1007/s00264-015-2719-5.

[17] L. Ritacco, C. Seiler, G. Farfalli, L. Nolte, M. Reyes, D. Muscolo, L. Aponte-Tiano, Validity of an automatic measure protocol in distal femur for allograft selection from a three-dimensional virtual bone bank system, Cell Tissue Bank 14 (2013) 213–220, http://dx.doi.org/10.1007/s10561-012-9307-3.

[18] L. Paul, P. Docquier, O. Cartiaux, O. Cornu, C. Delloye, X. Banse, Inaccuracy in selection of massive bone allograft using template comparison method, Cell Tissue Bank 9 (2008) 83–90, http://dx.doi.org/10.1007/s10561-008-9061-8.

[19] L. Paul, P. Docquier, O. Cartiaux, O. Cornu, C. Delloye, X. Banse, Selection of massive bone allografts using shape-matching 3-dimensional registration, Acta Orthop. 81 (2010) 252–257, http://dx.doi.org/10.3109/17453671003587127.

[20] L. Ritacco, F. Milano, G. Farfalli, M. Ayerza, D. Muscolo, J. Albergo, L. Aponte-Tinao, Virtual planning and allograft preparation guided by navigation for reconstructive oncologic surgery: A technical report, JBJS Essent. Surg. Tech. 7 (2017) e30, http://dx.doi.org/10.2106/JBJS.ST.17.00001.

[21] J. Flanagan, k. Ye, J. Stevens, C. di Bella, Computer navigated allograft transplant in the medial femoral condyle: A case report, J. Orthop. Rep. 2 (2023) 100136, http://dx.doi.org/10.1016/j.jorep.2023.100136.

[22] T. Dillon, P. Liang, M. Schermerhorn, E. Roche, A computational program for automated surgical planning of fenestrated endovascular repair, Commun. Eng. 2 (2023) 37, http://dx.doi.org/10.1038/s44172-023-00083-2.

[23] The Qt Company, Qt project, 2023, http://qt.io/. (Accessed 18 July 2023).

[24] Kitware Inc, The visualization toolkit, 2023, http://vtk.org/. (Accessed 18 July 2023).

[25] Kitware Inc, The insight segmentation and registration toolkit, 2023, http://itk.org/. (Accessed 18 July 2023).

[26] OFFIS e.V, Dcmtk toolkit, 2023, http://dcmtk.org/. (Accessed 18 July 2023).