# 3d printing of cardiac structures from medical images: an overview of methods and interactive tools

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Abstract

The percutaneous interventions in the treatment of structural heart diseases represent nowadays a viable option for patients at high risk for surgery. However, unlike during the traditional open heart surgery, the heart structures to be corrected are not directly visualized by the physician during the interventions. The interpretation of the available medical images is often a demanding task and needs specific skills i.e. clinical experience and complex radiological and echocardiographic analysis. The new trend for cardiovascular diagnosis, surgical planning and intervention is, today, mutually connected with most recent developments in the field of 3D acquisition, interactive modelling and rapid prototyping techniques. This is particularly true when dealing with complex heart diseases since 3D-based techniques can really help in providing an accurate planning of the intervention and to support surgical intervention. To help the research community in confronting with this new trend in medical science, the present work provides an overview on most recent approaches and methodologies for creating physical prototypes of patient-specific cardiac structures, with particular reference to most critical phases such as: 3D image acquisition, interactive image segmentation and restoration, interactive 3D model reconstruction, physical prototyping through additive manufacturing. To this purpose, first, recent techniques for image enhancement to highlight anatomical structures of interest are presented together with the current state of the art of interactive image segmentation. Finally, most suitable techniques for prototyping the retrieved 3D model are investigated so as to derive a number of criteria for manufacturing prototypes useful for planning the medical intervention.


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ORIGINAL PAPER

# 3D printing of cardiac structures from medical images: an overview of methods and interactive tools

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**Abstract** The percutaneous interventions in the treatment of structural heart diseases represent nowadays a viable option for patients at high risk for surgery. However, unlike during the traditional open heart surgery, the heart structures to be corrected are not directly visualized by the physician during the interventions. The interpretation of the available medical images is often a demanding task and needs specific skills i.e. clinical experience and complex radiological and echocardiographic analysis. The new trend for cardiovascular diagnosis, surgical planning and intervention is, today, mutually connected with most recent developments in the field of 3D acquisition, interactive modelling and rapid prototyping techniques. This is particularly true when dealing with complex heart diseases since 3D-based techniques can really help in providing an accurate planning of the intervention and to support surgical intervention. To help the research community in confronting with this new trend in medical science, the present work provides an overview on most recent approaches and methodologies for creating physical prototypes of patient-specific cardiac structures, with particular reference to most critical phases such as: 3D image acquisition, interactive image segmentation and restoration, interactive 3D model reconstruction, physical prototyping through additive manufacturing. To this purpose, first, recent techniques for image enhancement to highlight anatomical structures of interest are presented together with the current state of the art of interactive image segmentation. Finally, most suitable techniques for prototyping the retrieved 3D model are investigated so as to derive a number of criteria for manufacturing prototypes useful for planning the medical intervention.

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## 1 Introduction

Thanks to the outstanding advances in both paediatric cardiology and cardiac surgery, the number of children affected by congenital heart disease (CHD) surviving into adulthood continues to increase [1]. Therefore, adults with CHD represents an ever-growing population, of around 3 million patients in Europe [2], with continues to increase by 5% per year. It is therefore not surprising that the care, and management, of adult patients with congenital or acquired structural heart disease represents one of the most relevant areas of research in cardiology, documenting a grow of studies related to this vital area [3–5].

Given the widely-ranged complexity of possible structural heart defects, imaging is paramount in their treatments. Although two-dimensional (2D) imaging modalities such as echocardiography, computed tomography (CT), and magnetic resonance imaging (MRI) are undeniably valuable in the evaluation of adult patients with structural heart disease, these methods are still constrained by their overall lack of realism and inability to be "physically manipulated"; thereby, such techniques remain limited in their ability to effectively represent the complex three-dimensional (3D) shape of the heart and its peripheral structures. Quite the opposite, 3D medical data representation, obtained from medical imagery, has the potential of providing information concerning heart structure, giving at the same time the opportunity

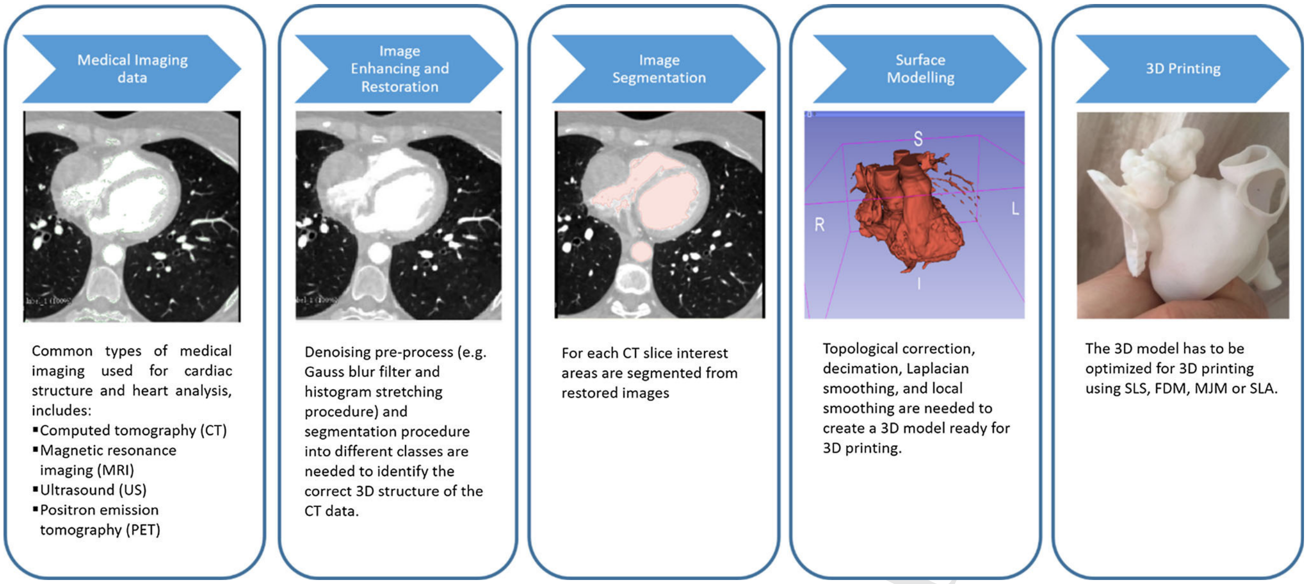


**Fig. 1** Patient-specific 3D modelling and printing workflow

of further investigations when combined with additive manufacturing methods and technology. Recently, a number of most advanced hospitals [6–8] introduced in their praxis the use of physical 3D models of the patient cardiac structure to be used for surgical planning or for training.

These few cutting-edge experiences suggested that the progress of 3D printing technology sector can provide a number of advanced tools helping the medical staff to confront with care and management congenital or acquired structural heart diseases. In fact, the possibility of creating a patient-specific tangible 3D fabricated model provides medical staff with information that goes beyond a simple 3D-shaded visualization on a flat screen. The "zero lead time" between design and final production of accurate models together with the possibility of creating specific models resembling the actual structure of the patient heart accelerate the recent medical trend towards "personalized" or "patient-specific" treatment.

According to recent literature [9,10], the most effective way for creating 3D models starting from 2D medical imaging is based on a virtuous process cycle that usually starts from 2D and 3D medical image acquisition and ends with 3D printing of a model of the patient heart (see Fig. 1).

In detail, such a process starts from medical imagery with particular reference to (but not exclusively) CT, multi-slice CT (MCT) and MRI. All these methods basically [11–14] provide 3D information in the form of cross-sectional "slices" of the entire body or parts of interest. Such slices consist of digital pictures stacked through the measurement volume, where each pixel represents the spatial position of the imaged element and its colour (usually in grey values) the reaction of the tissue to radiation or magnetic field (in case of CT and MRI respectively). Acquired images are then processed, usually by using semi-automatic and interactive methods, in order to segment regions of interest, e.g. heart chambers, valves, aorta and coronary vessels. These segmented areas are, then, converted into 3D models, using tools like volume rendering or surface reconstruction procedures. This process is very useful in clinical practice, since it allows for interactive and easy visualization of different tissues and anatomical structures. Surface reconstruction techniques provide 3D polygonal mesh model of the external surface of the part. The obtained 3D surface models are useful for performing dimensional verification (volume computation, thickness and centreline of blood vessels calculation, etc.), structural analysis (e.g. by using finite elements FE) and computational fluid dynamics (CFD) studies. Moreover, the availability of topologically correct and optimized surface models allows the manufacturing of a prototype of cardiac structure, using for instance additive manufacturing techniques.

Due to the increasing number of methods to comply with the above mentioned process, and since such a virtuous process has been only recently introduced in clinical practice, the main aim of the present work is to provide an overview of methodologies dealing with patient-specific 3D modelling of cardiac structures. First, main imaging systems medical imagery for acquiring 2D and 3D data inferred to heart structure are introduced (Sect. 2). Then, the most adopted algorithms for image enhancement and restoration are explored (Sect. 3) and an overview of interactive segmentation and classification algorithms is described (Sect. 4). Section 5 is devoted to briefly overview most promising techniques for 3D heart model reconstruction process. Finally, in



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Sect. 6, some considerations regarding 3D printing of heart structure are draft.

## 2 Medical imaging

Since the discovery of X-rays by Wilhelm Conrad Rontgen in 1895, medical images have become a major component of diagnostics, treatment planning and procedures, and follow-up studies. Moreover, medical images are increasingly used for education, documentation, and research since they provide description of morphology as well as physical and biological functions in 1D, 2D, 3D, and even 4D image data (e.g., cardiac MRI, where up to eight volumes are acquired during a single heart cycle) [15]. Today, a large variety of imaging modalities have been established; these are mainly based on transmission, reflection or refraction of light, radiation, temperature, sound, or spin. Most imaging techniques are non-invasive, allowing to seek for internal structures of the patient's body hidden by skin and bones. The output of the imaging acquisition process and input of the rapid prototyping following appropriate processing is a DICOM image (Digital Imaging and Communications in Medicine), which is the, traditional, virtual outcome of all medical professions utilizing images [16].

Over the years, a number of different medical imaging modalities has been developed, using different technologies and creating several kinds of images. Common types of medical imaging include: (i) X-ray (radiography, CT, etc.), (ii) MRI, (iii) ultrasound, (iv) nuclear medicine (e.g., positron emission tomography—PET).

### 2.1 Magnetic resonance imaging (MRI)

MRI is an imaging technique based on detecting different tissue characteristics by varying the number and sequence of pulsed radio frequency fields, taking advantage of the magnetic relaxation properties of different tissues [17]. MR imaging has the crucial advantage of not emitting X-ray radiations. Instead, the MR scanner provides a strong magnetic field, which causes protons to align parallel or anti-parallel to it. MR measures the density of a specific nucleus, normally hydrogen, which is magnetic and largely present in the human body, including heart [18], except for bone structures. The speed at which protons lose their magnetic energy varies in different tissues allowing detailed representation of the region of interest. This measurement system is volumetric, producing isometric 3D images (i.e. the same resolution in all directions).

### 2.2 Computerized tomography (CT)

As widely known, CT combines many X-ray images, taken from different angles, to produce cross-sectional (i.e. tomographic) images of patient areas. Especially in the recent advances, CT can provide detailed anatomical information of chambers, vessels, coronary arteries, and coronary calcium scoring. In particular, two imaging techniques are typically carried out in cardiac tomography: (1) coronary calcium scoring with non-contrast CT and (2) non-invasive imaging of coronary arteries with contrast-enhanced CT. Usually, *non-contrast CT* imaging exploits the natural density of tissues. As a result, various densities using different attenuation values such as air, calcium, fat, and soft tissues can be easily distinguished. Non-contrast CT imaging is a low-radiation exposure method within a single breath hold, determining the presence of coronary artery calcium.

In comparison, *contrast-enhanced CT* (see Fig. 2) is used for imaging of coronary arteries with contrast material such as a bolus or continuous infusion of a high concentration of iodinated contrast material. Furthermore, coronary CT angiography has been shown to be highly effective in detecting coronary stenosis. Moreover, coronary CT angiography can visualize not only the vessel lumen but also the vessel wall, allowing non-invasive assessment of the presence and the size of the non-calcified coronary plaque.

### 2.3 Ultrasound

In contrast to CT and MRI, ultrasound is a medical imaging modality that is based on reflection of sound waves. Depending on the transducer, 1D to 4D data is obtained. In the 1D case (signal), a longitudinal sound wave is traveling through the tissue of the human body. At transitions between different matter (e.g., muscle and fat), the sound wave is partly reflected and transmitted (refracted if the surface is not hit perpendicular).

Therefore, the echo runtime indicates the distance between transducer and tissue border while the echo strength is related to material properties. For cardiac usage, ultrasound is applied by means of an echocardiogram able to provide information on the four chambers of the heart, the heart valves and the walls of the heart, the blood vessels entering and leaving the heart and the pericardium. Echocardiography was, for a long time, limited to a 2-D examination. As 3D ultrasound is being more widely studied, new applications for imaging, visualization and quantification of the heart are emerging. As 3D ultrasound images (see for instance Fig. 3) are typically acquired in smaller sectors, to maintain adequate spatial and temporal resolution, registration can be used to fuse multiple 3D sectors together; this extends the field of view, allowing the quantification of larger structures while preserving resolution [19].

### 2.4 PET

Positron emission tomography (PET) is a non-invasive medical imaging modality that produces functional rather than





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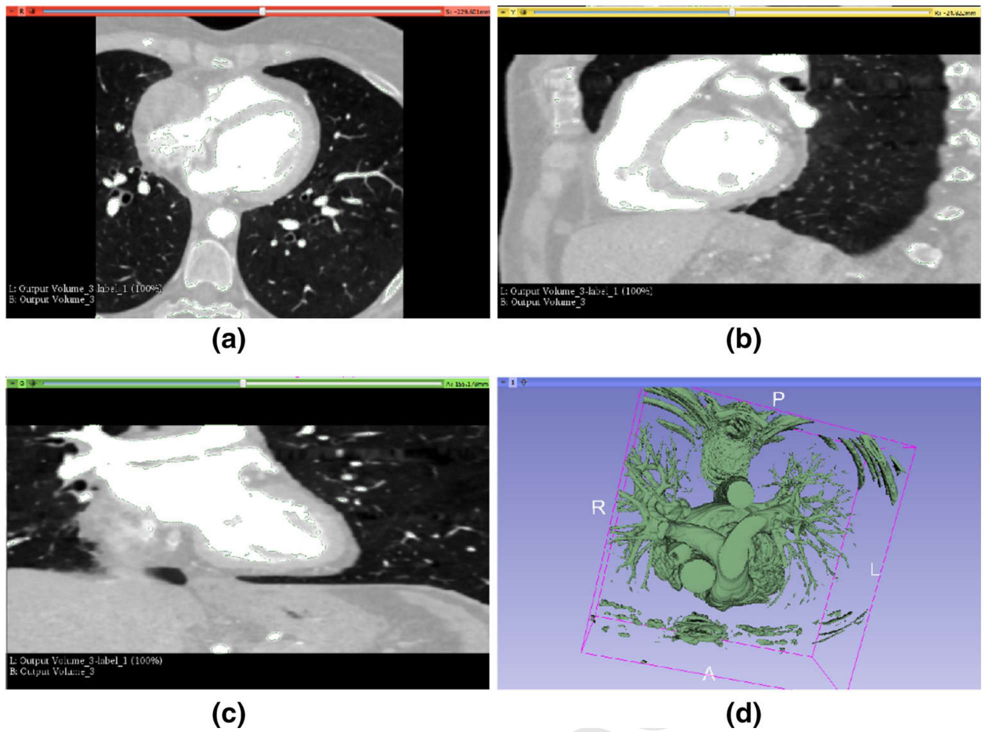


**Fig. 2** CT scan with contrast in diastolic phase: **a** axial view; **b** sagittal view; **c** coronal view; **d** rough 3D reconstruction from originally acquired images (i.e. without post processing phases), demonstrating the necessity of enhancing and restoring the input image prior to proceed with 3D model reconstruction



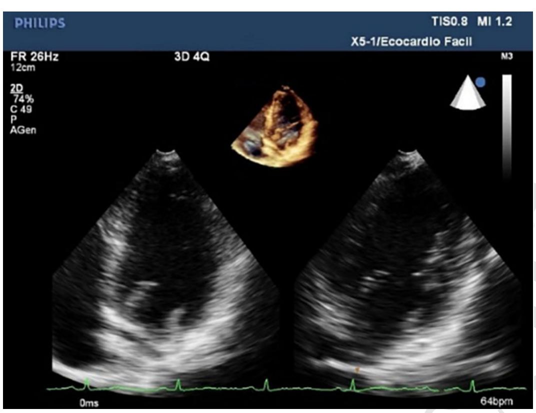


**Fig. 3** Ultrasound image of a patient heart

anatomical images, thereby providing greater insight to the patient's condition. Functional imaging means that the body's metabolism is being shown, as opposed to its structure. In a cardiac PET scan, the patient is administered with a drug that creates an effect in the body that is similar to exercise. Images of the myocardial blood flow are taken both before and after the induced stress and the images are compared to examine blood flow through the heart to determine if narrowing of the coronary arteries is restricting maximum blood flow [20]. PET can also identify dead tissue and injured tissue that's still living and functioning.

### 2.5 Remarks

CT, PET, MRI provide, as said before, 3D information in the form of thin cross-sectional "slices" of the entire body or parts of interest, and are, therefore, called tomography imagery. The slices are provided in the form of digital pictures stacked through the measurement volume, where each pixel represents the spatial position of the imaged element and its colour (grey or RGB values) the reaction of the tissue to radiation (X-rays or gamma-rays) or magnetic field, in case of CT, PET and MRI respectively. Each of the above-mentioned imaging methods has its own advantages and disadvantages, both for potential patient's health hazard (some of them require exposure to radiation) and information gathered and displayed. For example, CT and MRI are sensitive to different tissues properties, so that soft tissues are poorly visible in CT images, while they are distinctly evident in MRI.

## 3 Image restoration and enhancement

Digital medical imagery can be prone to degradation, due to several factors like patient motion or interferences, poor contrast, noise and blur. The artefacts are often intrinsically tied to the image acquisition method (e.g., X-rays show low contrast for soft tissues, ultrasound produces noisy images,



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and metallic implants cause imaging artefacts in MRI [21]). A huge number of methods for enhancing the quality and for restoring acquired data have been proposed in literature. To enhance the visual quality of medical images, the two main procedures are image restoration and image enhancement.

Image restoration algorithms act to denoise the images also by reducing the blur effect due to the data acquisition pipeline [22]. Denoising methods are based on the estimation and modelling of the blur and noise affecting the image. The main factors that influence the models include capturing sensors system, transmission media, image digitization, etc.

Enhancement belongs to the branch of digital image processing techniques that manipulate a digital image [23–25] to enhance the contrast, in order to extract, or accentuate, certain image features to improve the understanding of information content and obtain an image ready for automated image processing (e.g. for highlighting structures such as tissues and organs).

As mentioned above, restoration and enhancement methods for medical images depends on the imaging system. Therefore, an overview of most relevant methods is provided below.

### 3.1 Enhancing and restoration of MRI images

The main issue for cardiac images acquired using MRI is related to intensity non-uniformity, i.e. a smooth intensity variation across the image, resulting in biased intensities for the same tissue according to its location. Barely noticeable to a human observer, this distortion influences the subsequent steps of segmentation and classification. In fact, most of the automated, or interactive, quantitative methods for segmentation rely on the assumption that a given tissue has a similar voxel intensities throughout the data, so these methods are highly sensitive to variations on image intensities [26–28].

Numerous methods were developed to solve the intensity non uniformity problem; roughly these methods can be classified into three main groups:

1) Filtering methods: assumes that the non-uniformity is a low-frequency artefact that can be separated from the high-frequency signal of the imaged object by a low-pass filtering. Two main approaches can be followed to filter the original image: homomorphic filtering [29] and homomorphic unsharp masking (HUM) [30]. These methods are affected by other image features, such as edge effects, most present in high contrast images. Accordingly, some methods have been proposed to minimize these effects [26].
2) Surface fitting models. Since intensity non-uniformity is slowly varying, it is reasonable to approximate it by a parametric smooth function. As a consequence, the image correction can be addressed by dividing (voxel-by-voxel) the original image by the computed surfaces. The different algorithms using surface fitting models vary in the way the fitting is performed; moreover, these methods are linked to image segmentation, which leads to frameworks that simultaneously correct the non-uniformity and perform the segmentation [31].
3) Statistical methods. The statistical methods assume that the intensity non-uniformity follows a statistical distribution. In fact, Edelstein et al. [32] showed that pure noise in magnitude images is governed by the Rayleigh distribution. As a consequence, it is possible to apply well-known look-up table correction schemes like the ones proposed in [33,34]. These methods are among the most used when dealing with cardiac MRI images.

### 3.2 Enhancing and restoration CT images

The low contrast of CT images due to the large dynamic range acquisition (usually 16 bit) often does not allows to properly discriminate acquired regions of interest, especially when dealing with cardiac structures. The most common method for enhancing the quality of the image, and at the same time to better discriminate possible presence of pathologies, is to perform a histogram equalization (HE) followed by smoothing filters as demonstrated, for instance, in Fig. 4 [35]. The main feature in HE is to find the mapping function generated from the global histogram of an image, to obtain a uniform distribution in the corresponding output image. Unfortunately, traditional HE technique may introduce undesired effects such as level saturation or over-enhancement. To solve this issue, a range of methods are proposed in literature. Most relevant methods are adaptive HE method [36] and Bi-histogram equalization [37]. Fuzzy Logic and other IA-based methods have been also explored to remove image artefacts [38].

### 3.3 Enhancing and restoration of ultrasound images

Ultrasound images have, in general, low signal to noise ratio (SNR) mainly due to pulsed signals that have short duration in time and therefore a broad spectrum in frequency domain [39]. Moreover, the coherent nature of the signals gives rise to speckle noise; finally, sound waves are highly distorted when traveling through the tissues. Consequently, the acquired images are speckled and present multiple defects such as, for instance, reflections represented by parallel bright lines or by the so called "comet tail". Most errors are strongly avoidable by pre-processing techniques in ultrasound imaging. However, the acquired image is still to be enhanced. To this purpose a large number of methods have been proposed in literature, roughly classified in filtering methods and deconvolution methods. Since noise in ultrasound has been modelled as the combination of an additive error (e.g. elec-



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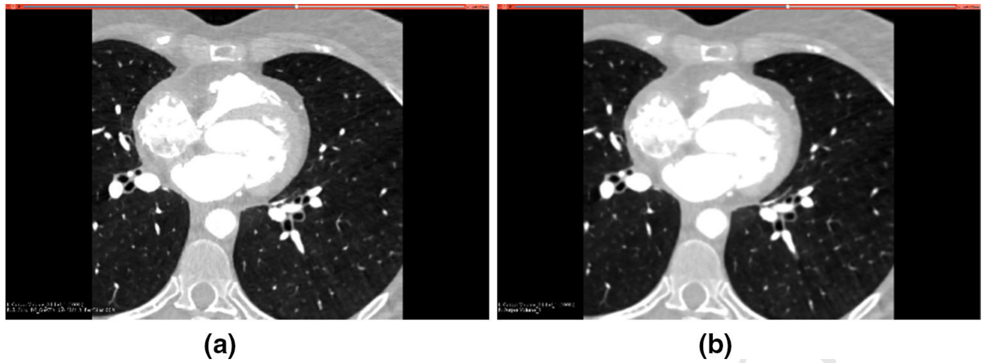


**Fig. 4** **a** Original image; **b** restored image obtained by applying a histogram equalization followed by a Gaussian filter with a sigma value (SD) equal to 0.6 mm



tronic or thermal noise) with a multiplicative error (speckle), filtering algorithms are required to be adaptable to the noise properties across the image. Consequently, ultrasound filtering techniques include adaptive filters based on local statistics [40], anisotropic diffusion [41] and wavelets [42].

Differently from filtering approaches, deconvolution is a technique used to improve resolution in ultrasound images by counteracting the effect of the Point spread function (PSF) of the imaging device i.e. the response of the system to an ideal point target caused by diffraction spreading of the ultrasound signals [43]. If the PSF is known, its effects on the image can be eliminated by dividing the spectrum of the image by the spectrum of the PSF. In case the PSF is not known, it can be estimated based on the image itself [44] (this is called "blind deconvolution").

### 3.4 Enhancing and restoration of PET images

PET image artefacts are primarily due to metallic implants, use of contrast media and respiratory motion. In particular, metallic implants (e.g. dental implants or metallic clips) are visualized by CT images as areas of high density [45]. Analogously, the presence of a contrast media can introduce errors in PET images similar to the ones produced by metallic implants. Both these errors, however, can be addressed directly by the medical staff by contouring the contrast regions and by excluding them from the image analysis [46].

Respiratory motion, instead, can induce an erroneous attenuation correction: because of respiratory motion the density of a particular organ could be attributed to an area whose density is different. This issue is far to be solved today since the best way to correct for respiratory motion would be to acquire gated images to discriminate different intervals of a breath cycle. Therefore, for examining PET images it is still crucial the help from medical staff and only a few approaches for interactive or automatic image enhancement are nowadays available [47].

## 4 Segmentation and classification

Segmentation is the process of dividing an image into a set of semantically meaningful, homogeneous, and non-overlapping regions with similar properties such as grey level, colour, texture, brightness, and contrast [48]. In medical imagery, the segmentation consists in identifying and subdividing different anatomical structures or regions of interest (ROI) in the images resulting in a partition of the image pixels in non-overlapping regions, belonging to the same tissue class.

Automatic segmentation of medical images is a valuable tool to perform a tedious task with the aim of making it faster and, ideally, more robust than manual procedures. However, it is a difficult task as medical images are complex in nature and often affect by intrinsic issues such as mixing up of tissue types, biased intensity, presence of artefacts, and closeness, in grey values for different tissues. As demonstrated in [49] a number of different approaches have been developed for automatic image segmentation that is still a current and active area of research.

Unfortunately, anatomical variability and intrinsic image issues limit the reliability of fully automatic approaches. Moreover, there is a substantial mistrust both from patients and doctors towards fully automatic algorithms. Accordingly, there has been a recent drive towards interactive segmentation [50]. Interactive approaches use a data-driven automatic algorithm to process a majority of the volume. As the automatic segmentation runs and displays the current state, a human user can influence the algorithm's behaviour to more closely align with an expected result [51].

Interactive medical image segmentation employs software tools such as, for instance, Seg3D [52] and 3D-Slicer [53] for applying algorithms and, at the same time, visualizing the results (see Fig. 5). Another class of interactive methods makes use of active contour models, contour interpolation algorithms or their combination [54]. Graph Cuts [55] and CO3 approaches [56] are considered, further-



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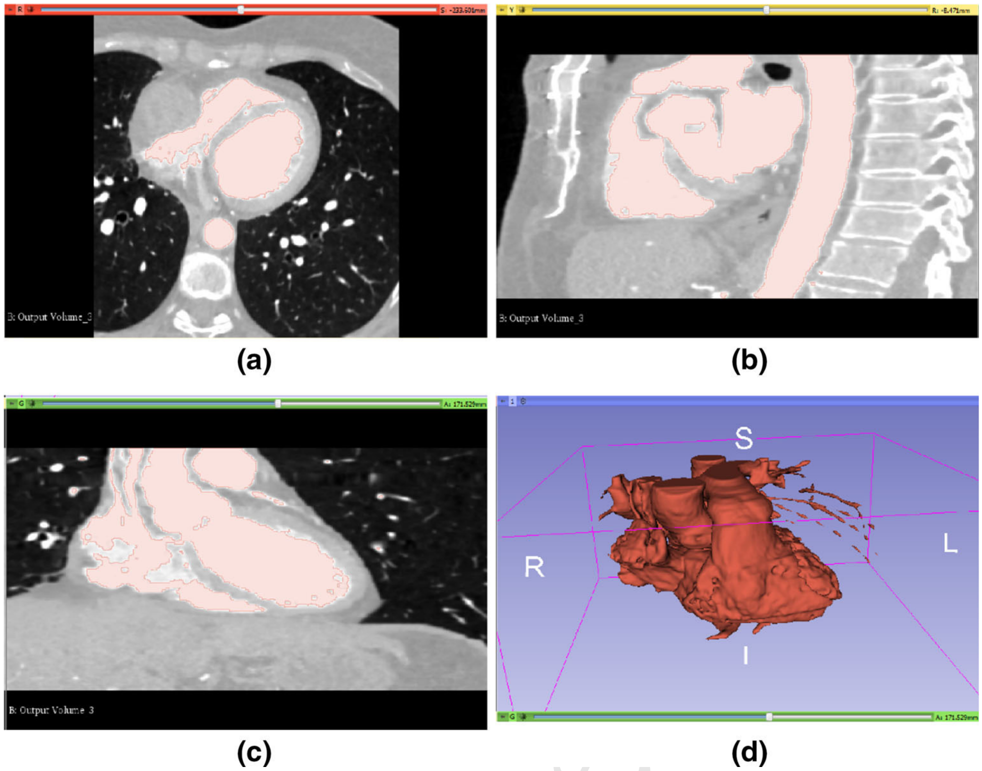


**Fig. 5** Example of threshold-based interactive segmentation of a single slice for the aorta and left ventricle: **a** axial view; **b** sagittal view; **c** coronal view; **d** 3D reconstruction from restored images



more, golden standard techniques for performing interactive segmentation.

Referring specifically to cardiac imaging, several segmentation techniques have been further proposed [57]. Most of the more recent studies focused on the segmentation of the diastolic and systolic left ventricle, since the related volume functional parameters are important predictors of heart diseases [58].

Schneider et al. [59] proposed a method to segment the Mitral annulus using graph-cuts. Zheng et al. [60] presented a segmentation method based on the marginal space learning by searching for the optimal smooth surface. Jolly [61] proposed a method for extracting the myocardium in 4-D cardiac MR and CT images using the graph-cuts as well as EM-based segmentation. Model-based techniques were also adopted for cardiac MRI or CT image segmentation using active shape models with PCA [62], atlas-based segmentation [63,64], methods for region growing [65,66], thresholding [67,68] and machine learning approach using decision forests [69] were also used.

## 5 3D heart model reconstruction for rapid prototyping

As shown in [70], the generation of a 3D cardiac geometry represented by a 3D surface mesh can be considered the very first step of the construction process of a 3D cardiac model. It has to be considered that the reconstructed geometry includes one or several cardiac chambers (LV, bi-ventricular, atrial or whole-heart models) and also other details such as the great cardiac vessels including "outflow and/or inflow tracts [71–73], the fibrous annulus of atrioventricular valves [74,75], part of the coronary tree, or some endocardial details such as papillary muscles and trabeculae carneae for ventricles or crista terminalis, pectinate muscles and fossa ovalis for atria [76–78]". Moreover, it is important to highlight that the anatomical accuracy required by a 3D cardiac model depend on its final application. For instance, in [79] it was concluded that structurally simplified models (without endocardial details or vessels) are well suited for a large range of 3D cardiac modelling applications aimed at EP simulation. Consequently, depending on the particular kind of application of the 3D model, the main aim of 3D reconstruction is to provide an accurate mesh after 3D image segmentation has been carried out according to one of the methods described in Sect. 4.

A surface model could be generated by using, for instance, a marching cube method [80] or other 3D contour extraction algorithms [81]. The resultant surface can be used as the starting point for either generation of higher order representation, such as non-uniform rational B-splines NURBS-based surfaces, or for meshing improvement using, for example, mesh



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growing methods [82,83], Delaunay meshing techniques [84,85], descriptive geometry [86] or other voxel-based methods [87,88].

However, such an automatically retrieved 3D model is not suitable, as it stand, for 3D printing; this is due to a number of reasons such as, for instance, the presence of many separate mesh units and/or incomplete topological structure. Therefore, topological correction, decimation, Laplacian smoothing, and local smoothing [89,90] are usually needed to create a 3D model ready for 3D printing. In general, the accuracy of the 3D printing object depends on the combination of the accuracy of the medical image, which should be as thin as possible, the appropriate imaging process for 3D modelling, and the 3D printing accuracy of the system.

One major challenge faced in creating physical models lies in disconnection between the digital 3D surface models and the original 2D image. Currently available industry specific image-processing software applications remains limited in its ability to generate digital 3D models that are directly applicable to rapid prototyping. As a result, true integration of the raw 2D image data into the generated digital 3D surface models is lost. The post 3D processing (i.e., correction of errant points and elimination of various artefacts within the digital 3D surface model) therefore relies heavily on the expert clinical and anatomic knowledge of the graphic editor, especially because a wide array of structural heart anomalies that significantly deviate from conventional cardiovascular anatomy may be present. Once the surface model of the cardiac structure is interactively built, it is possible to manually add to the 3D model some important features such as, for instance, myocardial structure, cardiac conduction system and other patient-specific features (e.g. pathologies).

It is worth noting that the 3D reconstruction needed for the subsequent 3D printing process requires a continuous interaction between the users (engineers and medical staff) and the CAD software package used to perform the reconstruction. Without this interaction it is quite unfeasible to extract significant information from 3D images to create a complex 3D model of the anatomical part to be investigated. On a “higher” level, the proposed framework of Fig. 1 involves methods to virtually explore different solution spaces. In fact, once the images are acquired using one of the methods proposed in Sect. 2, different data can be reconstructed on the basis of which anatomy has to be modeled for medical purposes. Accordingly, users are required to virtually explore a number of possible CAD solutions by interacting with the acquired and pre-processed 3D data.

Another option to add myocardial structure is to estimate the fibre orientation associated to each element of the volumetric mesh of a model from pre-established patterns [91–94], most of them derived from Streeter’s findings [95]. The final result of the 3D reconstruction consists of a 3D model representing the cardiac structure to be printed. As a consequence, despite several file formats exist, the model is almost universally stored in standard tessellation language (STL) format.

## 6 Additive technologies and 3D printing for cardiac structures

The most common additive technologies that can be used for prototyping cardiac structures are selective laser sintering, fused deposition modelling, multijet modelling/3D printing, and stereo-lithography. Selective laser sintering (3-D Systems Inc., Rock Hill, SC) uses a high-power laser to fuse small particles of plastic, metal, or ceramic powders into a 3D object [96]. Selective laser sintering has the ability to utilize a variety of thermoplastic powders and has a high geometric accuracy but is generally higher in cost than other additive methods. In fused deposition modelling (e.g. from Stratasys Inc.), a plastic filament (typically acrylonitrile butadiene styrene polymer) is forced through a heated extrusion nozzle that melts the filament and deposits a layer of material that hardens immediately on extrusion. A separate water-soluble material is used for making temporary support structures while the manufacturing is in progress. The process is repeated layer by layer until the model is complete. Multijet modelling or 3D printing (Z Corporation, Burlington, Mass) essentially works like a normal ink-jet printer but in 3D space. In this process, layers of fine powder (either plaster or resins) are selectively bonded by printing a water-based adhesive from the ink-jet print head in the shape of each cross section as determined by the computer-aided design file. Each layer quickly hardens, and the process is repeated until the model is complete [97].

In stereolithography, models are built through layer-by layer polymerization of a photosensitive resin. A computer-controlled laser generates an ultraviolet beam that draws on the surface of a pool of resin stimulating the instantaneous local polymerization of the liquid resin in the outlined pattern. A movable platform lowers the newly formed layer, thereby exposing a new layer of photosensitive resin, and the process is repeated until the model is complete.

Depending on their intended application (i.e. education, catheter navigation, device sizing and testing, and so on), physical models may be printed in multiple materials using a variety of 3D printing technologies, each with its own collection of benefits and shortcomings. For example, multijet modelling (see Fig. 5) technology can be used to generate full-colour models to highlight anomalous structures or specific regions of interest. Printing times are fast (approximately 6–7 h per model) and cost-effective (Fig. 6). 2

Although flexible models may be prototyped by multijet modelling technology, the properties of the material often

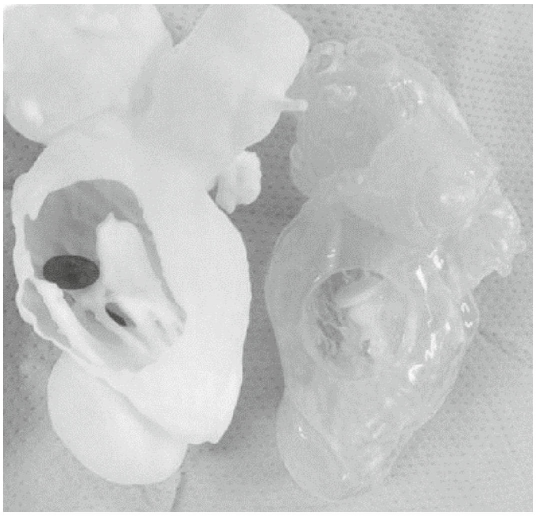

**Fig. 6** Two examples of 3d printed models: on the *left* it is shown the model prototyped using multijet printer; on the *right*, the model realized using polyjet matrix technology is depicted

fail to accurately mimic true tissue properties. PolyJet Matrix printing technology (see Fig. 5) offer the ability to print physical models in materials that more closely resemble the properties of native tissue, thus representing the new direction in rapid prototyping technology with its ability to print in different materials simultaneously. This unique technology will allow most physical models to be printed in durable materials (e.g., plastic), whereas specified segments (e.g., interatrial septum, septal defects, vascular structures, and so on) are printed in less durable, but more lifelike, materials (e.g. rubber polymers) for more realistic manipulation.

Given the broad spectrum of anatomic variations and pathologies, 3D printing could potentially be a game-changer in cardiology, particularly in challenging anatomies and rare pathologies, facilitating procedural planning, optimal sizing and simulation. The knowledge of the exact dimensions of the defect/communication/orifice that needs to be sealed and the relationship with adjacent structures is of paramount importance and often not readily available with conventional 2D imaging. 3D printing allows for direct visualization and simulation (trial and error) in order to identify the optimal device and angulation required to obtain the best possible result. The value of 3D printing in surgical pre-procedural planning lies primarily in the precise delineation of the underlying anatomy and is of paramount importance in complex congenital heart disease pre-procedural planning. Patient-specific implants and custom-made devices can be designed, produced, and tested, thus opening new horizons in personalized patient care and cardiovascular research.

A taxonomy of possible applications of 3D printing for cardiac structures can be found in [9] and mostly referred to paediatric and adult heart diseases [98,99] and to aorta and great vessels pathologies [100,101]. With reference to structural heart diseases, most relevant applications of 3D printing are related to the creation of patient-specific devices for closing the left atrial appendage [98] or for determining the ideal resection lines of the aneurysmectomy for patients affecting by cardiac aneurysms [102]. Other studies report the use of 3D models for myectomies [103], atrial and ventricular septal defects [104]. Referring to aorta and vessel pathologies, a number of studies have been carried out to create 3D printed models of systemic vasculature; as stated in [9], in fact, “Rigid and flexible 3D-printed models can aid endovascular interventions by enabling the assessment of optimal stent dimensions and positioning in cases of transverse aortic arch hypoplasia”. Finally, 3D modelling of heart can be really helpful for education, training and decision-making [9,105]. Training on 3D printed models can be performed virtually anywhere, avoiding the cost and complexity of operating in the controlled environments required for animals and human cadavers.

## 7 Discussion and conclusions

With the development of inexpensive 3D printers, 3D printable multi-materials, and 3D medical imaging modalities, 3D printing medical applications for hearth diseases among others, have come into the spotlight. Due to the availability of transparent, full-coloured, and flexible multi-materials, 3D printing objects can be more realistic, miming the properties of the real body; i.e., not only hard tissue alone but also hard and soft tissue together.

The study and experimentation conducted show that interactive approaches for image enhancement, segmentation, 3D modelling and printing have reached a promising point for medical applications. Moreover, the design framework introduced in Fig. 1 can be extended to other problems related to patient specific modelling since almost all medical interventions share techniques based on medical image acquisition and 3D reconstruction for diagnosis, education or intervention planning. It is therefore straightforward to add 3D printing methods to this traditional workflow, when the complexity of the anatomy to be treated requires physical models to be managed by medical staff. Some relevant examples can be found in hip and knees prosthesis design as well as in maxillofacial sector and in personalized hand-wrist-arm orthosis design. More in general, several different application areas can be interested in wide spreading 3D printing of cardiac structures. First, 3D printing can be really useful for aiding intervention planning, giving the medical staff the opportunity of handle a realistic and patient-specific model prior to proceed with the actual intervention. Secondly, the creation of 3D models is crucial for training; in fact, this can be performed virtually anywhere, avoiding the cost and complexity





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of operating in the controlled environments required for animals and human cadavers. Finally, 3D modelling of heart can be really helpful for decision-making [9, 105] giving the medical staff the opportunity to test several different options specifically addressed to the patient own anatomy.

While the opportunity of using 3D printing for simulating medical surgery has been widely accepted in the medical field, for training purposes only a few studies are related to the impact on learning, all recalled in a review work [106] where authors demonstrate that despite there is no solid evidence that the use of 3D models is superior to traditional teaching, more studies are still needed to examine the short- and long-term impacts of 3D models on learning using valid and appropriate tools.

Development and optimization of the entire procedure, from image acquisition to 3D printing fabrication, are required for personalized treatment, even in emergency situations. In addition, to produce an effective 3D printing object, multidisciplinary knowledge of the entire 3D printing process chain is needed; namely, image acquisition using a protocol suitable for 3D modeling, post-processing of the medical images to generate a 3D reconstructed model, 3D printing manufacturing with an appropriate 3D printing technique, and post-processing of the 3D printing object to adapt it for medical use.

On the other hand, several major limitations, such as those associated with the technology and the time and cost of manufacturing 3D phantoms, remain to be overcome. In fact, during the virtual exploration of solutions for the 3D reconstruction the presence of artifacts could lead to erroneous medical interpretations. Therefore, the final model could provide wrong indications on geometry or, worst, on pathologies. To avoid these errors, that could strongly impact on the intervention planning or even on the actual medical surgery, the intervention of experts, interacting with CAD systems and/or with image processing-based algorithms is still needed to assess the accuracy of the final products and correct for errors that may occur during the automated phases of the procedure. Finally, an expanded heart team including physicians and engineers is needed to assess the correctness of the products and correct inaccuracies of automatic procedures, when translating the medical imaging into 3D printing. This opens, for the next future, the opportunity of creating new professionalism across medical science and engineering to confront with the incredible boost of methods and techniques related to 3D printing in biomedicine. 3

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