J Digit Imaging (2012) 25:352–358
DOI 10.1007/s10278-011-9416-8

DICOM for Implantations—Overview and Application

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Published online: 20 August 2011

Abstract Surgeons have to deal with many devices from different vendors within the operating room during surgery. Independent communication standards are necessary for the system integration of these devices. For implantations, three new extensions of the Digital Imaging and Communications in Medicine (DICOM) standard make use of a common communication standard that may optimise one of the surgeon's presently very time-consuming daily tasks. The paper provides a brief description of these DICOM Supplements and gives recommendations to their application in practice based on workflows that are proposed to be covered by the new standard extension. Two of the workflows are described in detail and separated into phases that are supported by the new data structures. Examples for the application of the standard within these phases give an impression of the potential usage. Even if the presented workflows are from different domains, we identified a generic core that may benefit from the surgical DICOM Supplements. In some steps of the workflows, the surgical DICOM Supplements are able to replace or optimise conventional methods. Standardisation can only be a means for integration and interoperability. Thus, it can be used as the basis for new applications and system architectures. The influence on current applications and communication processes is limited. Additionally, the supplements provide the basis for further applications, such as the support of surgical navigation systems. Given the support of all involved stakeholders, it is possible to provide a benefit for surgeons and patients.

Keywords Digital Imaging and Communications in Medicine (DICOM) · Infrastructure · Medical devices · Navigation

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Introduction

Today's surgeons are supported and assisted by many devices within the operating room (OR) during surgery. On the one hand, these devices shall facilitate safer, more precise or otherwise better surgeries, but on the other hand, the devices require user input and consume time for handling. To use modern technologies in an optimal way, integration of devices, an information system, is a prerequisite [1, 2]. For device integration, many proprietary solutions are offered for the OR. Some of them are discussed in [3]. Unfortunately, many ORs are heterogeneous environments with devices from different vendors. For the integration of these devices, independent communication standards are necessary. This fact becomes even more important for perioperative workflows that involve

planning, simulation and documentation before and after the intervention. Particularly in university hospitals, the situation is more difficult because of "scientific software" that needs to be integrated into the daily routine (e.g. for clinical trials or new medical image processing).

There are four main categories of problems that arise due to missing integration:

- Data input—Data has to be entered manually several times which is error prone and extends intervention and setup time. CDs and other data storage media have to be used to convey information from PC-based software tools into the OR.
- Data output—Protocols and records of surgical procedures remain on the devices.
- Data accessibility—Non-standardised data formats require appropriate software everywhere the data should be accessed.
- Data archiving—It is difficult to ensure proprietary data formats to be read in a couple of years from an archive.

Even if standardisation will not solve all those problems entirely, it helps to minimize them.

The Digital Imaging and Communications in Medicine (DICOM) standard committee has founded working group 24 ("Surgery") with the aim to develop new standards for systems integration in surgery and to promote the usage of technical standards in the surgery. On behalf of this working group, the authors were involved in the development of three DICOM Supplements which already became part of the standard:

- Surface Segmentation (DICOM Supplement 132)
- Implant Templates (DICOM Supplement 131)
- Implantation Plan SR Document (DICOM Supplement 134)

Each supplement provides data structure and service definitions for surgical use cases. The paper provides a brief description of these data structures and services and gives recommendations to their application in practice.

Background

DICOM is a communication standard which was originally defined for data exchange in radiology information systems. It is maintained and expanded by working groups (WG) in order to follow new developments in radiology but also to extend its usage into other clinical domains. One of these groups is WG 24 "DICOM in Surgery" that aims at the extension of DICOM towards surgical requirements. "Polygonal Surface Description" was the first work item WG 24 dealt with—in cooperation with WG 17 "3D". The result of these efforts was DICOM Supplement 132 "Surface Segmentation". The second supplement, "Implant Templates", bases on data structures which were introduced by the surface segmentation supplement. It specifies attributes for the description of implant template catalogues. The third supplement, "Implant Planning SR Document", introduces a standardised template for the documentation of patient-specific planning results, which includes references to images and/or surface segmentations and one or more implant templates. The two main objectives of these last two supplements are the availability of implant templates and the possibility of archiving planning results.

Methods

In this paper, the planning of total hip replacement (THR) interventions will be investigated as one of the principal use cases which were considered in the definition of the implant template and implantation planning data structures. THR was selected since the process of THR planning is relatively well-described and standardised by international orthopaedic communities and is generally one of the most frequent interventions in orthopaedic surgery [4]. Another important workflow is dental implantation. Even though dental implants are usually not as complex as orthopaedic or traumatology implants, the underlying workflow is much more complex, especially regarding surgical templates. For these reasons, the dental implantation workflow was selected as the second use case discussed in this paper.

The Total Hip Replacement Workflow

The principal steps of the THR workflow were based on the material of the WG 24 Project Groups [5] with updates from the literature [6, 7].

Diagnosis

The first step in the workflow is the diagnosis of a disease that can be treated with THR. Symptoms like stiffness and movement-induced pain of the hip joint are an indication for degenerative arthritis. For the diagnosis, radiological X-ray pictures will be taken and based on the images a degenerative arthritis may be detected. Ultrasound and other modalities are adducted for further investigations. Degenerative arthritis may be an indication for replacement of the bony structure of the hip joint with an artificial joint to achieve a better mobility for the patient and to reduce pain.

After the decision of the surgeons and the patient that a THR is the most appropriate treatment, the second step, the planning of the intervention starts. The principal aim of implantation planning is:

- Selecting the right type and size of the implant according to the patients anatomy and
- selecting the right type and size regarding biomechanics (movement, durability, etc.).

Restrictions regarding the choice of implants due to financial issues, availability and management rules, etc. are not in the scope of the paper and may be addressed in future studies. These are processes which are not addressed by standards, i.e. DICOM.

Imaging and Implant Selection

Conventionally, implantation planning is done using 2D templates which are printed on transparent rigid plastic. Those templates are physically overlaid on the X-ray images of the patient. The templates show the outlines and important planning landmarks as well as informative data like implant type and size. The templates are dedicated to certain magnification factors which are typical for hip X-rays [8]. During the planning, the surgeon switches between different templates, each one representing one or more implant sizes. Normally, the surgeon selects the implant which size and shape best fit the patient's anatomy and with physical parameters that best suit the patient's biomechanical needs. At the end, the selected sizes and types of the implants are recorded and the implants will be provided for the intervention.

Based on this classical workflow, researchers in Computer-Aided Orthopaedic Surgery (CAOS) proposed new computer-assisted workflow [9, 10]. The conversion to computer-assisted template planning was favoured by three effects: firstly, printed X-ray images have been largely replaced by digital technologies [11], forcing surgeons to adapt to on-screen planning; secondly, digital implant templates allowed for a richer representation and higher accuracy of planning [12, 13]; thirdly, in difficult cases or for generally very complex intervention types, three-dimensional planning was enabled through 3D templates and volumetric imaging.

In CAOS, the templates are provided in digital form and overlaid with the patient images virtually by computer software. For accurate template scaling, artificial calibration objects are positioned within the X-ray [14] or the magnification is estimated based on anatomical landmarks. The calibration object is often detected automatically within the patient image by the software and the right magnification factor for the image is calculated. Once the scaling is determined, the best fitting templates are selected by the surgeon using the same criteria as during conventional planning. Normally, the planning application will create an implantation plan containing information regarding size and type of implants. This implantation plan helps to prepare the needed material and implants for the intervention.

Surgery

Images generated during the planning may help the surgeon during the implantation. If the surgery is assisted by a navigation system, the target positions of the implants, regarding anatomical markers, have to be transmitted from the planning application to the navigation system. This is often done using storage media such as USB-Stick or CD-ROM and usually restricts the user of a specific navigation system to use the corresponding planning software.

The Dental Implantation Workflow

In oral and maxillofacial surgery, the possible workflows are more complex than in other disciplines, since the production and customizing of models and prostheses is done more often outside of the surgical institution. The implants are the artificial roots of those prostheses and to achieve a satisfactory result, they need to be chosen correctly and placed accurately. We will focus on a workflow which utilizes surgical templates that were produced in an external dental laboratory since this is a common use case. We identified and divided this workflow into six major steps which are present in most “real world” workflows. Some parts may be extended, or additionally, parts may be added according to the needs of the stakeholders.

Visual Model

A visual model of the intended teeth is used to reconcile the postoperative result of the surgery with the patient. Therefore, several casts from the patient's teeth are taken and sent to a dental laboratory. With additional information regarding colour and style, the laboratory creates the visual model or so called “Wax Up”.

Scanning Template

In this second step, a bite splint or scanning template is produced. It facilitates the spatial registration between the patient and the images of the patient which are acquired for planning. This bite splint often contains models of the future teeth to make it possible that they are visible in the radiographs.

Data Acquisition

Radiology images of the patient are acquired. CT is the most common modality for dental implant planning. The patient has to wear the scanning template during the acquisition.

Planning

Implant templates are selected and virtually placed in the patient images. With the help of the markers in the scanning template and the knowledge about the spatial relation of the markers, images can be verified. The position and orientation of the selected implants in relation to the patient images and the scanning template is stored as planning result.

Surgical Template Creation

The last part is the creation of a surgical template. It can be used to drill the holes for the implants accordingly to the planned positions. The surgical template may be the modified scanning template. Normally, the surgical template fits on the remaining teeth of the patient.

Surgery

During surgery, the surgical template is used to guide the surgeon drilling the holes for the implants. It is possible to control the trajectory, the size and the depth of the drilled hole. Often, drilling of the holes and placement of the implants into the holes is performed in separate interventions with some weeks or months in between to give the tissue some time to heal. The implantation itself follows according to the prepared holes.

Results

Even if both presented workflows are from different domains, we identified a common core structure that can be supported by data structures based on DICOM (see Fig. 1). This implantation planning core workflow consists of the selection and placement of implants based on implant templates in a patient model. Finally, the planning result summarizes the intervention planning and provides data for further steps (see Fig. 2). Most implant related interventions contain the selection of the most appropriate implant and many of those selections require medical images as one criterion. Although the different selection procedures may base on totally different criteria and are done within different phases of the intervention, as long as the selection can be supported by visualisation, simulation or documentation, the DICOM Implant Supplements are helpful. It was possible to direct the development of the DICOM Supplements to meet this core workflow and we will introduce this standard extension in the next paragraphs. For the complete documents, please refer to the standard itself [15] and its supplements [16].

Implant Templates and Surface Segmentation

The most important extension of DICOM WG 24 is the Supplement 131 “Implant Templates”. For the description of 3D data, this supplement uses data structures which were introduced by Supplement 132 “Surface Segmentation”. Supplement 132 “Surface Segmentation” started before Supplement 131 “Implant Templates” and has become part of the standard already.

The implant template supplement contains three information object definitions (IODs):

- Implant Template IOD
- Implant Template Group IOD
- Implant Assembly Template IOD

The first provides a data structure to store all the information of an implant that is needed for planning. This includes 2D and 3D drawings as well as meta information such as the manufacturer and catalogue number of the represented implant. Additionally, the implant template contains information about mating features which can be used to geometrically constrain the combination of implants in an assembly. For computer-assisted alignment with anatomical features in patient images, planning landmarks (points, lines or planes) can be contained in a template.

Implant templates can be grouped using the Implant Template Group IOD. Groups can be issued by manufacturers to structure a repository of parts according to their product lines but could also be issued by a hospital to summarize all available models and sizes. Implant template groups facilitate switching between the implant templates during planning, e.g. to select a different size. Each group defines a common coordinate system for all implants which are in the group. Once one template in the group is aligned with the patient anatomy, all group members can at least roughly be aligned in a similar pose through the spatial registration provided by the group coordinate system (Fig. 3).

An Implant Assembly Template Instance specifies intended combinations of components in implant assemblies together with the spatial alignment of the templates in the assembly.

Implantation Plan SR Document

To provide support for the whole core workflow of implantation, WG 24 developed Supplement 134 “Implantation Plan SR Document”. This supplement provides data structures to store the results of a planning activity which used DICOM implant templates. The report includes references to all patient information which was used during planning, the selected implants and their alignment with patient space. Additional data which seems important or useful during the intervention and for archival can be

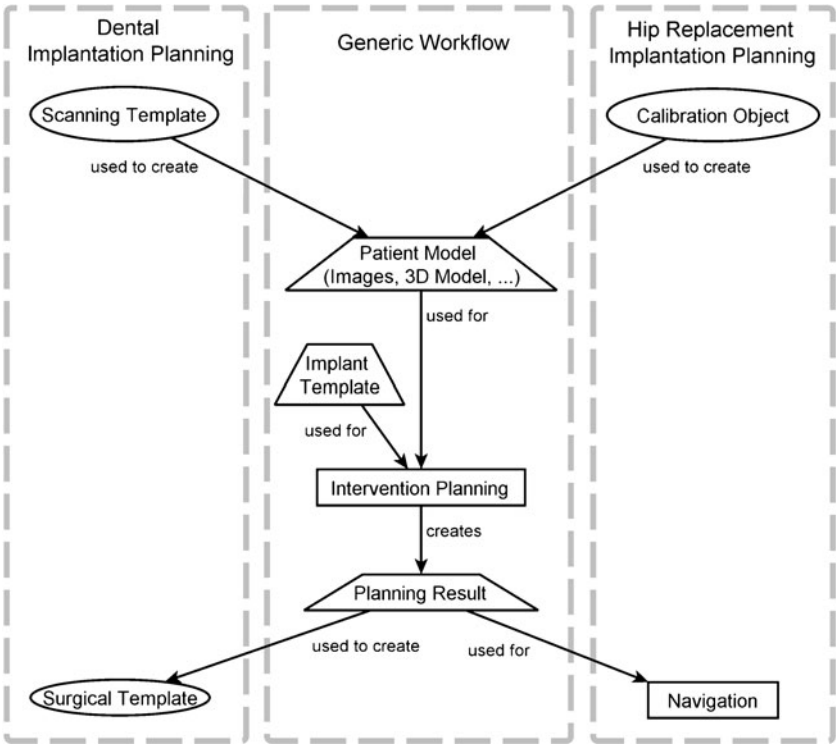

Fig. 1 The figure shows a simplified chain of planning workflow data artefacts (*trapezoids*) which are related to real-world objects (*ellipses*) and processed by activities (*rectangles*). The two domain specific workflows hip replacement and dental implantation use one common generic implantation workflow

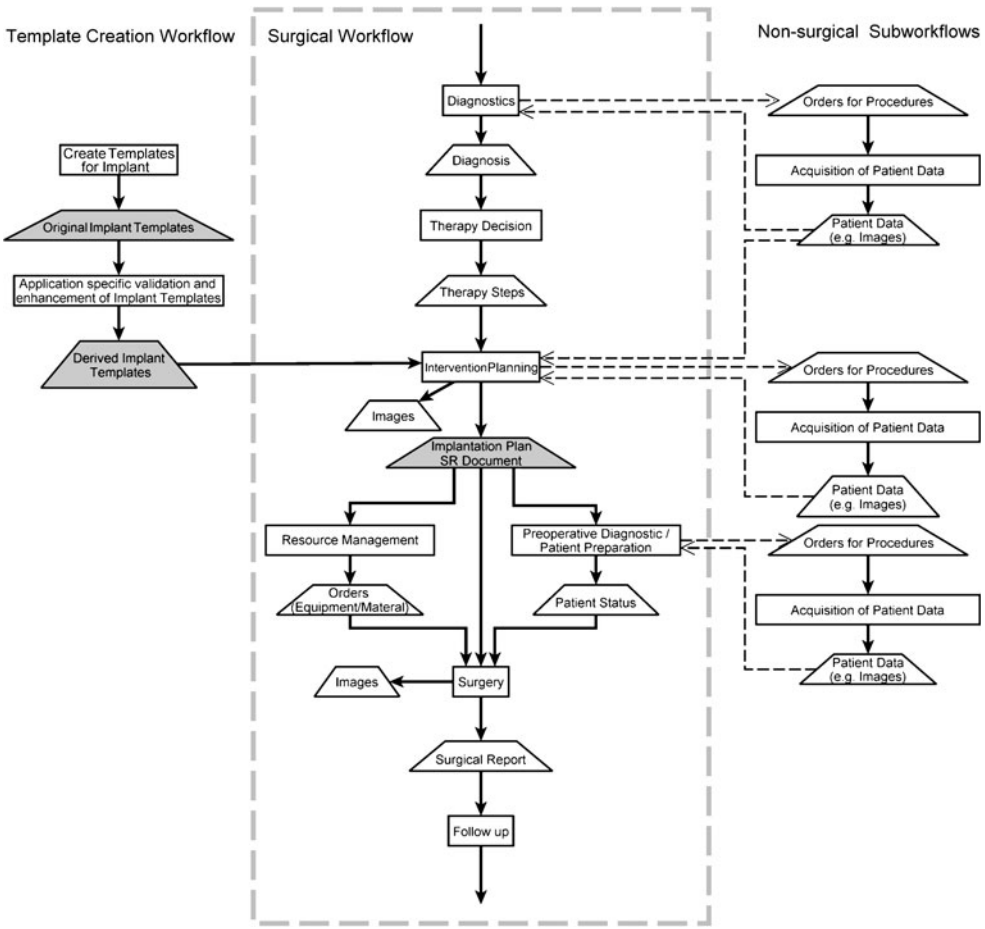

Fig. 2 Basic THR workflow (*rectangles*) and resulting data artefacts (*trapezoid*). Data artefacts that are covered by the new data structures are *gray*

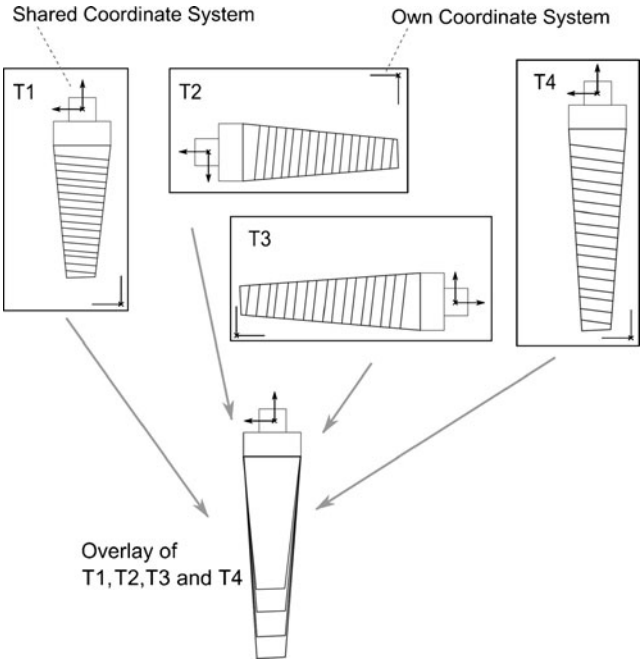

Fig. 3 Spatial relations between implant templates within one Implant Template Group that consists of four Dental Implant Templates (T1, T2, T3 and T4). Each one has its own coordinate system and defines a shared coordinate system. A common alignment is possible based on the shared coordinate system although the position within the own coordinate system differs between the templates

referenced. The Implantation Plan SR Document uses the DICOM technique of structured reporting [17] which makes it very flexible and provides basic document management like verification of documents.

Application of the Surgical DICOM Supplements

The surgical DICOM Supplements are able to replace conventional methods. For example the DICOM implant templates replace the transparent rigid plastic templates. Additionally, the supplements have the potential to enhance the workflows with new possibilities such as the support of navigation systems (see Table 1).

Looking at the current workflow of THR, the implant template supplement provides the basis to replace the proprietary implant template databases which are nowadays contained in implantation planning software and need to be maintained by every software vendor. Regarding the dental workflow, the same holds true for dental implant templates. The possibility to have one common standard-based database of implants from different manufacturers will facilitate the use of the implant templates by many applications and assisting devices such as planning applications or navigation systems. Additionally, the standard facilitates a faster and broader availability of implant templates.

The implantation plan can be applied to both workflows, too. In THR, it replaces the paper-based conventional planning result which is only readable by humans and not by machines. In the dental workflow, it can be used to transfer the planned information to the milling machine that creates the surgical template.

Furthermore, DICOM provides the possibility to use the archiving functionality of PACS for Implant Templates and Implantation Plan SR Documents.

Table 1 Some examples how the surgical supplements support the discussed workflows

Activity examples	Support by surgical supplements
Segmentation of bony fragments of a broken femur in preparation for the planning	The DICOM Surface Segmentation facilitates the storage of 3D representations of anatomical structures
Visualisation of an acetabular cup on an X-ray image to verify the right size	The DICOM Implant Template contains necessary information about the shape and scaling in 2D and 3D.
Selecting bearing heads that fit to a selected shaft.	The DICOM Implant Template contains basic information about variability (degrees of freedom) and possible combination of implant components (Implant Template Assemblies).
Selecting a dental implant template that is one size bigger to determine whether it is fitting or not	The Implant Template Supplement describes data structures for Implant Template Groups. Each group contains implant templates of similar implants.
Storing the selection of implants and the utilized images	The Implantation Plan SR Document can contain information about selected implant templates, used images and other information that are results of an implantation planning.
Send spatial information regarding the position of the selected implants and the patient images together with identified fiducials to a dental laboratory for the production of a drilling template.	The Implantation Plan SR Document can contain information about spatial registration between various DICOM objects like implant templates, images, fiducials and segmentations
Initialize and provide all data to the navigation system for a THR intervention.	The navigation system can retrieve all necessary data from the PACS using the surgical supplements

Discussion

The proposed applications of the DICOM Supplements are two examples of many potential applications. Nevertheless, they were among the important workflows that influenced the standardisation and we propose the shown application as the most appropriate one for the new DICOM extensions. In addition to the standard, this is necessary since DICOM does not describe intended workflows in detail. Integrating the Healthcare Enterprise (IHE) does so, but the development of a surgical technical framework in IHE will take some time. The explanations above show that the implant templates as well as the implantation plan can be used in both. The additional benefits provided by the supplements cannot be depicted since the workflows are derived from the current conventional workflows and have to be extended once they support the surgical supplements.

Beside the core workflow, there is a number of other data objects that are already covered by DICOM. This holds true especially for the THR workflow (see Fig. 2). Further standardisation may help to overcome a long "chain of spatial transformations" in dental implant planning. This chain is error prone and may be optimised using rapid prototyping which requires sufficient interfaces.

Conclusion

The acceptance of the proposed standardised data structures depends not only on their completeness, correctness and functionality but also on the willingness of the stakeholders. We are convinced that standardisation can lead to more integrated workflows which will support the user and optimise the patient's treatment. The key to an optimal support by standardised interfaces is the awareness of the users about the importance and possibilities. The development of IHE profiles the next step to give a guideline for the underlying infrastructure and to gain more visibility among companies and users.

Acknowledgements This work is sponsored by funds of the European Regional Development Fund (ERDF) and the state of Saxony.

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