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Research paper

Biomodeling and 3D printing: A novel radiology subspecialty

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ABSTRACT

3D biomodels are a new kind of medical image that enables easier interpretation of medical imaging findings, virtual surgical planning and 3D printing of anatomical biomodels and personalized surgical tools. New applications emerge every week in all surgical specialties for diagnostic, treatment and educational purposes. High performance software is available for biomodeling but it still requires human supervision to ensure biomodel fidelity with patient anatomy. Radiology technologists, bioengineers or other health care providers may have sufficient training to provide accurate segmentation in most cases. However, radiologists should be involved to add their expertise in medicine and medical imaging since there is a great deal of medical professional responsibility involved in the biomodeling and virtual planning process. The aim of this work is to review the key role of radiologists in the usual workflow of patients that require 3D technologies for diagnostic and treatment purposes in ensuring safe practices. Imaging requirements and a short description of the biomodeling process necessary to achieve high quality 3D biomodels is presented. General applications and the main difficulties for implementation of 3D technologies are reviewed.

Introduction

Image interpretation of diagnostic imaging studies, such as computer tomography (CT) or magnetic resonance imaging (MRI), is a real challenge for clinicians. Most of them rely on the radiologist report to create an abstract picture of their patient's disease, which then apply to plan their surgical strategy. However, there is much more information in an imaging study than it is possible to report. For example, it would not be practical to describe every twist and turn of arteries and veins around a certain lesion. Even obtaining this information from two-dimensional images is an almost impossible task. On the other hand, vessel information is key to avoid bleeding complications in surgery. 3D biomodels are three-dimension (3D) representations of patient imaging findings (Fig. 1). They include information from selected anatomical structures that can be visualized selectively, rotated 360 ° and visualized in transparency mode for detailed analysis and anatomy understanding. 3D biomodels add supplementary information to the radiologist report, presenting data to clinicians in an easier way to interpret, resulting in a more efficient method for conveying patient small detail. 3D biomodels do not replace 2D digital imaging and communication in medicine (DICOM) images, diagnosis still needs to be performed with 2D views to avoid all possibility of error that could eventually arise from the biomodeling process. However, they can be considered diagnostic from the descriptive point of view, since they improve radiologists' interpretation of imaging findings and clinicians interpretation of the radiologist report, adding important anatomic information, vital for complex surgery success. 3D language also improves doctor-patient communication since they make disease understanding less challenging to patients [1]. 3D biomodels are created using specific biomodeling software from the same DICOM series acquired for diagnostic purposes and can combine information from different imaging studies (CT, MRI, PET) [2]. The anatomic structures to be part of the 3D biomodel are selected according to surgical needs for each clinical case. 3D biomodels follow therefore the definition of medical images, since they are images of body parts created with the purpose of analysis of a clinical condition and/or medical intervention [3]. As medical imaging specialists, radiologists play a critical role in obtaining medical images with the necessary requirements for biomodeling and in certifying 3D biomodels quality and precision. Even though advanced technology is available for biomodeling, the process is still semiautomatic, requiring human supervision and manual correction of structure boundaries. This fact is extremely important for oncologic lesions, which generally need to be delineated with manual tools. As has been stated by the 3D Printing Special Interest Group of the Radiological Society of North America, radiologists are a must in the workflow of 3D technology supported clinical cases, where they will either create the 3D biomodel themselves or strictly supervise its precision, to warrant safe procedures [4].

The current work aims at describing imaging requirements for high quality biomodels, the biomodeling process, applications of 3D technologies in diagnosis, treatment and education for different

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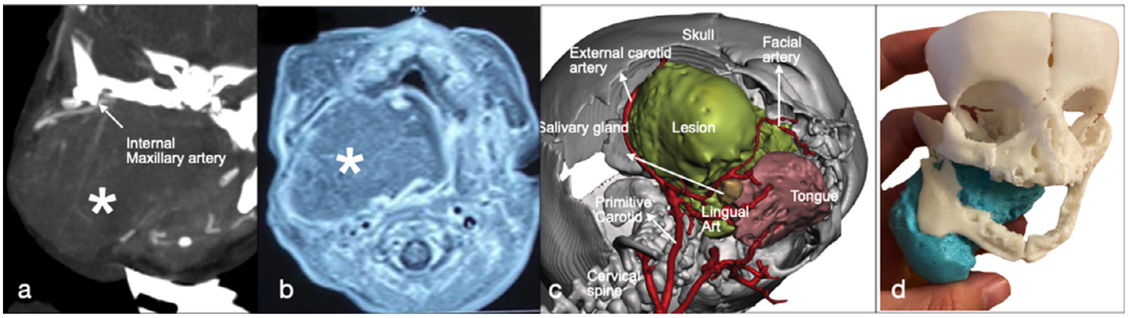

Fig. 1. *3D biomodel* Neonate patient with prenatal diagnosis of a giant heterotopic neuroglial cervical tumor. (a) Enhanced CT, coronal view, depicting a huge solid oropharyngeal mass (*). Window width and center adjusted for vessel assessment. (b) Axial T1 FS Gadolinium enhanced MRI sequence, showing peripheral mass enhancement. (c) Annotated virtual anatomical 3D biomodel used for surgical planning, including bone, mass, tongue, salivary gland and vessel information. (d) Real-sized PLA 3D-printed biomodel of skull, mandible and mass, used for surgical planning.

surgical specialties, and finally, radiologists key role in this new addition to patient workflow.

Image requierements

3D biomodels are generated from diagnostic imaging studies, such as CT or MRI, with specific biomodeling software which uses post processed data (not raw-data). To create quality biomodels imaging studies need to be isovoxel volume datasets, saved in DICOM format. Most CT scanners available acquire volumetric images, but special attention needs to be paid to post processing techniques in order to obtain section thickness equal or below pixel size (isovoxel). Quality biomodels can already be obtained with section thickness below 1 mm. In order to reduce bone 3D biomodel artifacts, it is preferable to obtain them from soft tissue CT reconstructions (Fig. 2). In MRI, on the other hand, 3D volumetric sequences are infrequent in usual acquisition protocols, so MRI protocols of diagnostic imaging studies that may need biomodeling generally require planning ahead. It is possible to obtain biomodels from MRI sequences acquired by plane. However, biomodels will show a stair-step artifact, according to the slice thickness used (Fig. 3). Since volumetric acquisitions take longer, unnecessary delays should be spared by deciding on a case-based approach which sequence to acquire volumetrically. This sequence should be that where the patient's disease has the greatest contrast with surrounding tissues. There are published protocols optimized for diagnostic and biomodeling quality for different clinical settings [5,6]. In general, efforts must be made to reduce motion and metal artifacts as much as possible, applying the same guidelines to achieve imaging studies of diagnostic quality (Fig. 4).

Biomodeling process

CT images are preferable to precisely biomodel bones. Soft tissue organs can be obtained either from CT or MRI. Soft tissue lesions can be sometimes obtained from CT, although generally contrast with surrounding tissues is better achieved with MRI. Images from CT and MRI can be merged through software to obtain combined CT/MRI biomodels. This poses another challenge in terms of precision since overlaying also demands manual correction and validation (Fig. 5).

The process to go from DICOM images to 3D biomodels is called segmentation (Fig. 6). Segmentation is an advanced image post processing technique, which involves labeling each voxel as part of a certain anatomical structure [2]. The segmentation software then renders all same-labelled voxels into 3D surfaces, or triangle meshes, to create a 3D model for each segmented anatomical structure which can be exported as Standard Triangle Language (.STL) files (Fig. 7) [2]. There are many segmentation software available, some of which can be downloaded from the internet for free. Depending on the anatomical structure and software capabilities, the segmentation process can be more or less automatic, although, so far, all of them require human supervision. Radiologist supervision of this process is particularly important for oncologic patients. Oncologic lesion segmentation can be challenging due to pixel intensity value heterogeneity, low contrast with surrounding tissue or very irregular shape, making exact boundaries hard to delineate, even for experienced radiologists. The

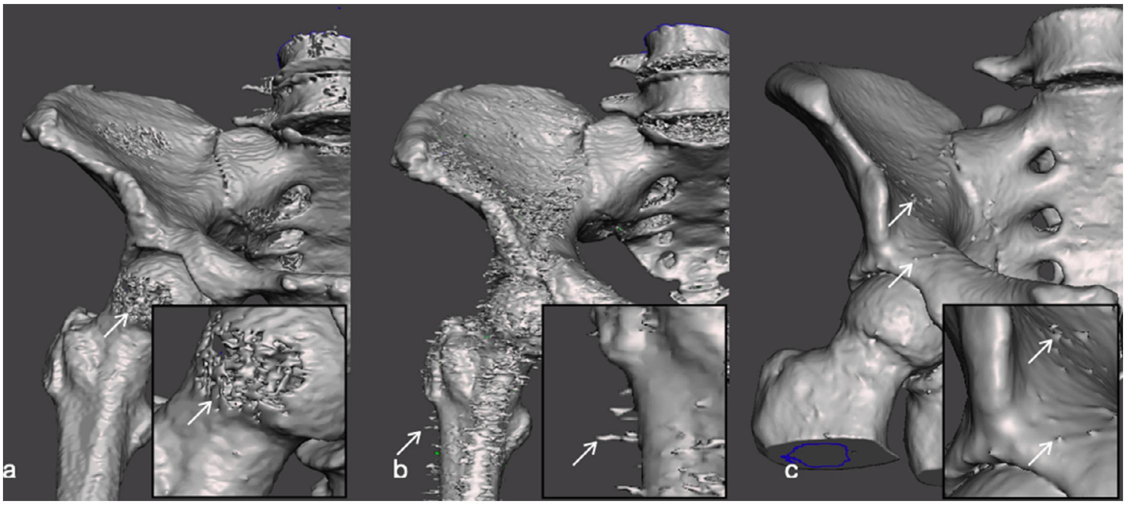

Fig. 2. *Porosity and spike artifacts* Hip and femur virtual 3D biomodel depicting differences in biomodel quality when generated from CT bone reconstruction using bone kernels (a and b), and when segmented from CT soft tissue reconstructions (c). (a) Porosity artifact, (b) Spikes artifact, (c) Few spike artifacts.

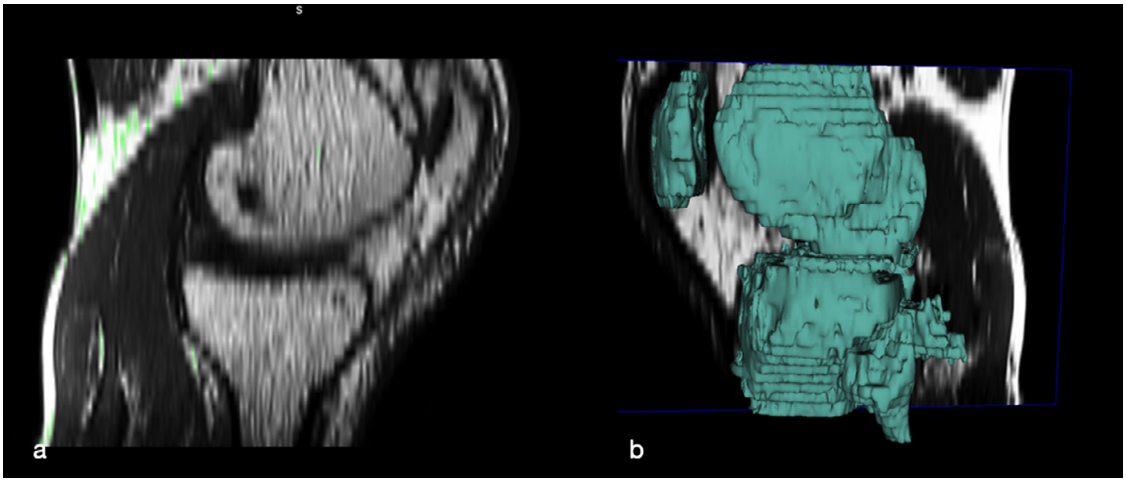

Fig. 3. *Stair-step artifact* (a) Sagital view of an axial (non volumetric) T1 MRI sequence. (b) 3D biomodel overlaid to MRI DICOM image, depicting stair-step artifact. 3D biomodel was created from this DICOM MRI non volumetric sequence. Each step has the same thickness as the slice thickness. 3D post-processing smoothing tools can improve this artifact, however biomodel precision would be compromised.

segmentation process is finalized with the 3D files going through a process of "cleaning" and "smoothing". This algorithms remove noise, reduce artifacts, close holes and smooth the STL file surface. The right amount of 3D file post processing helps improve model visualization. However, it needs strict supervision since excessive use of this tools can alter biomodel precision and fidelity with patient's anatomy (Fig. 8). As will be depicted below, 3D biomodels are the starting point for virtual surgical planning and personalized surgical guide design, which rely on segmentation precision for a favorable outcome.

3D biomodels in diagnostics

3D biomodels are used in virtual and real tangible 3D-printed format. Virtual 3D biomodels can be navigated using 3D viewing software, which allow coloring, 360 ° exploration, selective and transparency visualisations, all of which improve detailed anatomic comprehension (Fig. 9). Clinicians can either install 3D-viewers in their computers to navigate biomodels themselves or watch .mp4 videos of the biomodel navigation focused on the clinical case key elements prepared by the 3D team. Biomodels can also be visualized using virtual and augmented reality for a more immersive experience [7]. 3D-printed models are an exact real-size replica of an anatomic region, materialized using different 3D-printing technologies and materials according to the intended use [8]. Polylactic acid (PLA), is one of the most popular materials, made from renewable resources such as corn starch and biodegradable under certain conditions, which has excellent mechanical properties to for 3D printing rigid parts for anatomic study and procedure simulation (Fig. 10) [8]. Other materials like thermoplastic polyurethane (TPU), great for printing parts with a degree of flexibility, and resins which can achieve higher 3D printing precision and are more resistant, are also frequently used for medical 3D printing (Fig. 11) [8].

The use of 3D biomodels for diagnostic purposes enables comprehensive understanding of patient's anatomy and better anticipation of anatomic difficulties, particularly in complex cases, leading to faster and safer surgery, reduced errors and complications, thus resulting in improved outcomes [9,10]. The most commonly reported advantages of including 3D technologies in surgical planning include reduced surgical times, reduced blood loss and infection rates, reduced r-ray exposure and improved patient outcome [10,11].

Volumetric assessment is another advantage of using 3D technologies, which are applied to evaluate organ transplant or metastasis resection indication, treatment response or disease progression in oncologic patients or surgical indication in conditions such as neurofibromatosis. [12–14].

Doctor-patient communication is another well reported benefit, since 3D virtual and printed biomodels are much easier for a patient to understand than complex 2D gray-scale images from CT or MRI. This allows patients to better understand treatment risks and empowers them to make well informed decisions [1,10].

3D biomodels in treatment

Virtual surgical planning and simulation with 3D printed parts enables patient-specific simulation and rehearsal as well as specific tool design for surgeries, improving procedure precision.

Special biomodeling programs allow safe oncologic margin simulation and osteotomy plane design, creating a new inexistent surgical preparation phase between medical imaging interpretation and the actual surgery (Fig. 12). Major treatment decisions are planned before having the patient under anesthesia, thus saving time and improving results comparing to surgical planning with traditional methods [15]. Surgeons of all levels of experience have reported their preference to add 3D planning and printed parts to their workflow, and changes in surgical strategy have been reported by up to 70% of surgeons in training[16] [18].

The "mirror technique" is a particularly useful tool for patients that require reconstructive surgery. It is based on the symmetry of our body, and involves the use of the healthy contralateral region as a template to restore normal anatomy and symmetry (Fig. 13) [17–19].

A further step is the design and 3D printing of personalized surgical tools, such as cutting and positioning guides, which are sterilized and used during surgery to exactly reproduce the virtual surgical plan (Fig. 14) [15]. Traumatology, orthopedics, maxillo-facial and plastic surgery are the surgical specialties that mostly benefit from their use. Surgical guides can be considered as molds which uniquely adapt to a certain region of a patient's anatomy, and include saw slots to guide an osteotomy in extension and orientation, so as to reproduce precisely the cutting planes decided during the virtual plan. The use of surgical guides allow limb and joint preservation in many oncologic surgeries [20, 21].

Real-sized 3D printed parts are used before and during surgery to simulate procedures and prepare surgical supplies. In orthopedics, fixation plates or repairing are pre contoured to fit patient specific anatomy and screws are selected according to patient size [17,22]. Screw and plate location can also be virtually planned ahead. As a result, x-ray exposure can be significantly reduced, another

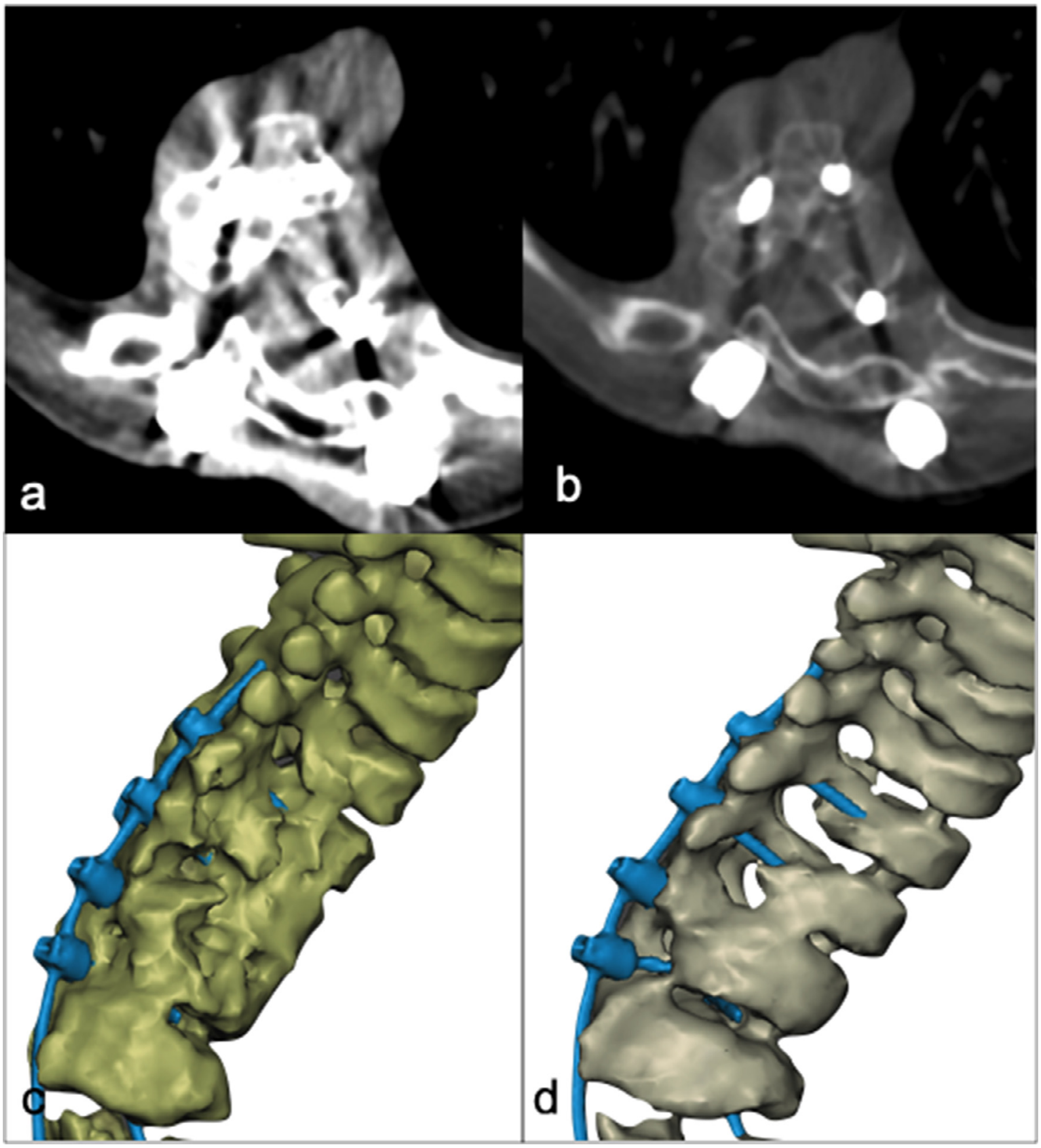

Fig. 4. *Metal artifact* Axial CT images of a scoliotic spine with metal fixation material from previous surgery without (a) and with (b) metal artifact reduction software post-processing. 3D spine biomodel created from CT with reduced metal artifact (d) shows better anatomy definition than the one created with the original CT (c).

advantage reported when using 3D technologies to support complex surgeries (Fig. 15) [23].

An increase in upfront costs is frequently reported as a drawback for using 3D technologies [10]. However, this is a controversial issue since there are recent publications informing that considering the reduction in operating times, there is no adverse impact on overall costs and other that even describe savings [24,25]. Ballard et al. describes a shortening in procedure time ranging from 23 to 62 min, which lead to reduced operating room costs up to 3720 US dollars per case has been reported by a review in literature by Ballard et al. in clinical centers which include virtual surgical planning and 3D printing in their workflow [25]

Finally, thanks to 3D technologies and the availability to 3D print in metal and other biomaterials, it is now possible to customize implants and prosthesis for joint and bone replacements. Patient-specific implants reduce standard-size related post-operative complications, accelerate recovery due to rapid osteointegration, improve inicial and long-term stability and have better esthetic results [26,27]. Since specific antibiotics can be included in the manufacturing process, infection rates are also reduced [26,27].

3D biomodels in training and education

3D printing enables new methods for education and training of human resources using surgical simulation, associated with faster learning curves [17,28–30].

Procedure rehearsal and patient-specific training are key to complex surgery success. Virtual surgical planning and 3D printing of patient-specific simulators allow the surgical team to prepare for a particular setting, practice to define specific strategies and preview potential complications [17, 28–30]. From an academic point of view, 3D printed simulators are a change in paradigm. Experienced

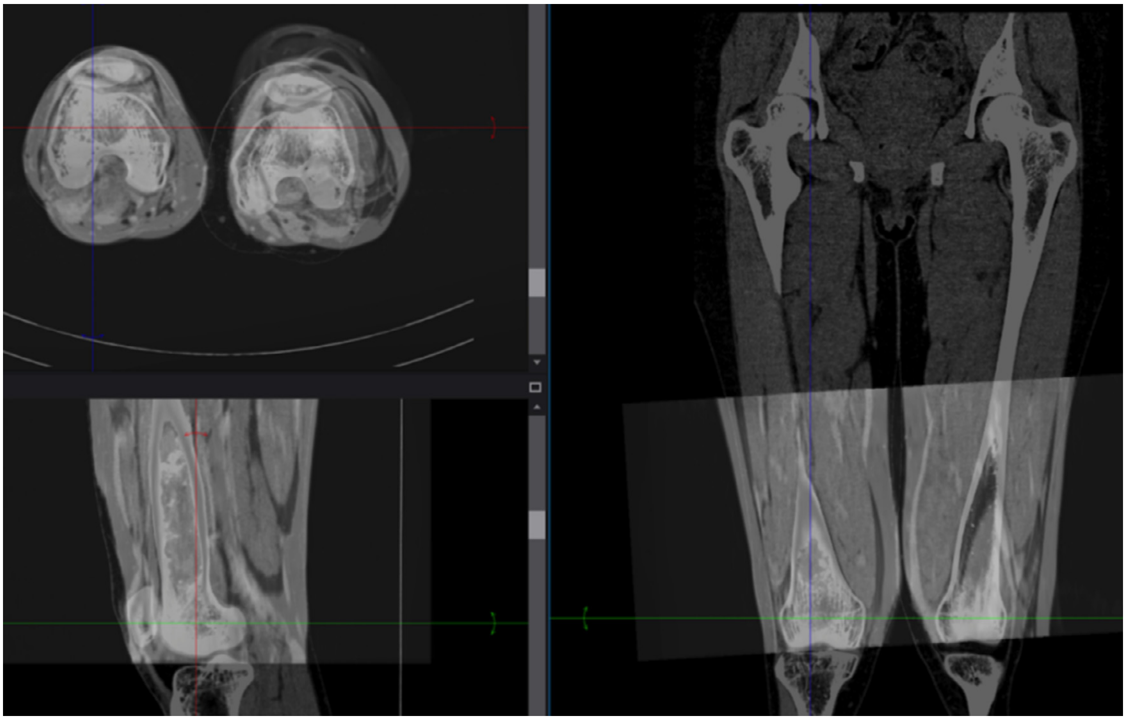

Fig. 5. *CT/MRI Registration process* Using CT image as reference, different MRI sequences can be overlaid to combine data from each study in the same 3D biomodel. This process is semi-automatic and requires manual adjustments to achieve perfect matching of anatomic structures to ensure biomodel precision.

surgeons can teach procedures and different technical strategies outside the operating room, removing space and time constraints, thus potentiating the number of human resources trained at a time. Each case can be 3D-printed as many times as necessary, granting opportunity to many surgeons to practice with the same case. Simulation settings are a safe environment to learn, ask questions and make mistakes. Anatomy simulators are perfect to learn and practice invasive procedures such as cannulation, lumbar puncture, biliary or airway endoscopic procedures and endovascular interventions (Fig. 16) [31–35]. Simulators can be patient specific or generic, with normal or anatomic variants [36]. It is also possible to print 'negative' moulds to make organ simulators with silicone or agarose gels to simulate soft tissue surgery simulators [37].

General applications

The use of 3D technologies is increasing every day with new applications in different medical subspecialties are being published every week. Below is a short review of the most common applications by surgical subspecialty.

3D Application in cardiovascular surgery

3D technology is particularly useful for surgical planning of complex congenital heart disease, valve replacement and great vessel repair [38]. Virtual biomodels are sometimes enough to understand anatomic features to plan surgical approach. Some cases benefit from 3D printed parts (Fig. 17). A literature review by Wang et al. describe 3D printing in cardiovascular surgery as a unique patient-specific method to assess complex anatomy and considers it helpful for intraoperative orientation, decision-making, creating functional models and teaching cardiac, vascular and catheter-based heart surgery [38]. Vessel simulators are very useful for endovascular treatment simulation in complex cases with vessel variants or complex anatomy [32,33].

3D Application in thoracic surgery

Lung nodule volumetric assessment has been used for a long time now as a biomarker for surgical indication [39]. 3D biomodeling adds the possibility of understanding nodule anatomic relations with vessels and bronchi and has been associated with faster lobectomies, segmentectomies and subsegmentectomies, reduced bleeding rates and shorter hospital stays [28,40,41]. A combination of biomodels and augmented reality has been successfully used for a series of patients [28]. Virtual surgical planning is particularly useful for oncologic resection of rib cage lesions and bone defect repair, either with bone grafts or customized metallic implants (Fig. 18) [28,40,41]. Some 3D printing materials used in thoracic surgery have specific *in vivo* properties and tissue reaction overtime, such as growing with the patient or reabsorbing over time (referred to as 4D printing) [42]. An example of implants of this kind are patient-specific bronchial splints used to treat pediatric patients with severe life-threatening bronchomalacia, which extralumenally suspend the airway open [43]. Lung volumetric assessment has been key during COVID-19 pandemic for infiltrates and atelectasis quantification and development of coefficients with prognostic value [44].

3D Application in traumatology and orthopedic surgery

Spine surgeries supported with 3D technologies report improved anatomic understanding compared to using traditional DICOM images alone, better communication within the surgical team and enhanced results in placing screws and fixation material [45,46]. Real-size 3D printed biomodels of scoliotic spines allow pre surgical planning of the corrective reduction, selection of fixation material and simulation of the procedure (Fig. 19). The accuracy of surgical technique using 3D printed biomodels combined with design and 3D printing of pedicle guiders has been reported higher than the accuracy of freehand techniques, in addition to resulting in shorter operative time [47].

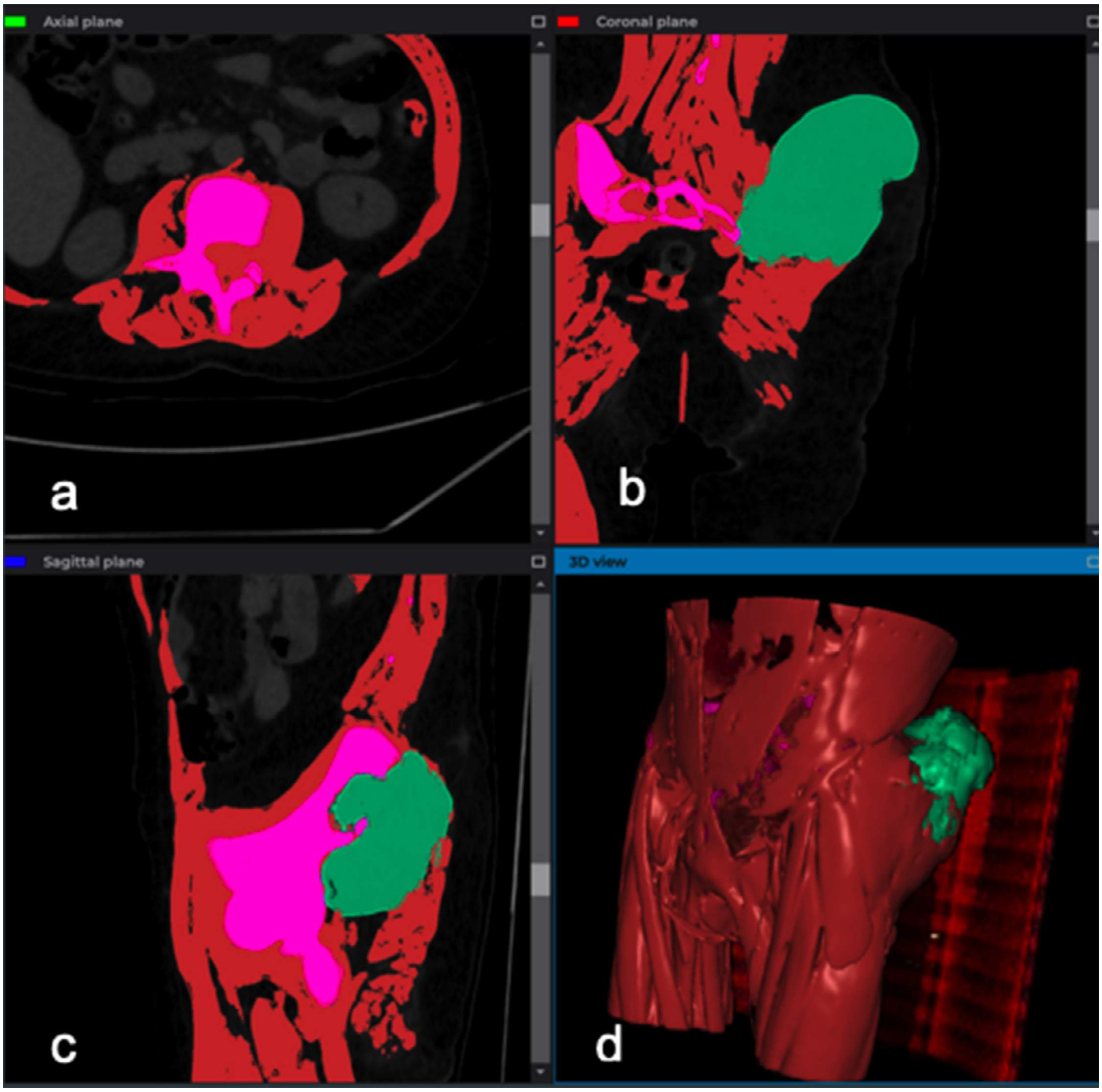

Fig. 6. *Segmentation* Segmentation process of DICOM image voxels for a patient with a tumoral lesion in the left hip. (a), (b) and (c) show DICOM images in axial, coronal and sagittal planes, respectively, with a color mask representing different anatomic structures. (d) shows the 3D surfaces reconstructed for each mask. This 3D object can be exported as an STL file, compatible with 3D printing.

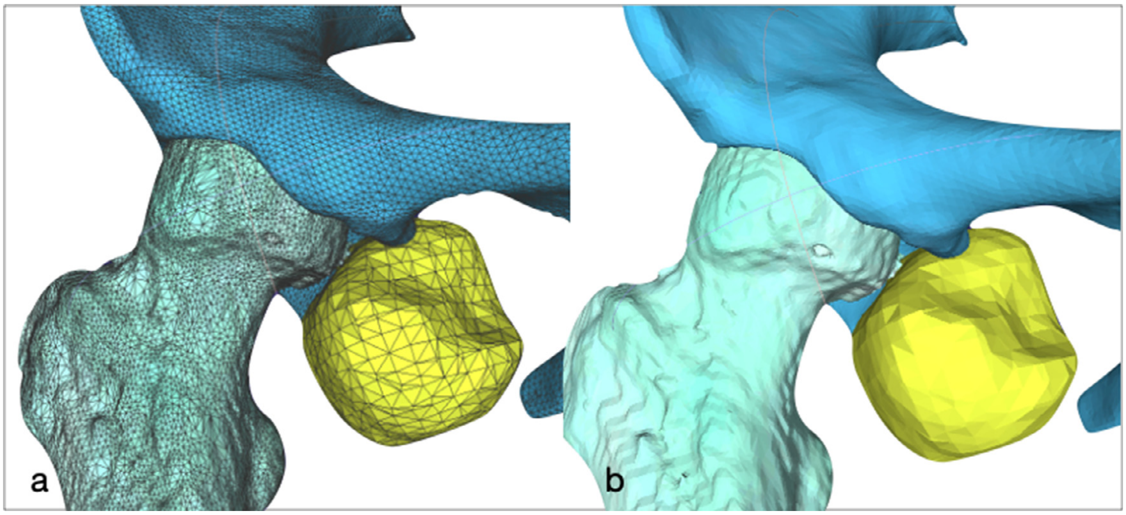

Fig. 7. *STL file* (a) shows the triangle mesh view of 3D files which gives name to the file format STL ("Standard Triangle Language"). The smaller the triangle size in the mesh, the higher anatomical detail in the 3D object in the biomodel (b).

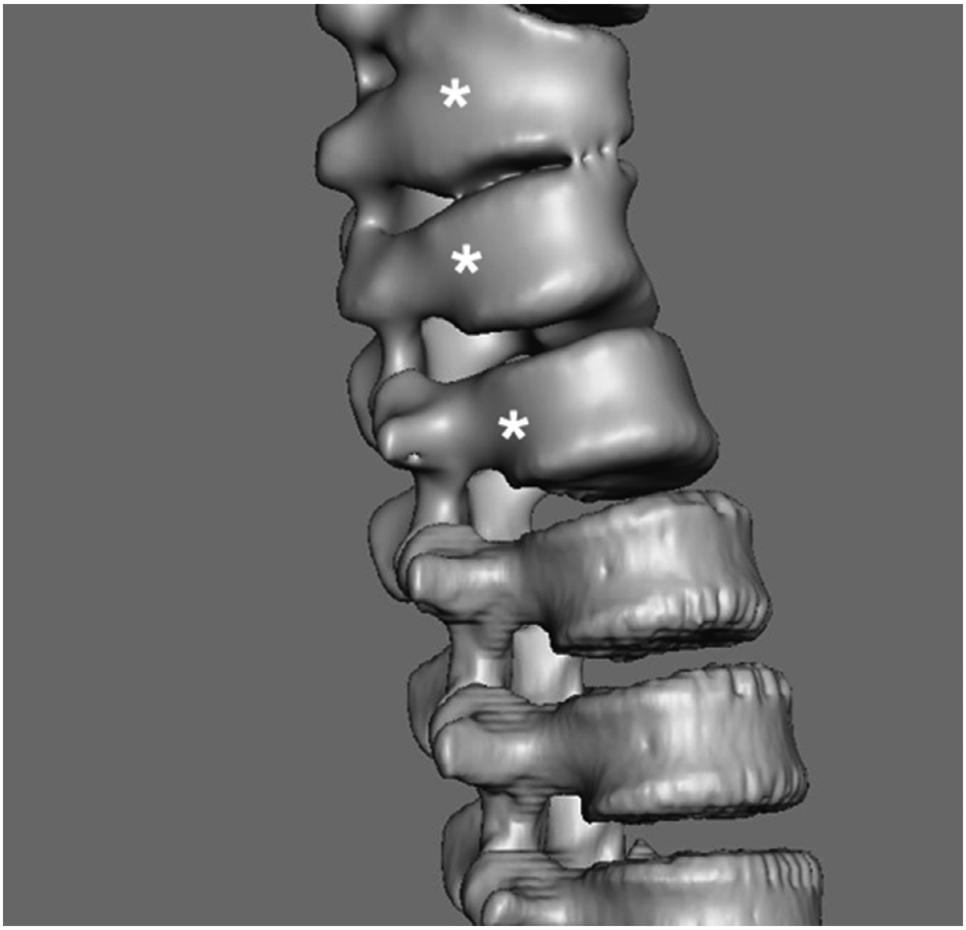

Fig. 8. *3D post-processing tools* Spine 3D Biomodel showing excessive "smoothing" of the upper vertebrae (*) compared to original surface appearance. Anatomic detail is reduced at the expense of reducing "stair-step" artifact.

For complex fracture surgery, improved functional and esthetic results, with less invasive surgeries, reduced operating times and bleeding complications have been informed when comparing surgery with and without 3D technology support [17,29,38,48]. The "mirror technique" using the 3D printed "mirror" image of the uninjured side is particularly useful for repairing the clavicle, acetabulum, calcaneus, shoulder, ribs and scaphoid [17]. Even though it may involve scanning a healthy area, implying radiation dose for the patient, the reduction of fluoroscopy time during surgery, together with the improved results and thus reduced number of followup imaging, may compensate for it.

Virtual planning and surgical guide design have been reported to increase precision of valgus and varus malalignment surgery, making surgery more efficient and involving less x-ray exposure [15,49]

Finally, patients with congenital hip displasia benefit from the use of 3D technologies. Virtual 3D biomodels enable osteotomy strategy planning and surgical guide design to assist restoring the joint normal anatomy and functionality [50].

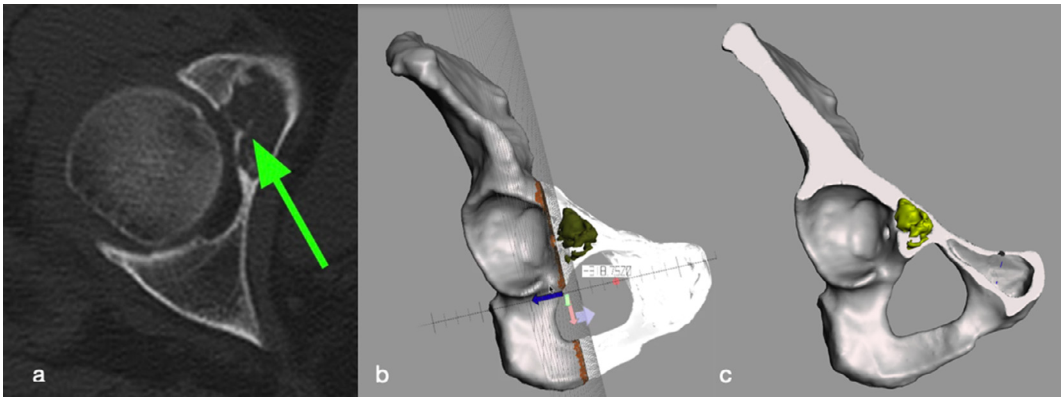

Fig. 9. *3D biomodel navigation* (a) Axial CT depicting an intraosseus acetabular lesion (arrow) with no representation in bone surface. (b) 3D biomodel including bone and tumor information, demonstrating transparency tool (b) and selective plane cuts (c) to assess mass anatomical relationships and plan surgical strategies.

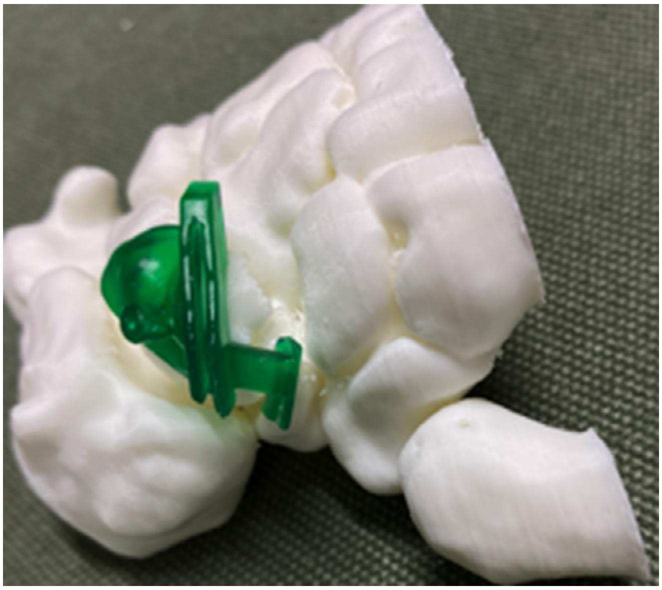

Fig. 10. *3D printed biomodel* Simulation of complex surgery for scaphoid pseudoarthrosis repair. Real-size bone biomodel of left carpal region printed in PLA (white) and customized cutting guide (green) specifically designed for this case during virtual surgical planning 3D printed in resins.

3D Application in plastic and maxillo-facial surgery

In both subspecialties best practices rely on precise osteotomies, bone modeling and plate contouring, all of which benefit from virtual surgical planning, surgical guide design and 3D printing of real-size biomodels. The "mirror technique" is specially applicable in these surgeries where symmetry and esthetic results are paramount. 3D technologies have been applied for mandibular and maxillary reconstruction, particularly useful in situations of delayed reconstruction with bone contraction or malocclusion (Fig. 13) [52]. Bones like the mandible are sometimes reconstructed using bone segments from the patient's own fibula or iliac bone. Digital simulation allows planning to achieve the original bone anatomical curves and angles with the bone graft segments. Custom cutting and positioning guide design for mandible segment resection and graft preparation result in perfect bone adjustment leading to a gain in precision and faster patient recovery [53]. Advantages on oncologic procedure simulation have already been discussed for other surgical specialties.

In orthognatic surgery, numerous studies have demonstrated that 3D technologies help clinicians shorten operative times, increase surgical safety and improve predictability of surgical outcomes for surgeries that included occlusal splints, osteotomy/cutting guides, positioning guides, spacers, fixation plates and implants [18,51].

3D Application in urology

Renal tumors are among the most frequent oncological lesions, are everyday more effort is being made to save as much kidney as possible. 3d technologies are great for anatomic assessment of lesion relationship and to evaluate possible vessel anatomic variants and simulate procedures, key to a successful partial resection (Fig. 20). Pre and intraoperative surgical planning has been related to better clinical outcomes in kidney and prostate cancer [54,55] . It has been applied successfully for surgical planning and training on percutaneous nephrolithotomy, partial nephrectomies, renal transplantation, laparoscopic pyeloplasty, prostate brachytherapy and transurethral resection of bladder tumors [37]. Simulation devices for laparoscopic surgery and robotic surgery phantoms have also been developed [37].

3D Application in neurosurgery

Brain anatomy is complex and medical images comprise anatomical and functional information. 3D technologies has been applied to neurovascular physiological anatomy assessment, complex central nervous system tumors and neuroanatomy, spine instrumentation, deformities and biomechanics implications and for educational purposes (Fig. 21) [56].

3D biomodeling allows merging information from CT and different MRI series, so that biomodels include all this information for treatment decision making [57,58]. In this way it is possible to assess lesion relationship with bone, brain regions, neural tracts and vessels. Using diffusion or perfusion MRI series, for example, it is possible to represent different regions in a lesion to decide where to take tissue samples for a biopsy.

Many simulators have been developed for training on epilepsy surgery, brain tumor microdissection techniques, neuromuscular and skull base surgery, ventriculoscopy and ventriculostomy, craniosynostosis, skull lesions or defects and tumor and their development is expected to increase in the next few years (Thiong'o 58).

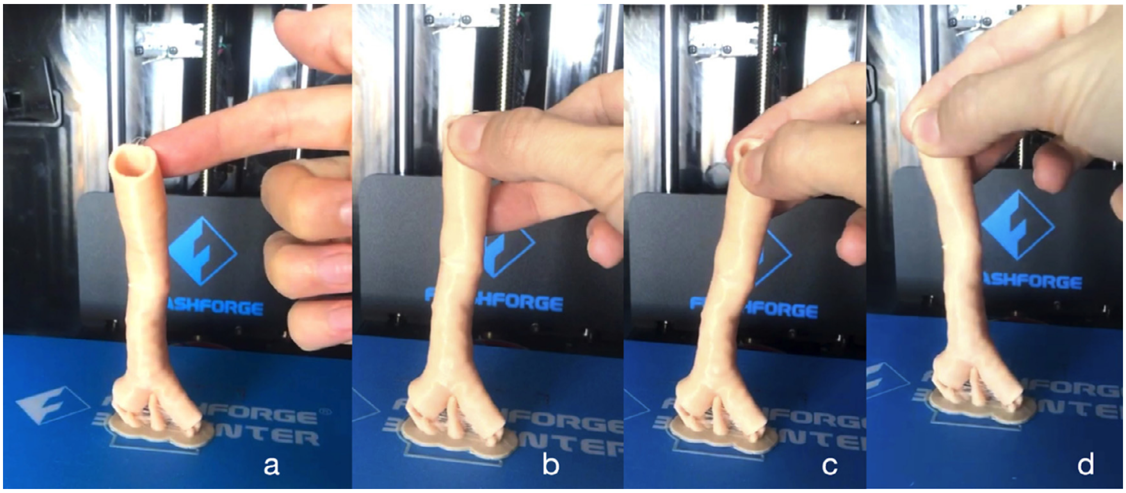

Fig. 11. *Flexible materials* 3D biomodels of trachea and main bronchi in TPU, a flexible material, for simulation of airway invasive procedures.

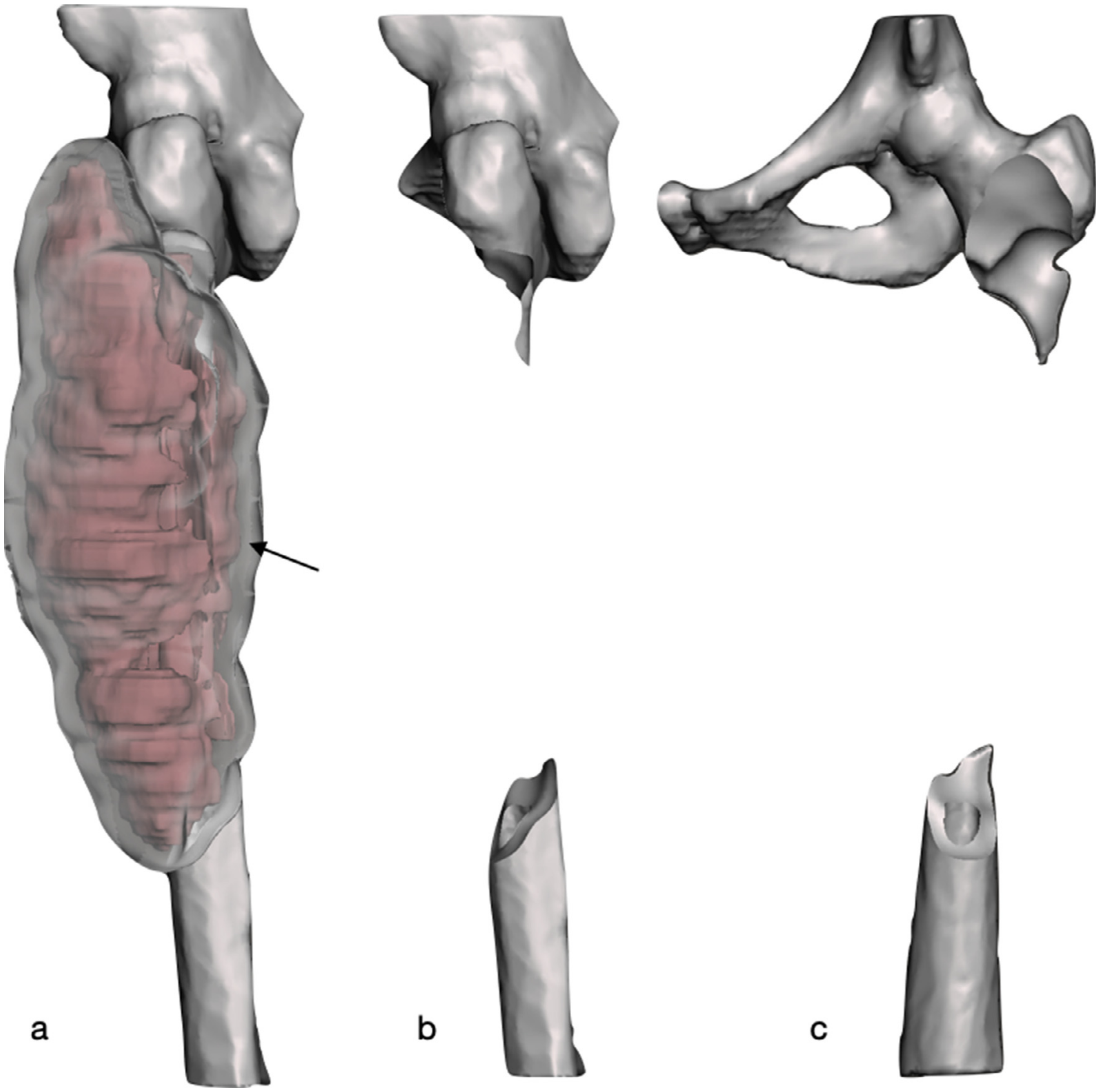

Fig. 12. *Virtual surgical planning* Virtual simulation of oncologic margin and virtual surgery of a patient with left femoral Ewing's sarcoma. (a) Virtual 3D biomodel which combines pre- and post-chemotherapy imaging data. Bone biomodels was obtained from post-chemotherapy CT. Because of Ewing's tumor aggressiveness, resection is generally planned with pre-chemotherapy lesion margins, so tumor biomodel was obtained from pre-chemotherapy CT. Arrow points to the simulation of a 10 mm safe oncologic margin. (b) and (c) Virtual simulation of surgical resection with safe margins to assess remaining bone. This simulation lead to a change in surgical strategy.

3D Application in pediatric surgery

Pediatric surgery is challenging and hands-on training is restricted. Surgical simulation training on 3D biomodels and simulators provide an opportunity to practice surgical skills before encountering similar scenarios in real-life environment [59,60]. Simulators have been developed for neurosurgery, laparoscopic pyloromyotomy, choledocal surgery and transplantation medicine among others [59–62].

3D biomodels, surgical planning and 3D printing are useful tools for complex tumor resection as well as for reconstruction of complex malformations, which are more common at this age. Since they provide better understanding of tumor, adjacent tissue and vessel relationship [63]. Virtual surgical navigation improves the surgical team communication, helps decide the best treatment strategy and anticipate surgical complications (Fig. 22).

There is a strong role for 3D printing in both surgical planning and implant creating for pediatric airway obstruction, including 4D printing of bioabsorbable materials, as previously described [43, 64].

They are particularly valuable to communicate with the patient's family, allows better understanding treatment risks and empower them to make conscious treatment decisions [1, 63, 64].

Difficulties for implementation

Image processing to create virtual and 3D printed biomodels is considered as a drawback for the widespread use of this technology in the emergency settings. Depending on case complexity, image quality and the need for different imaging modality registration, an anatomical model can take from a few minutes to many hours to be ready. Furthermore, virtual surgical planning requires a meeting between clinicians and the 3D team to design the surgical strategy, time for surgical guide design, clinicians' approval of the guide design and finally time for 3D printing, post-processing and sterilization. This usually takes a few days to some weeks, particularly when cases are outsourced. 3D printing big anatomical pieces in PLA, such as the hip or large bones, take many hours, and printing metallic customized implants as well. However, there are studies that publish that point of care 3D printing of metallic customized implants is feasible

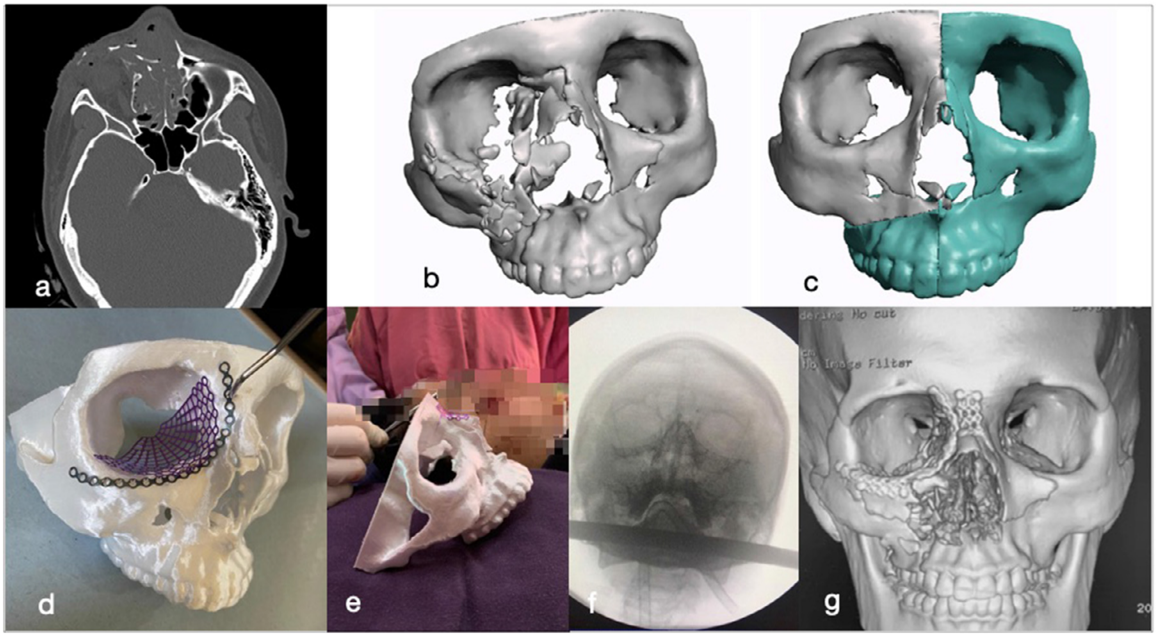

Fig. 13. *"Mirror technique"* (a) Axial CT bone view depicting a complex fracture of many facial bones. (b) Virtual 3D biomodel of facial bones with complex bone fracture. (c) Virtual surgical planning using the "mirror technique" to repair the affected side using as template the contralateral healthy bone. (d) Real-size 3D printed model of the results of the virtual planning for pre-surgical simulation and plate pre-contouring. (e) Biomodel was sterilized and used to support the surgical procedure. Intraoperatory fluoroscopic control (f) and post-surgical CT (e) showing surgical result similarity with virtual plan.

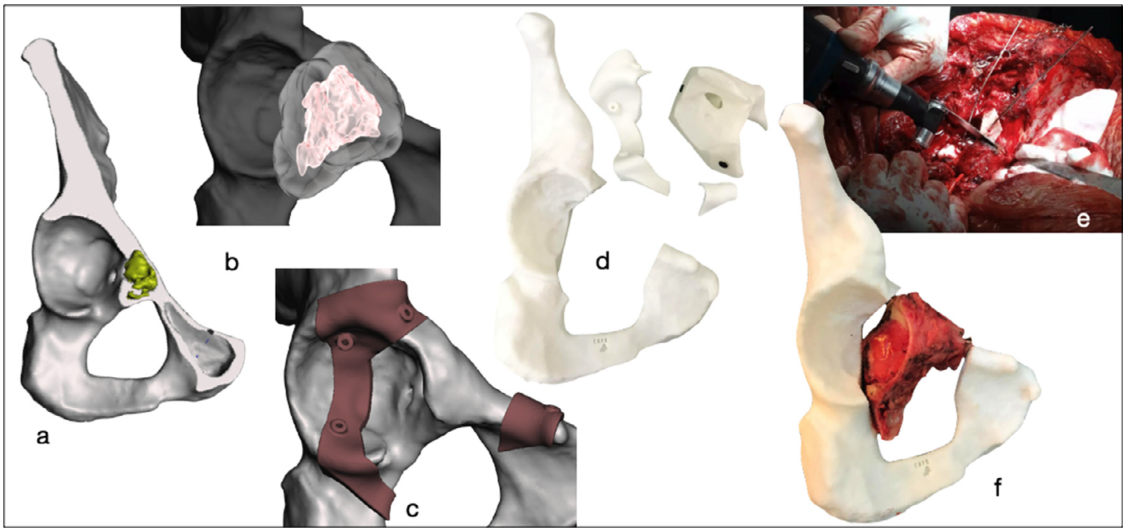

Fig. 14. *Virtual surgical planning and guide design* Acetabular lesion presented in Fig. 9. (a) Virtual biomodel including bone and tumor data. (b) 10 mm safe oncologic margin simulation. (c) Virtual surgical planning including osteotomy plane and cutting guide design to safely remove lesion with safe margins. (d) PLA real-size 3D printed bone parts and surgical guides for procedure pre-surgical simulation. (e) Surgical procedure. Acetabular osteotomy using cutting guides to exactly reproduce virtual plan. (f) Size and shape matching of resected acetabular fragment with virtual planning as an extra safety and precision check.

within a clinically-acceptable timeframe, provided adequate infrastructure is in place [65].

Another disadvantage to consider is that even though operation time is shorter, surgeons' time of dedication for pre-operative planning is longer, and this costs are often not reimbursed [24].

Despite increasing availability, virtual planning and 3D printing is not yet universally accesible, due to lack of trained human resources, lack of financial resources and time constraints when outsourcing companies are far from the point-of-care.

Finally, costs considerations area an important issue that has already been discussed [10,24,25]

Role of radiologists

Biomodeling and 3D printing is essentially image-centered [66]. Radiologists, as medical imaging specialists, should play a central role in the workflow of patients that require this technology, in order to ensure biomodel fidelity, particularly of those which will then be used for procedural practices [4,66–68]. To certify precision, it is crucial that radiolgists become familiar with the methods of transformation of DICOM data to files compatible with 3D printing [66]. Even though advanced technologies using artificial intelligence can automatize most of the segmentation process, it still requires human supervision, particularly soft tissue and oncologic lesion segmentation,

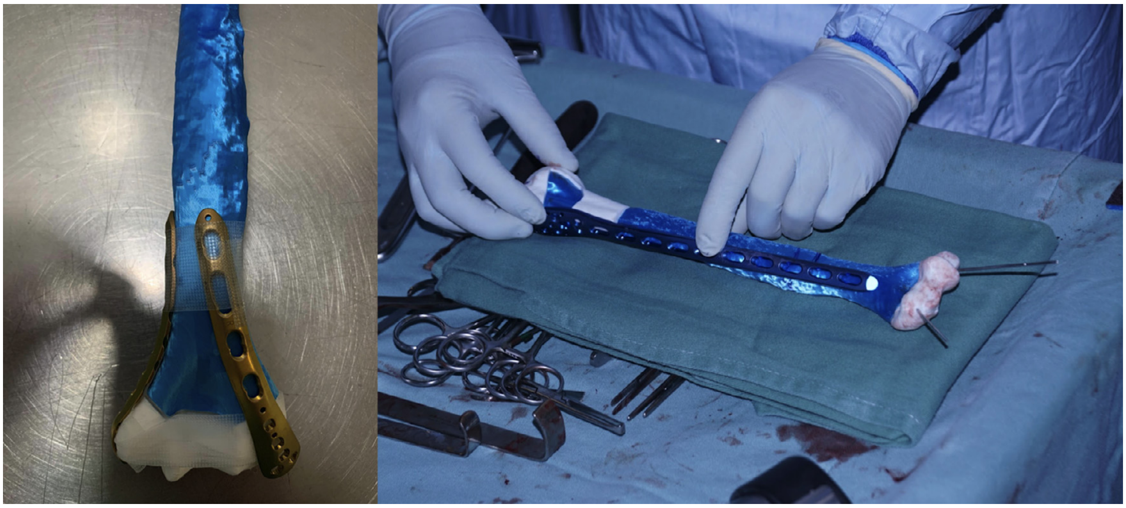

Fig. 15. *Plate pre-contouring* 3D printed humerus in PLA for size-matching of fixation material, pre-contouring and pre-surgical simulation for an Ewing's sarcoma resection.

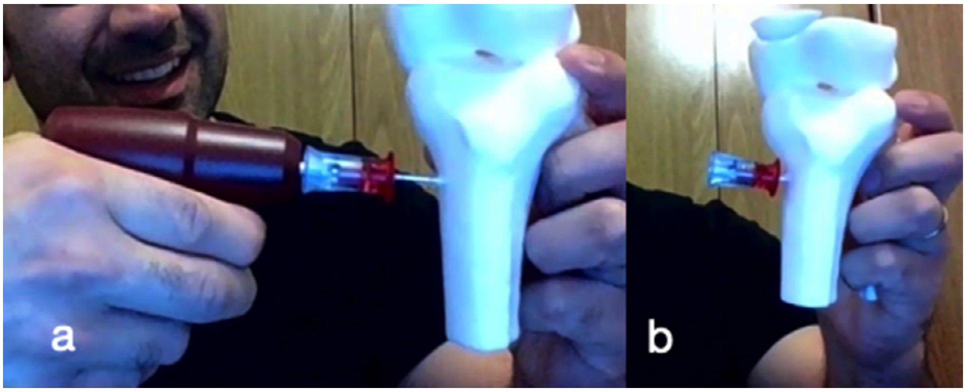

Fig. 16. *3D biomodels for training* (a) Intraosseus access training procedure in a PLA 3D printed tibial bone. Material resistance was set to be similar to *in vivo* by selecting model infill percentage. The biomodels has medular cavity which allows certification of correct access position (b) Intraosseus access final position.

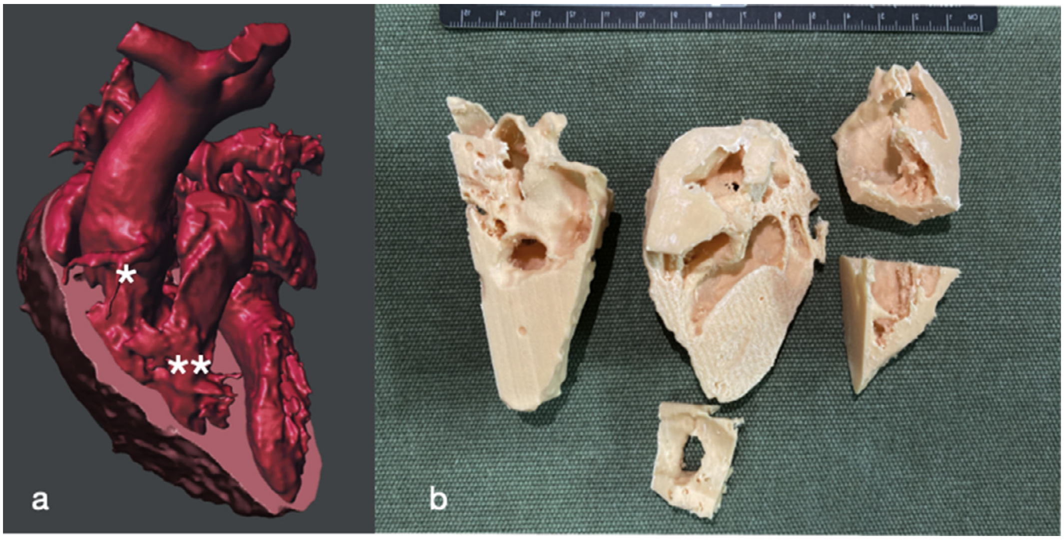

Fig. 17. *3D biomodel for cardiac surgery* Virtual (a) and TPU (flexible) real-size 3D printed (b) heart for right ventricle double outlet surgical planning. (a) The virtual model included myocardium and blood circuit 3D models. Aortic outlet (*) and pulmonary outlet (**). (b) Heart was printed in parts for better anatomy assessment and used to simulate surgery and prepare patch for blood circuit repair.

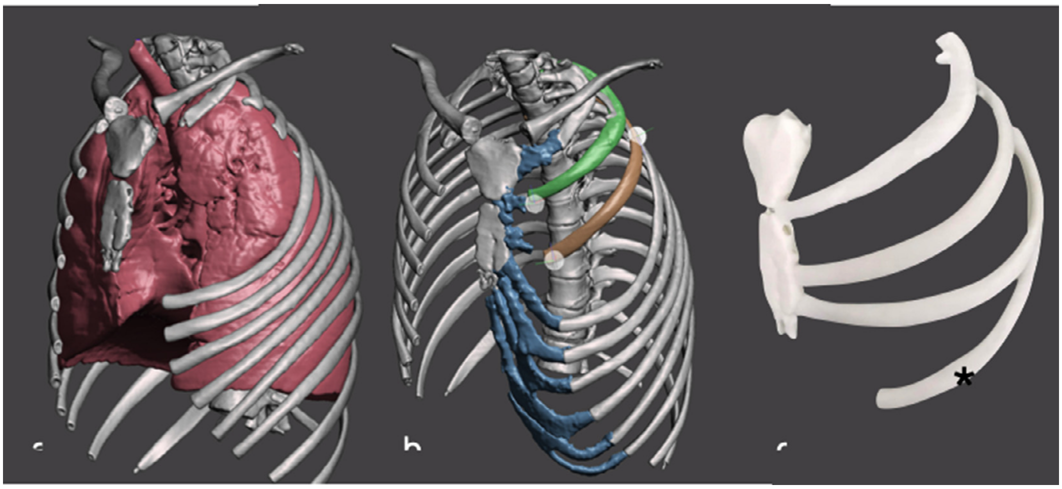

Fig. 18. *Virtual surgical planning for thoracic surgery* The "mirror technique" was used to plan the repair of a huge rib cage defect secondary to a rib sarcoma resection during infancy. (a) virtual 3D biomodel with bone and lung components. (b) virtual planning of ribs using contralateral healthy bone anatomy as template. An extra rib (*) was designed to cover the space between the 3rd and 4th rib developed by bone deformity caused by natural girl's growth with the thoracic defect. (c) The designed thoracic piece was 3D printed to help prepare the bone allograft from a cadaveric donor to be used to repair the defect during surgery.

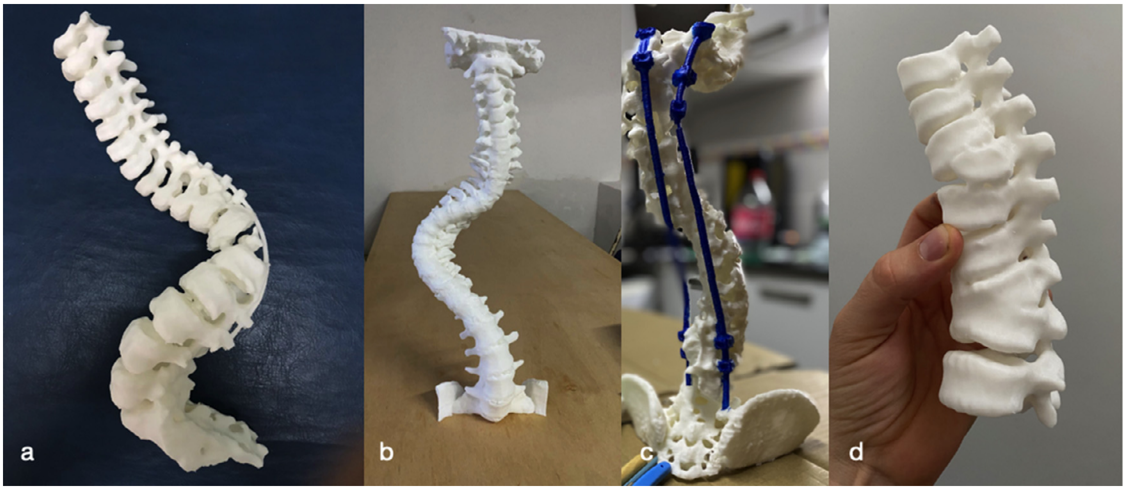

Fig. 19. *3D printed biomodels for spine surgery* (a), (b) and (c) depict different scoliosis real-sized 3D printed models in PLA for pre-surgical simulation. (d) Spine segment with hemivertebrae and vertebral fusion 3D printed for educational purposes.

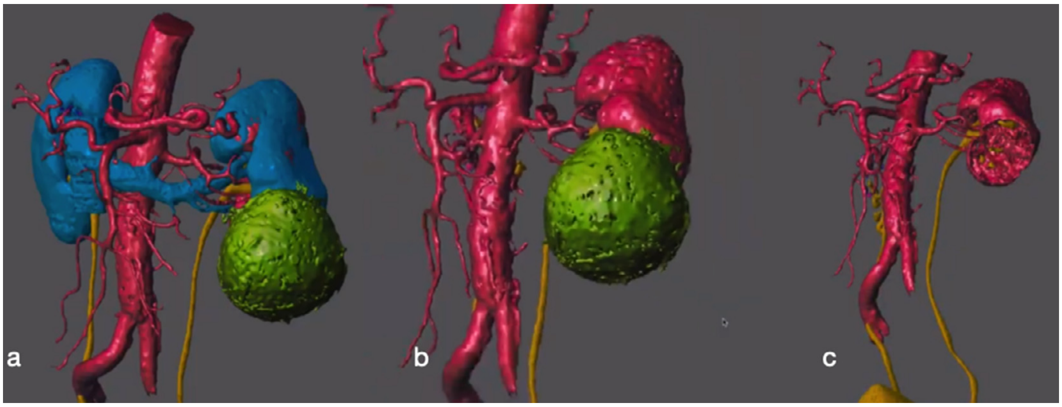

Fig. 20. *3D biomodel for renal tumor assessment* (a) Virtual 3D model with arterial (red), venous (blue), tumor (green) and urinary tract (yellow) components. (b)Tumor-arterial vessel relationship. (c) Selective view without lesion to assess urinary cavities and urether anatomy.

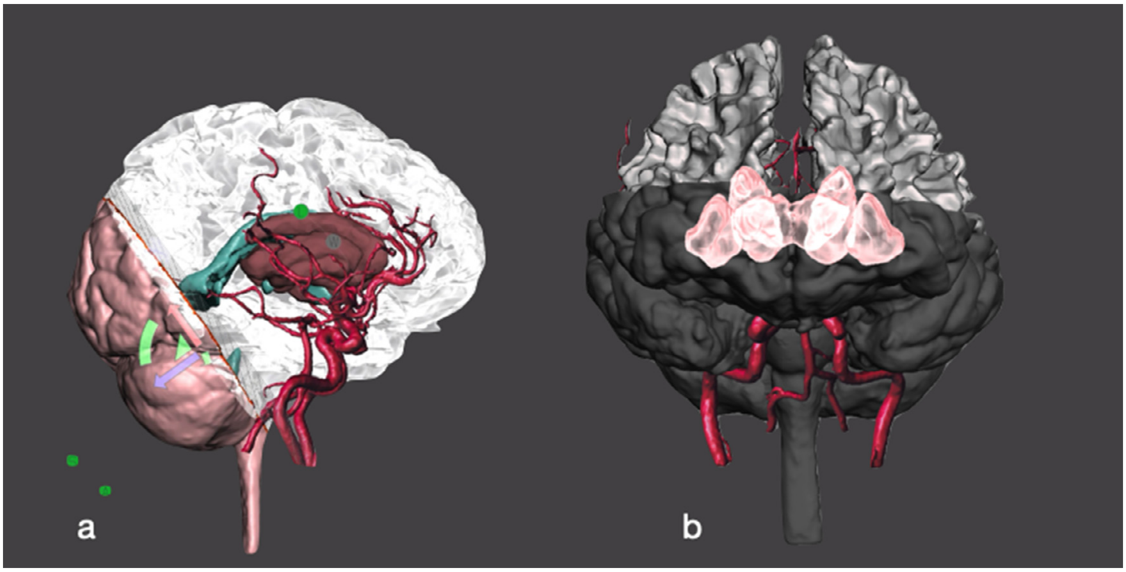

Fig. 21. *3D biomodel for neurosurgery* Virtual 3D biomodel obtained from MRI, for educational purposes, to learn anatomy, with vessel, basal ganglia, ventricular system, white and gray matter components. (a) Transparency tool. (b) Selective view of basal ganglia transparency to learn relationship with neural tissue.

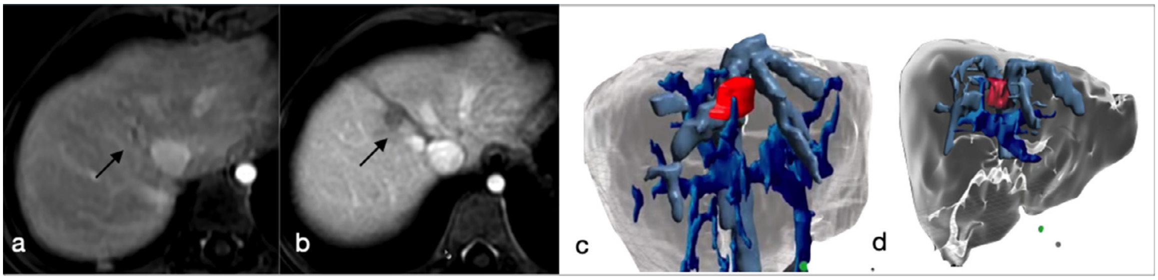

Fig. 22. *3D biomodels in pediatric surgery* Pediatric patient with a second relapse of and hepatoblastoma. MRI T2 Axial view of relapse lesion in 2020 (a, arrow) and 2021 (b, arrow). Virtual 3D biomodel with hepatic contour, tumor, portal and hepatic vein components in 2020 (c) and 2021 (d), used for surgical planning of complex lesion resection.

which generally involve manual boundary delineation. There is a great deal of medical professional responsibility in the segmentation process. As an example, the edges specified during segmentation for an oncologic lesion will determine the osteotomy planes during virtual surgical planning, which will then be used to design surgical guides to be used during the surgical procedure. In other words, whoever does the segmentation plays a pivotal role in patient oncologic treatment decision, and errors in this process would lead to disastrous consequences for the patient [4].

Another challenge is registration of images from different modalities to create combined MRI/CT biomodels. This involves perfect overlaying of DICOM MRI sequences over CT images as reviewed in Fig. 5. There are tools to achieve this in a semi-automatic manner, but radiologist supervision is a must to make necessary adjustments to ensure precision. Although radiology technologists, bioengineers or other health care providers may have sufficient training to provide accurate segmentation in most cases, radiologists can provide additional expertise in dealing with these or others issues such as imaging artifacts [66]. State-of-the-art 3D printing relies on optimization of image acquisition [66, 68]. Radiologists play a key role acquiring images of diagnostic quality but also suitable for 3D biomodeling: defining if CT or MRI are more convenient for high-quality 3D biomodels of a certain disease, deciding which MRI sequence better demonstrates a given pathology, selecting the series to be acquired volumetrically or reducing artifacts which can degrade 3D biomodel quality [4,66, 68]. In addition, radiologists' leverage to be part of the 3D team includes thorough understanding of disease and treatment strategies, making it easier to know relevant anatomical structures to be added to a virtual 3D biomodel. Moreover, virtual surgical planning implies fluid communication with the surgical team and radiologists speak a common language, facilitating planning virtual surgeries and making guide design decisions. Some 3D biomodels require cutting into parts for better visualization of specific disorders, which may then be 3D printed in these parts. Radiologist skills are also excellent for this task.

For the above expressed, there is no doubt radiologists occupy a primary role in 3D biomodeling, virtual surgical planning and 3D printing, and that we can then consider this area as an emerging subspecialty in radiology. Although an increasing number of radiologists have accepted the challenge of learning this new imaging post processing techniques, efforts must be made to focus on training the radiology community. For those in the radiology community who don't feel attracted to this new subspecialty there is still opportunity to get involved in order to guarantee quality medical images for 3D biomodeling and advocate for the importance of our specialty to participate in the workflow to assure safe procedures.

Workflow

3D teams are the definition of multidisciplinary team work. Workflow for patients that benefit from this technology includes coordination between radiology technologists and radiologists, to acquire

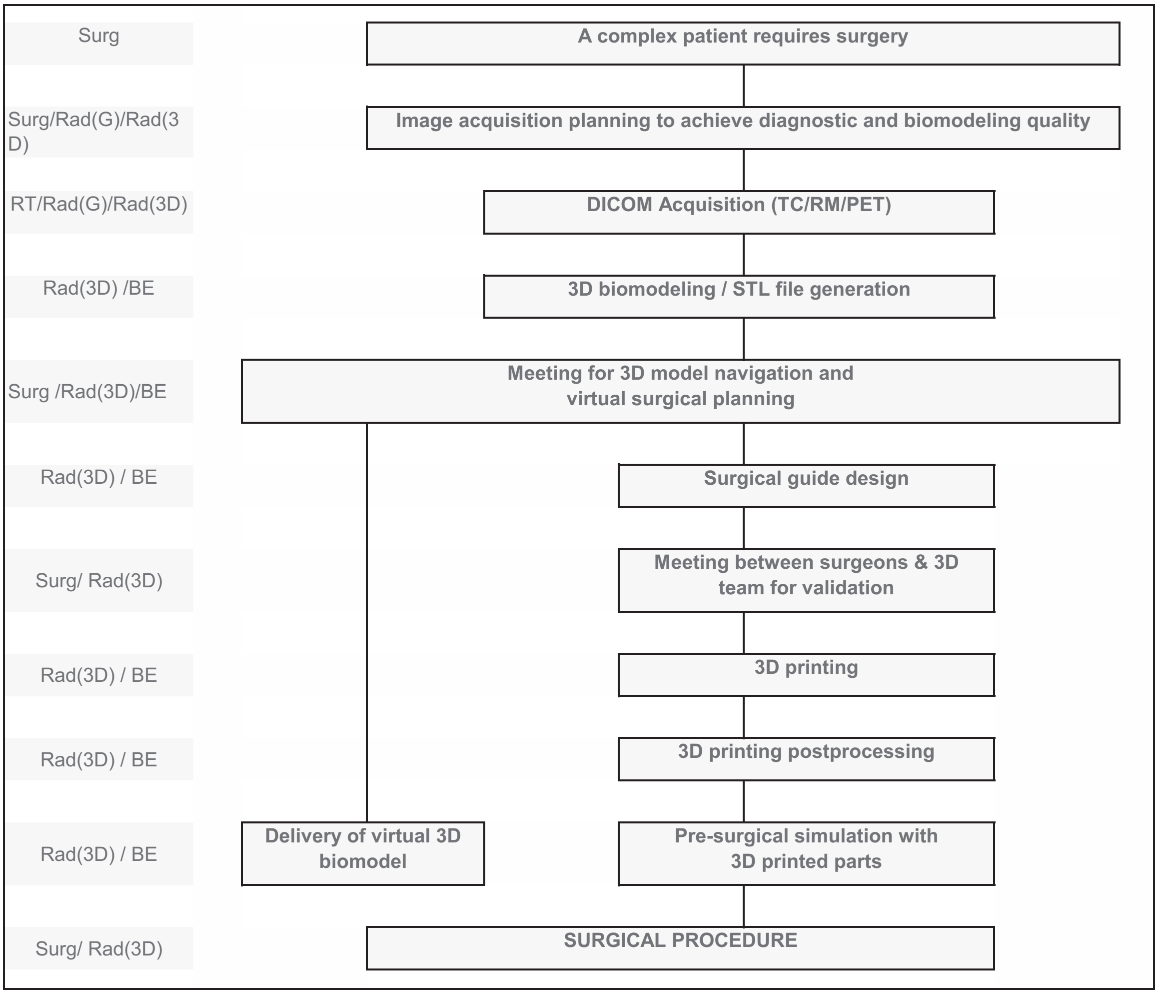

Fig. 23. *Workflow diagram* Left column indicates the working group member for each stage of the workflow for a patient that requires 3D technology support for surgery: surgeons, *Surg*, general radiologists, *Rad(G)*, 3D specialist radiologist, *Rad(3D)*, radiology technologist, *RT*, bioengineer *BE*.

high-quality images suitable for diagnostic and biomodeling purposes; between bioengineers and radiologists specialized in this area to create precise 3D biomodels; between surgeons, radiologists and bioengineers to navigate biomodels, virtually plan the surgery and discuss guide design; between radiologists and bioengineers during guide design and 3D printing process; and finally, between bioengineers, radiologists and the surgical team for pre-surgical simulation. The chart in Fig. 23 summarizes workflow for patients that require 3D technologies.

Conclusions

3D biomodels are a new kind of medical image, created using specific semi-automatic biomodeling software from the same DICOM series acquired for diagnostic purposes. There are new applications emerging every week in all surgical specialties for diagnostic, treatment and educational purposes. Although radiology technologists, bioengineers or other health care providers may have sufficient training to provide accurate biomodels in most cases, radiologists play a central role in the workflow of patients that require this technology, in order to ensure biomodel fidelity and safe practices, and as such, we can consider this area as a new subspecialty in radiology. Efforts should be made to raise awareness among the surgical and the radiology community about the key role of radiologists in this emerging subspecialty.

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The author would like to specially acknowledge radiologists and 3D specialists Juan Sattler and Jose Perdomo for their invaluable collaboration in 3D biomodelling. Many of the patients presented in this article were a joint effort. Segmentation of the presented cases were performed with either Invesalius (v3.1)(69), Slicer (v4.1) 70, 71) or Inobitec DicomViewer Pro (v2.5). 3D biomodel navigation, virtual surgical planning and guide design was performed with Autodesk Meshmixer (v 3.5). 3D prints were prepared with Cura Ultimaker (v4.1) and Chitubox Basic (v1.9)

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