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Preliminary results of the first Spanish virtual body donation program. Usefulness in Anatomy, Morphological Sciences, and healthcare implications

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SUMMARY

The donation of human bodies for medical education purposes currently faces a shortage that could, in some way, limit the practical teaching of anatomy, aggravated in pandemic times.

Medical diagnosis has undergone a revolution due to the so-called “imaging techniques”, which obtain digital files containing, totally or partially, a virtual copy of the body.

This enables a new type of donation that has been termed, in recent publications, “virtual body donation”. According to this, a virtual body donation program, has been implemented, including a repository of digital samples, generated from image scans, provided by patients.

This article presents the program casuistry, analyzes the usefulness of this type of material, both from the educational and healthcare care points of view, and deals with some difficulties or problems in the constitution and management of these programs, as well as the solutions that could be implemented.

The program promotes an innovative form of teaching anatomy and related sciences (pathology, anthropology, and others). It also has advantages for the training of professionals in virtual dissection techniques and virtopsy. In addition, its usefulness in research appears to be unlimited in anatomy, anthropology, and other disciplines.

Virtual models, generated by these programs and organized as “object’s repositories”, extend

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their usefulness timelessly and they can be indefinitely studied. The need to expand these virtual donations to a multicenter and cooperative implementation is emphasized, with the purpose of creating extensive digital object's repositories and including as many specimens as possible, both normal and pathological.

Key words: Body donation – Image analysis – 3D modelling – Virtopsy – Virtual dissection

LIST OF ABBREVIATIONS

VBD: Virtual body donation

VBDP: Virtual body donation program

VRO: Virtual repository of objects

DICOM: Digital Imaging and Communications in Medicine

DICOMDIR: File containing information of the DICOM files (series, instances, indexes and others)

PACS: Picture Archiving and Computer System

IAPT: Image analysis and processing techniques

3D: Three dimensions

CT: Computed Tomography

MRI: Magnetic Resonance Imaging

INTRODUCTION

Organ donation for healthcare purposes is the foundation of organ and tissue transplantation programs, the Spanish model being one of the most accredited worldwide (Matesanz, 2004). These programs have their own legal regulations (Ley 30/1979, 1979; Real Decreto 1723/2012, 2012).

However, if the objective of the donation is teaching or research, in Spain there is a lack of specific regulation. Usually, it is each school of medicine that establishes its own rules, being the written consent, signed while alive by the donor, the main rule that governs the relationship between the donor and the university (McHanwell et al., 2008).

Human body donation for teaching or research purposes provides a limited number of corpses, which could be scarce for some academic or research needs, as in Radiological Anatomy, for example. In the Third World, where often there is a low supply of cadavers, or where cultural or religious beliefs prevent whole-body donation, an effort to find other specimens in place of cadaveric donation should be made.

It would be also important to find a substitute for wet cadaveric materials during the Covid pandemic or other similar future epidemic threats.

During the last years the diagnosis in medicine has undergone a revolution with the development of "imaging techniques." Basically, these techniques acquire the virtual body of the patient, either totally or partially.

Based on this, a new donation possibility ("virtual body donation" -VBD) has been proposed for use in teaching or research. Characteristics, requirements, documentation, and legal regulation of such programs has been recently published (Aso et al., 2019).

Following the guidelines of this publication, a VBD program, including a repository of objects (VRO) made up of the specimens produced by the donations, has been implemented.

In the present paper, the experience, casuistry, and usefulness of this program are analyzed, both at a medical training and healthcare care levels, as well as the difficulties or problems inherent to such type of initiatives.

MATERIAL AND METHODS

Methodology

Informed consent

The methodology for the inclusion of patients in the VBD program begins with the informed consent. Normally, it is the doctor responsible for the patient who has the mission of explaining the program, giving him/her the information document, and signing, together with him/her, the authorization form for the donation.

This form follows the directives of the European Union on the rights of patients and regulations (Reglamento UE 2016/679, 2016) and includes the necessary information about the donated material (Dicom files).

It is very important for the patient to know what is subject to donation. The patient is informed about the fundamentals of medical image, which include files that follow the DICOM protocol (Digital Imaging and Communications in Medicine), stored in the PACS (Picture Archiving and Computer System) (Napoli et al., 2003; NEMA, 2001).

A DICOM file can be viewed as a stack of images described by an index, called DICOMDIR. Each file includes a header, which contains data of the patient (Name, date of birth, weight, etc.), of the acquisition (type of imaging technique, place, Hospital, and others), as well as information on the images (i.e.: calibration, gray levels, bits per pixel, resolution) (Rorden, 2018).

Patients are also informed that these files content graphical data that can reproduce his/her appearance and other elements that can identify him/her, as well as personal information. Likewise, they are informed that the files will be treated using image analysis and processing techniques (IAPT) (Bankman, 2020) that allow, in turn, to obtain other new products like 3D models, both for visualizing and printing.

The patients are informed that the files and the new products of image processing will be treated anonymously, and that he/she may or may not consent to the inclusion of certain parts of the anatomy, such as the face, which could identify him.

The program includes an information dossier, and both this and the donation form have been approved by the Hospital's Ethics Committee.

Once the informed consent has been obtained, the following phase is started, generating the objects of interest.

General issues concerning the VBD (patients inclusion criteria, informed consent, database requirements, personal data protection, anonymity, and others, can be consulted in a recent publication (Aso et al., 2019), as well as other ethical and medicolegal aspects of the program.

Generation of objects

Actions on DICOM files, aimed to scientific purposes, are known as "image analysis and processing techniques" (IAPT).

Classically, they can be classified as follows:

- ***Techniques of image analysis***

  They operate on graphic files without modifying them, aimed at obtaining information on some characteristics of the object.

  Interactive inspection, measuring angles, distances, volumes, and indices, is an interesting example and can be done repeatedly and remotely. Euclidean or geometric morphometrics, are additional examples useful in anthropology or forensic medicine.

- ***Techniques of image processing***

  These are manipulative operations intended to modify some characteristics of the file. The result, even temporarily, is an image (a file) different from the one was taken from the start.

  The clearest example is the segmentation of regions of interest. This procedure isolates one anatomical part from the rest. Once separated, all kinds of inspections or measurements can be carried out on it.

  One of the main applications of segmentation is the selection of structures for their three-dimensional reconstruction.

  3D reconstructions merit a special review. Most programs that allow 3D reconstructions make it possible to generate and analyze models, either by their own software or by exporting to other three-dimensional environments (Autodesk 3DS Max, 2019; Javan et al., 2020). Basically, 3D reconstruction provides either volumes or isosurfaces.

  Table 1 shows the most important characteristics and differences between volumes and isosurfaces. In the isosurface, the object is only composed of a mesh of triangles arranged in one or several surfaces.

Table 1. Characteristics of 3D models.

Volume	Isosurface (Mesh)
Clouds of voxels with different shadows of grey	Meshes arranged by means of triangles joining the object points
Offer a very detailed imagen of the specimen	Only superficies of object are rendered
It is not possible to store the volumes	Can be stores as 3D formats (.obj,.stl,...)
Can be split or cut, being the section surface homogeneous	Can be cut or split, but its section shows only the plane or line when the surfaces were cut
We cannot give them physical properties	They can have physical properties

However, in the volume, all the anatomical elements are shown, represented by their respective voxel, each of which contains its specific properties (location, gray range, etc.).

Once cut, the surface of a volume section will show all the texture of the original tissues. In contrast, cutting an isosurface will show multiple planes and hollow areas between them.

Although the external appearance is very similar, the techniques applicable to the volume are much more extensive and deeper than to the isosurface, as can be understood since the latter only has planes of triangles.

In both cases, the quality of the reconstructions is immense, and techniques like the rendering of materials have been used with spectacular results (Dappa et al., 2016).

- ***Combined techniques***

Both procedures (analysis and process) can be used in conjunction. Frequently, a processing task is firstly carried out and, afterwards, an analysis technique is applied to the result.

Some examples are Registry, Fusion, Navigation, Augmented and Virtual Realities.

Augmented reality is based on inserting virtual objects into a real-world environment (for example, 3D models). Virtual reality involves the inspection of a completely virtual environment. The use of augmented reality has been proposed as a complementary method to autopsy (Affolte et al., 2019).

Other important procedure is 3D Printing, one of the most useful products in teaching and research (Javan et al., 2020), as well as in surgical planning, as will be discussed later.

IAPT procedures are possible by means of dedicated software. There are a variety of packages, many of them freeware or public domain, which can be useful (Inria teams, 2021; Schindelin et al., 2012; Roset et al., 2004; Yushkevich et al., 2006; Kikinis et al., 2014; Fogal et al., 2010; Heckel et al., 2009; Amorim et al., 2015; Cignoni et al., 2008).

The virtual objects generated by the IAPT are stored into an Object Repository (VRO).

It is one of the most interesting parts of the program and, probably, also one of the most useful for teachers, researchers, or other professionals with an interest in these techniques.

IAPT typically generate new elements from DICOM files. These elements can be: Flat images (two-dimensional), triplanar reconstructions, three-dimensional reconstructions in the form of volumes of isosurfaces (meshes). In turn, these elements can produce other objects through post-processing. For example: virtual anatomical preparations of muscles, bones, nerves, etc. (Fig. 1).

The management of the donation program and the repository of objects follows the guidelines previously published (Aso et al, 2019), including a Hospital Monitoring Committee and a computerized database for managing the specimens generated and stored in the VRO.

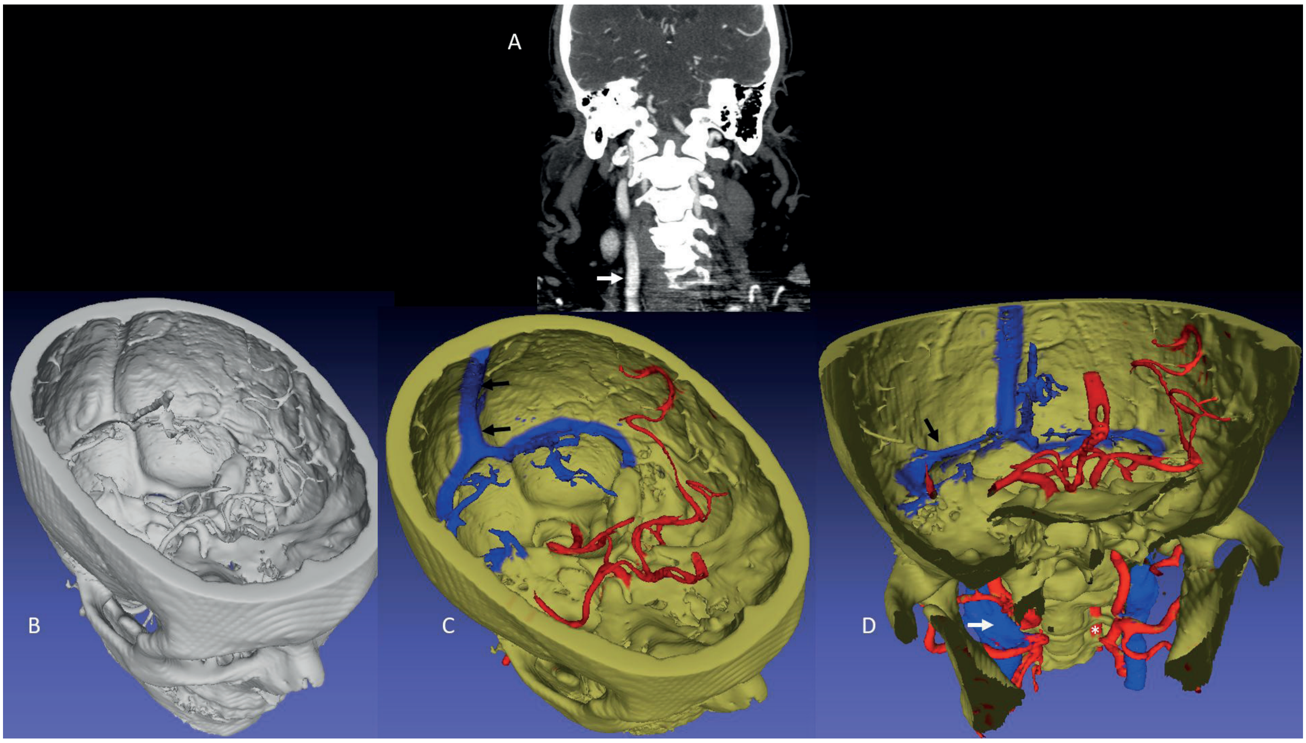

Fig. 1.- Craniocervical CT angiogram (**A**) in a patient with vertebral artery dissection. Images **B**, **C** and **D** are preparations made by the students from CT angiography, aimed to show the encephalic vascularization and its relationship with the bone. Black arrows show parts of venous circulation. White arrow in D points to jugular vein. These latter structures were segmented and depicted by students, as a part of their learning of cephalic circulation.

RESULTS

From January 2020 to June 2021, a total of 63 patients was included into the VRO: 44 men and 19 women. Acceptance of the donation has been excellent, accounting only one refuse, a foreign patient who, probably, did not understand the utility or purpose of the project, mainly due to a linguistic barrier.

Each donation, after IAPT procedures, has generated, in turn, a subset of objects that included:

- Three-dimensional models in the form of isosurfaces (mesh or meshes) (N=71)
- Videos of interaction with specimens (dissections of volumes, mainly, or of isosurfaces) (N=4)
- Flat or mapped images (imbibed with information using a dedicated software) (N=11).
- 3D printed objects (N=15)

The average number of objects generated by each patient was three, with a minimum of one and a maximum of 11.

A total of five final degree (Medical School) projects have been carried out using this procedure with very good results. The matters were related to interactive visualization of the models and geometric morphometrics. A subspecialty subject in bio-anthropology, physical and forensic, is regularly using the VRO for teaching in school of medicine, applied to sexual dimorphism identification, including both theoretical and practical learning.

Two investigation works are currently under way, related to reconstruction of historical skulls, based on indexed graphic cranial and CT-scout profile databases provided by VRO. Graphic similarities of skull can be identified, providing a method for reconstructing the cranial morphology and facial appearance, by using geometrics morphometrics techniques and multivariate statistics (principal component analysis, thin plate spline deformations and others).

One of the final degree projects, investigated, by means of a questionnaire, the acceptance of the interactive visualization of models among medical students. The results showed an enthusiastic assessment in 98% of them on the usefulness of the method in practical teaching of the subject of Anatomy. Many students indicated the great advantage of being able to use the models in their place of study, studying them in a group, and of the possibility to telematic consult the teacher in real time about questions on the model, even after post-processing carried out by students themselves.

Another feature frequently referred was the need of formation in image processing techniques in the curriculum of the degree in Medicine, encouraging to implement learning activities on the subject.

From a healthcare point of view, the useful of interactive visualization of objects and managing of 3D printed models were revealed to be cardinal in presurgical planning. The procedure was tested in 8 cases, mostly related to spine and cranial interventions. Topographical identification of landmarks, planning of placing site, size of implant, and surgical obstacles avoidance were the most advantageous features.

Other important results were related to preoperative training of the entire surgery team. For the surgeons, drill essaying, cutting bone and tumors removal on 3D printed models were revealed to be excellent resources. X-Ray technicians were accustomed prior to the operation to the projections to be used in the operation. Nurses and auxiliars had the opportunity to anticipate surgical requirements or even seeing the surgical step-by-step prior the real intervention.

All these advantages were emphasized by personal involved in surgical actuations in an enthusiastic way.

DISCUSSION

Anatomy Teaching

The teaching of anatomy has been subject to great challenges since the advent of new technologies. Some of pioneer teaching strategies have been recently reviewed (Vázquez et al., 2007) and they appeared to be a powerful tool in both theorical and practical teaching. VBD can offer numerous resources to these teaching procedures, especially in practical approaches, i.e.: classrooms for virtual dissecting normal and pathological cases (Bolliger and Thali, 2015), virtual museums, and new visualization environments and procedures (Virtual and Augmented Realities) (Yushkevich et al., 2006).

At the same time, virtual donation notably increases the number of specimens and materials (virtual anatomical preparations from the post-processing of donations) that can be stored and reused indefinitely.

Another great advantage in pre-graduate teaching is that the student can have the specimen and perform with the preparations commissioned by the teacher. Since the model is indestructible because backup copies are available, the student can, interactive and repeatedly, rehearse different approaches until they find the one that best suits the requirements.

As an example, Fig. 2 summarizes the result of a conversion of a radiological model (CT in “A”). Firstly, to a grey scale 3D model (“B”) and, secondly, to a color solid model (“C” and “D”). This process was accomplished by a group of students assisted by the professor, learning the radiological anatomy (CT) of the case. They also acquired enough skill to prepare virtual models, being able to isolate, identify and depict the intracranial circulation. They were instructed to virtually remove the brain, and isolate (dissect) the intracranial mass (olfactory meningioma), as well to expose the entire Willis polygon. Afterwards, they presented the final model (solid 3D) with different cranial bone virtual removal enabling to see the separated (segmented) structures from various angles.

This procedure was very useful for the students in learning, for instance, the Willis polygon because it was an interactive practical lesson.

In turn, these models, generated by the students themselves, can become part of the VRO in the same way as in an Anatomic Museum (Fig. 1).

It was also found that work in group is favored, as to each student could prepare his/her own specimens, to later become part of a common project.

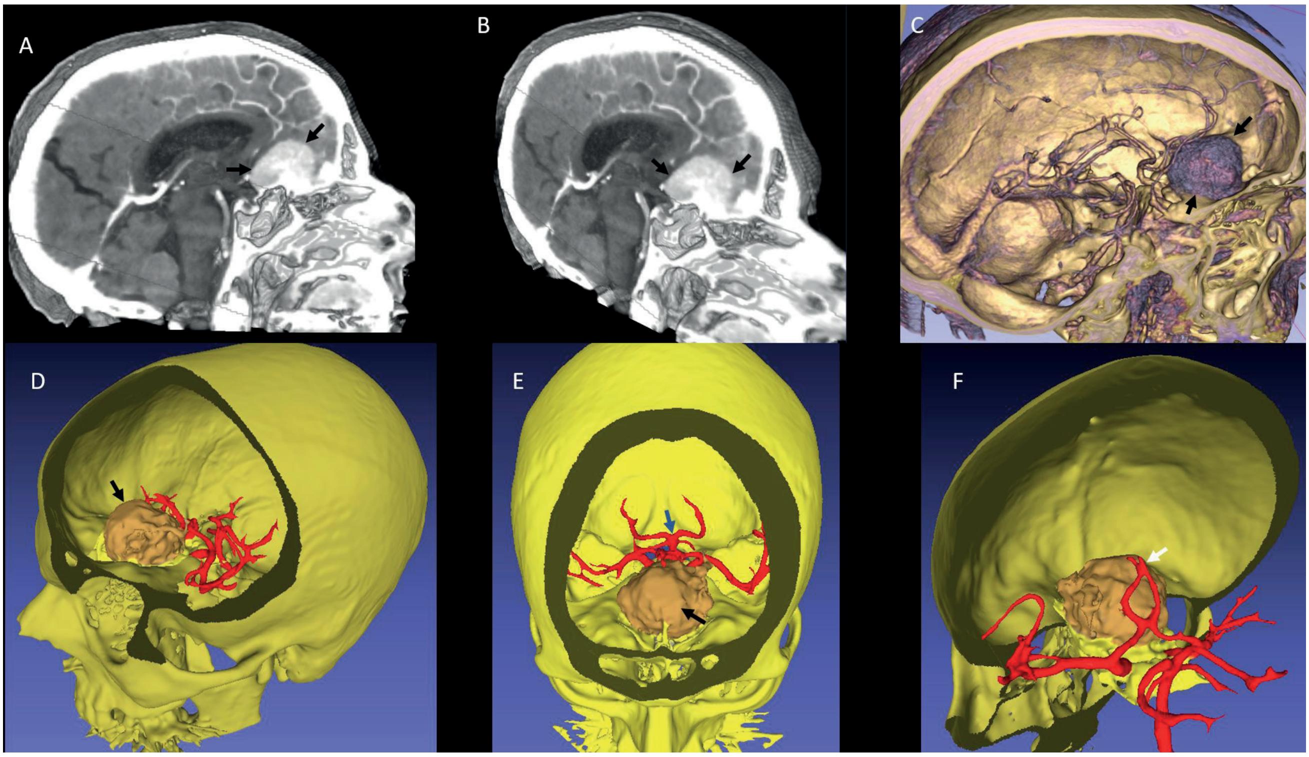

Fig. 2.- Differences between "Volume" and "Isosurface". The preparation corresponds to an olfactory meningioma (arrows in A, B, C and D). In **A** and **B** a rendered volume is presented. Note the different levels of gray that depicts the entire anatomy of brain and tumor. In the isosurface (**D**, **E** and **F**) several surfaces (composed by triangles) conform the object shape. Blue arrow in E and white arrow in F point to different parts of Willis polygon showing its relations with the mass.

One characteristic that appeared relevant was the need of learning and training in the use of IAPT techniques. In pre-graduate teaching, any discipline or sub-discipline that deals with training with these techniques was found.

Fundamentals of IAPT procedures includes the concept and structure of digital image, how it is organized on the servers, how to retrieve, store and work with it. Segmentation tasks, interactive visualization, reconstruction, and a long list of procedures, are part of IAPT procedures in which, both undergraduate and graduate students, should be trained.

Morphological Sciences Departments (Anatomy, in particular) are the ideal environment to perform this type of training.

Research

VBD programs create new sources and methods of research. DICOM files include mathematical information of the specimen, like calibrations, enabling accurate measurements, and references for the location of landmarks. Precise calculation of surfaces, volumes, index, densities and other magnitudes or relations are possible, even automatically.

Some new research techniques, such as geometric morphometrics, find in DICOM files an ideal medium for clinical investigation ([A]so et al., 2018).

As an example, CT image databases were used to generate a graphical craniofacial consensus, allowing similarities to be found between living individuals and skeletal remains. This technique has been useful in the reconstruction or modeling of an unknown face from VBDP patients whose craniofacial geometric morphometry was like the problem case.

Clinical Teaching

Postgraduate teaching, in particular the training of residents, is easy with virtual models and allows, for example, to virtually test the reduction of fractures, or to simulate the use of new stabilization devices (implants, and others) in cases with pathology.

In the Hospital, the acceptance of this type of teaching has been enthusiastic, appearing an interesting educative line to follow and consolidate.

Transversality of these systems must also be emphasized since they are not limited to applications in Medicine. Other professionals, like nurses, physiotherapists, occupational therapists, could benefit from the teaching and research applications of this programs. In the hospital, the reception of these teaching resources by these professionals has been excellent.

Healthcare

Around 75% of the cases, showed direct healthcare utility in surgical planning. As an example, two cases of pelvic fractures were presented, in which it was possible to presurgical essay both the operative technique as the implants on virtual objects and, specifically, on 3D printed models (Fig. 3). In one patient, suffering from a D11 crush fracture on a severe scoliosis, it was possible to repeatedly plan and rehearse on the virtual and printed model how to perform a percutaneous arthrodesis, with very good results (Fig. 4).

The usefulness of the method in planning percutaneous spinal arthrodesis in this case was evident, mainly to simulate the crowding of the towers for the percutaneous introduction of the screws, enabling to find the best way to place them comfortably in surgery. In another case, it helped to rule out a percutaneous approach, because such tower crowding made the technique impossible, opting for an open procedure.

Another additional case was a penetrating injury of the superior longitudinal venous sinus in which the surgical planning was established after reconstructing and printing the 3D model with segmentation of each of the parts.

3D printing goes beyond the mere reproduction of form. Different materials were tested until the finding of the best reproduction of bone characteristics. Once found the best material, its characteristics allowed to accurately simulate the trepanation, the milling, brocading, and bone cutting. All these maneuvers were found to be a perfect resemblance of the actual surgical ones (Fig. 5).

Likewise, the 3D printed objects should have radiological fidelity, enabling radiology to be used as an assistant in the essays on the printed model (Fig. 6).

Fig. 3.- 34-year-old male patient with pelvis fracture (AO classification 61C2.3) that progressed to pseudoarthrosis. **A**: Note the pseudoarthrosis of both ilio-pubic branches (red rings) with significant displacement. **B** and **C**: essaying the surgery on the 3D printed model. **D**: The plates are shaped and adapted to the model. **E**: Surgical approach. The plate is visible on the right side. Previous shaping of the plates allowed us to save significant surgical time. **F**: X-ray of the result.

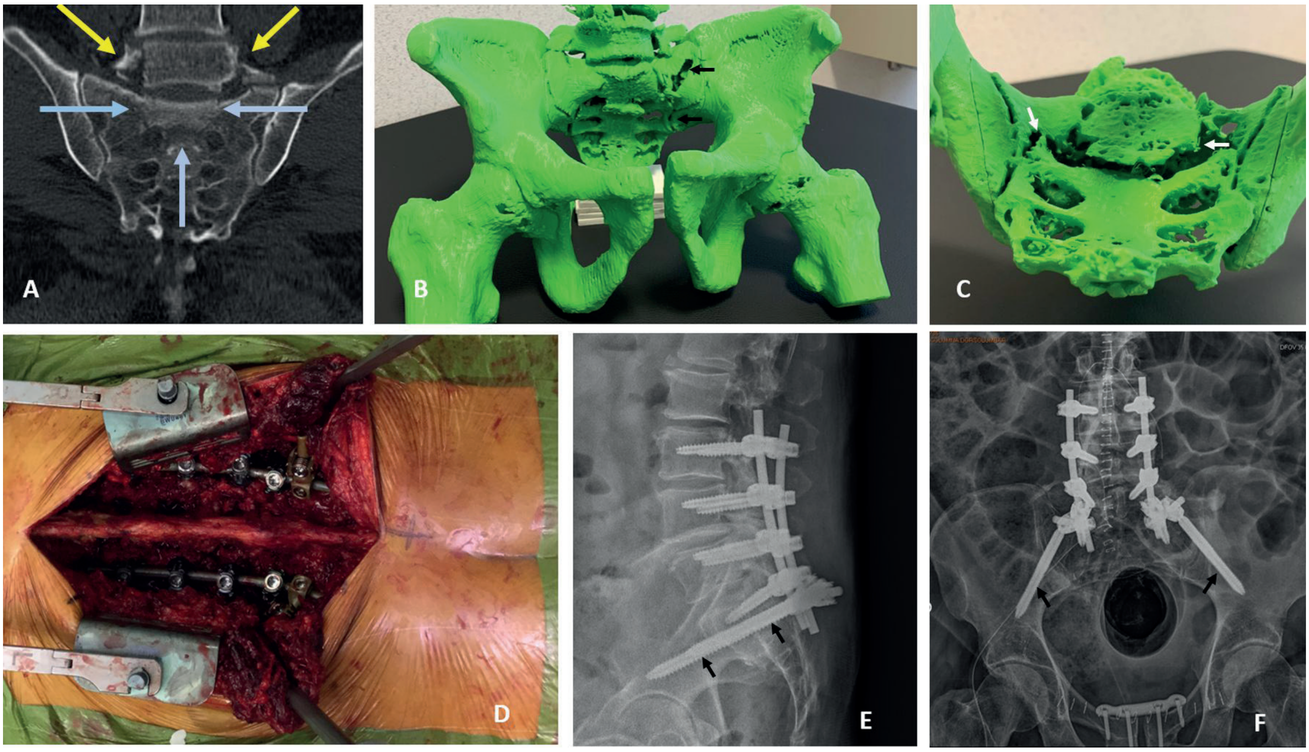

Fig. 4.- 60-year-old man with spinopelvic dissociation. **A**: the arrows mark the fracture of both transverse processes of L5 and the classic sacral "U-shaped" fracture. **B** and **C**: 3D printed model. **D**: intraoperative image showing L3-L4-L5-S1 instrumentation. **E** and **F**: radiological result. Arrows in B and C show fracture lines. A sacro-pelvic screw was placed (arrows in E and F). The insertion path and dimensions of this screw were previously planned and trained on the 3D printed model.

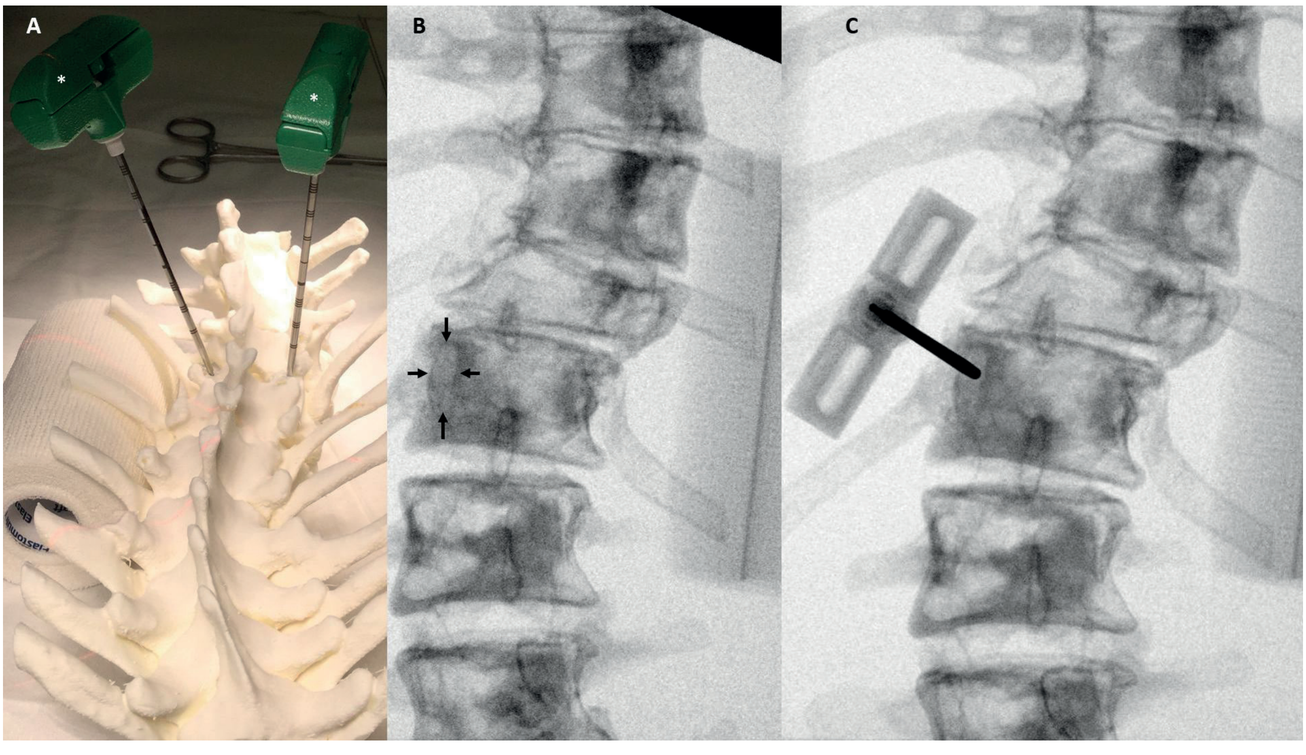

Fig. 5.- Image corresponding to the preoperative simulation of pedicle (arrows in B) cannulation in a spinal fracture in a case of severe scoliosis. **A**: Shows the 3D printed model simulating pedicle cannulation. **B** and **C**: Plain X-ray of the printed model. In C the cannula is placed with the tip over the pedicle AP projection. Asterisk in A are placed on bone access needles, used in Kyphoplasty.

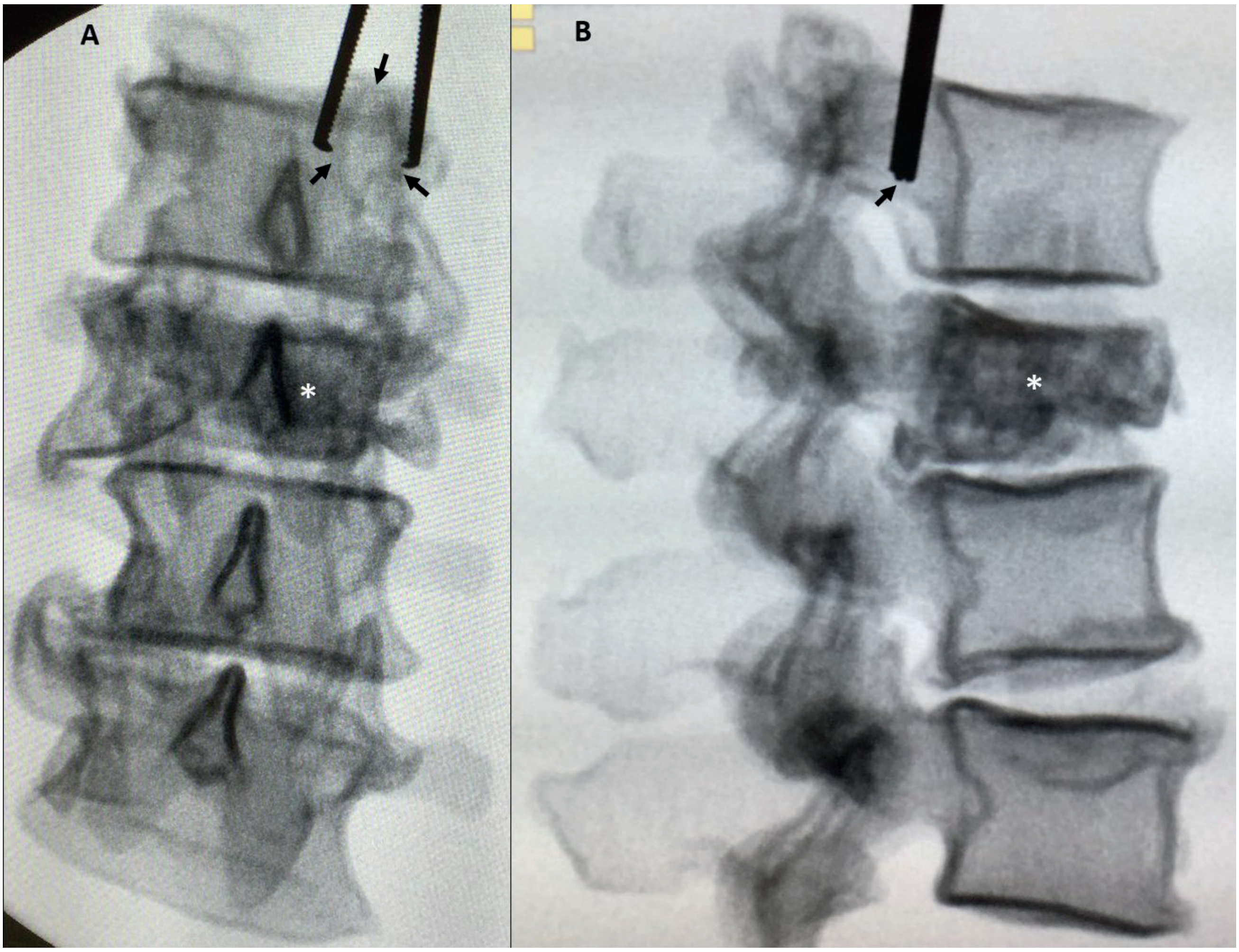

Fig. 6.- Radiological image of a 3D printed model corresponding to a crush fracture. Note the excellent quality that render almost indifferentiable the X-ray appearance of the model from an actual spine. The X-ray of the specimen is used to reproduce in the 3D printed model the same actions that would be carried-out in surgery. From the educational point of view, the image demonstrates how plain X-rays of the models can be also used to explain radiological anatomy. Arrows mark the optical cut od the pedicle in **A**, and the corresponding level in **B**. Forceps are used as a reference of pedicle position.

This allows simulating operations and interacting with implants that, in turn, can be measured and adjusted to fit the model on which it will be implanted.

Another important matter found of great usefulness is the information to the patient associated to surgical informed consent.

In all the cases, the procedures have been explained to the patients and relatives, using the 3D models, which has facilitated their understanding of the technique and significantly helped in the tasks of informed consent. The degree of satisfaction of patients with this kind of information was excellent.

Weaknesses

The first weakness of this work is the relatively small number of specimens collected to the date (due in part to the current pandemic situation). Surely, an expansion of these programs can help increase the casuistry, being desirable that it be adopted in a cooperative manner between several centers.

Another weakness, already pointed out, derives from the still scarce training in IAPT by healthcare personnel. There is still a gap between technology development and its level of use by the health professionals, which could very well be filled through teaching in morphological sciences.

The last weakness derives from the still incipient development of imaging techniques. For example, 3D printing is a procedure that requires time and that, for the moment, cannot be applied to emergency care cases. A greater introduction in the assistance and teaching of these techniques can also serve as a spur to the development of faster and more efficient technologies, not only for printing but also for the rest of the tasks inherent to image analysis and processing.

Future perspectives

It must be considered that with the technology available today a significant number of IAPT can be carried out, but that, in the future, it will be possible to extend these actions to fields currently in development (holography, study of diseases by means of CT voxel analysis or MRI, cerebral tractography, etc.). This will probably require an organization of virtual resources that can be used, so the present program and its extension to other centers could be an element of interest for the not-too-distant future.

There is a new generation of learners called “digital natives” (Prensky, 2001) and medical students are not an exception. The task of medical educators is to use the new technologies as a complementary tool in teaching, but technologies are just one tool, not a replacement of traditional face-to-face method of learning (Guze, 2015).

Under this perspective, the VBDP appears to be a promising reality to complement the traditional learning of Medicine, as well as a continuous source of material suitable to be organized and explored by the emergent and future image techniques. They can provide also a legal and ethical framework, protecting the rights of patients and allowing both the medical teaching, investigating and clinical use of the material donated by them.

CONCLUSIONS

The recently proposed virtual donation programs are an effective means of providing useful models both in medical and healthcare teaching as in research.

The experience in the use of these systems is very satisfactory and opens many possibilities for both clinicians, teachers, and researchers in anatomy, morphological or related sciences.

Patients have shown enthusiastic adhesion to the program, being the refusal an exception. Students also considered very useful the program and its implication, and the work with the virtual specimens as an excellent complementary method of learning anatomy.

The generation of virtual repositories of objects from digital acquisitions revealed to be extremely useful in healthcare (surgical planning), teaching (both undergraduate and graduate) and research. For this reason, an extension to regional centers that could favor the transversality of these systems is desirable.

Departments and chairs of morphological sciences are considered the ideal environment to take advantage of the implementation and growth of virtual donation programs, either by means of the use of specimens generated by other institutions in teaching and investigation, creating Medical Digital image teaching programs, or implementing virtual donation programs themselves as a complement to the human body donation of corpses.

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