Applications of 3D-Printing in Cardiovascular Diseases

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3D-Printed Models
Non Invasive Imaging

Modelling tissue architecture
- CT
- MR
- 3D TEE/TTE

Modelling vascular lumen
- CT/CTA
- MR/MRA
- 3D rotational angiography

Segmentation-STL generation
- Automated
- Semi-automated
- Manual

Computer-aided design modelling
- Optimizing STL
- Exemplifying anatomy
- Device designing
- Smoothing
- Trimming
- Patches

Selection of 3D printer
- 3D printing technology
- Availability of materials
- Machine resolution
- Time-to-print
- Build preparation

Selection of materials
- Physical and mechanical properties
- Colour, transparency
- Biocompatibility
- Cost
- Recyclability

Postprocessing of printout
- Cleaning
- Removal of support materials
- Ultraviolet curing
- Sterilization
- Labelling
3D-Printed Models

Current Applications

- Medical teaching
- Enhance communication between cardiologists and patients
- Explore valve and vessel function
- Surgical and catheter based procedural planning

**Table 1: Applications of 3D-Printed Modeling in Cardiovascular Diseases**

<table>
<thead>
<tr>
<th>First Author (Ref. #)</th>
<th>Clinical Condition</th>
<th>Printing Method</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodian et al. (11)</td>
<td>Aortic arch pseudoaneurysm</td>
<td>Stereolithography; rigid models</td>
<td>Creation of custom-made occluder for aortic pseudo-aneurysm</td>
</tr>
<tr>
<td>Jacobs et al. (47)</td>
<td>LV with aneurysm; RV tumor</td>
<td>Binder jetting; multicolor plaster-based material</td>
<td>3D model facilitated surgical resection</td>
</tr>
<tr>
<td>Schmauss et al. (48)</td>
<td>RV tumor</td>
<td>Stereolithography; multicolor rigid material</td>
<td>3D model facilitated surgical resection</td>
</tr>
<tr>
<td>Maragamnis et al. (8,9)</td>
<td>Severe AS</td>
<td>Polyl; rigid and flexible materials</td>
<td>Evaluation of AS models under patient-specific flow conditions</td>
</tr>
<tr>
<td>Yang et al. (55)</td>
<td>Hypertrophic cardiomyopathy</td>
<td>Polyl; multiple materials</td>
<td>Septal myomectomy guidance and procedural planning</td>
</tr>
<tr>
<td>Russ et al. (32)</td>
<td>Circle of Willis, cardiac arteries and femoral artery</td>
<td>Polyl; TangoPlus flexible material</td>
<td>Pre-interventional procedural practice in flow loop</td>
</tr>
<tr>
<td>Little et al. (51)</td>
<td>Severe MR</td>
<td>Polyl; multiple materials</td>
<td>MV model used for selection of repair devices in catheter-based clip and plug repair procedure</td>
</tr>
<tr>
<td>Chauwu et al. (38)</td>
<td>ASD</td>
<td>Not specified; rigid model</td>
<td>Pre-procedural planning of transcatheter occlusion of ASD</td>
</tr>
<tr>
<td>Al Habbari et al. (49)</td>
<td>LA and RA tumor</td>
<td>Polyl; multiple materials</td>
<td>3D model facilitated surgical resection</td>
</tr>
</tbody>
</table>

**Echocardiography**

- Binder et al. (15) | Normal and dysfunctional MV | Stereolithography; rigid models | Demonstrated feasibility of MV models on the basis of 3D TEE |
- Kapur et al. (20)  | MV annulus | Fused deposition molding; rigid plastic | Generated MV annulus models to facilitate MV repair |
- Oliveri et al. (18) | VSD; paravalvular regurgitation | Polyl; rigid material | Demonstrated feasibility and accuracy of 3D TEE-based models |
- Mahmood et al. (16) | Normal and dysfunctional MV | Polyl; rigid annulus, flexible leaflets | Demonstrated feasibility of 3D TEE-based MV models creation |
- Vukićević et al. (19) | LV and calcified MV apparatus | Polyl; multiple materials, differentiated tissue stiffness | 3D TEE and CT datasets combined to model for pre-procedural planning |
- Bidro et al. (17)   | Normal and dysfunctional MV | Fused deposition molding; plastic | MV models created using automated image segmentation |

**CMR**

- Markl et al. (14)   | Thoracic aortic vasculature | Polyl; TangoPlus material | Conversion of patient CMR data into physical vessels replica |
- Schievano et al. (10) | Dysfunctional PV | Polyl; rigid material | Demonstrated accuracy of CMR-based models for percutaneous valve implantation |
- Griei et al. (12)   | Normal and congenital heart | Laser sintering; rigid material | Demonstrated accuracy of CMR-based models |
- Bigino et al. (12)  | Hypoplastic aortic arch and RVOT | Polyl; flexible, TangoPlus | Evaluation of TangoPlus materials for arterial vessels replication |
- Valverde et al. (50) | Aortic coarctation | Fused polymer filament; rigid and flexible | Demonstrated utility of models for interventional planning |
- Costello et al. (43) | VSD | Polyl; rigid materials | Demonstrated utility of heart models for medical student teaching |

AS = aortic stenosis; ASD = atrial septal defect; AV = aortic valve; CMR = cardiac magnetic resonance; CT = computed tomography; LA = left atrium; LV = left ventricle; MR = mitral regurgitation; MV = mitral valve; PV = pulmonary valve; RA = right atrium; RV = right ventricle; RVOT = right ventricular outflow tract; TEE = transesophageal echocardiography; VSD = ventricular septal defect.
3D-Printed Models
Patient Specific Aortic Stenosis

3D-Printed Models
Patient Specific Aortic Stenosis

Dimitrios Maragiannis et al. Circ Cardiovasc Imaging. 2015;8:e003626
3D-Printed Models
Patient Specific Aortic Stenosis

Clinical Echocardiogram

Patient-Specific Model’s Echocardiogram

Calcific AS

Calcific AS
3D-Printed Models
Patient Specific Aortic Stenosis

Clinical Doppler

Patient-Specific Model Doppler

Ao Valve Doppler

Ejection Time: 318 ms
Peak Velocity: 487 cm/sec
Mean Gradient: 66 mmHg

Ejection Time: 317 ms
Peak Velocity: 482 cm/sec
Mean Gradient: 64 mmHg
3D-Printed Models
Patient Specific Aortic Stenosis
3D-Printed Models
Patient Specific Aortic Stenosis

CT Images → Segmentation → 3D Reconstruction

Step 1
Step 2
Step 3

Digital Patient-specific 3D Model

Step 4

Multi-material 3D Printed Patient-specific Model

Step 5

Marija Vukicevic et al. JIMG 2017;10:171-184
3D-Printed Models
Patient Specific Aortic Stenosis

AS Patient-specific Model In Flow Loop
Patient Echo
Patient Doppler
Model Echo
Model Doppler

Marija Vukicevic et al. JIMG 2017;10:171-184
3D-Printed Models
Patient Specific Aortic Regurgitation

Figure 1. Modeling of patient-specific aortic regurgitation and Doppler comparison

Marija Vukicevic, Dimitrios Maragiannis, Matthew Jackson, Stephen H Little Circulation. 2015;132:A18647
3D-Printed Models
Transcatheter Valve and stent implantation

Marija Vukicevic et al. JIMG 2017;10:171-184
3D-Printed Models
Mitral Valve

Feroze Mahmood et al. JIMG 2015;8:227-229
3D-Printed Models
Implanted TMVR

**CENTRAL ILLUSTRATION:** Creation of a Patient-Specific Multimaterial 3D Model of the Mitral Valve Apparatus

- **3D PRINTED MODELING**
  - Imaging Data
  - Segmentation
  - Digital Model
  - Multi-material 3D Printed Model

- **PROCEDURAL PLANNING**
  - Neo-LVOT axis
  - Implanted TMVR
  - Neo-LVOT cross-section
  - Implanted TMVR
  - CT Scan of 3D Printed Model with Implanted TMVR


Marija Vukicevic et al. JIMG 2017;10:171-184
3D-Printed Models
Mitral Valve perforation repair

CT Imaging Data

Digital Patient-specific Model

3D-printed Model

3D-printed Model with Occluder Device

Digital Model with Valve Perforation

Physical Model with Valve Perforation

Implantation of Occluder Device
3D-Printed Models

LAA closure

James M. Otton et al. JCIN 2015;8:1004-1006
3D-Printed Models
Hypertrophic Cardiomyopathy

Dong Hyun Yang et al. Circulation. 2015;132:300-301
3D-Printed Models

ASD occlusion

Yan Chaowu et al. Circulation. 2016;133:e608-e610
3D-Printed Models

VAD placement

Adults with CHD-HF
- d-TGA s/p Atrial Switch
- L-TGA
- Ebstein’s Anomaly
- Failing Fontan

Preparation for Ventricular Assist Device Placement

3D image acquisition

3D Model Based Pre-surgical Planning for ACHD-HF VAD Implantation

Segmentation

3D printed model improves preoperative surgical preparation

3D Printer to create solid model

3D virtual file creation

3D-Printed Models

Pacemaker leads

Terry Bauch et al. Three-Dimensional Printing for In Vivo Visualization of His Bundle Pacing Leads. AJC. 116.3. 2015, 485–486
3D-Printed Models

Coronary Arteries

Visualization Models

Flow Models

Interventional Models

Marija Vukicevic et al. JIMG 2017;10:171-184
Current Limitations

- Materials do not match the true **mechanical properties** of cardiac tissue
- **Static models** of a dynamic organ is difficult to simulate the function of the cardiovascular system
- Relative high **cost**
- There are **no clinical trials** establishing the benefit of 3D printing
- **No standard protocols** in image processing and post-processing
Future Directions

- 3D-Printed models in routine clinical practice for individual patient treatment
- **Selection** of appropriate patients for structural heart therapy
- Personalized 3D-Printed *cardiovascular prostheses*
- Personalized 3D-Printed *annuloplasty surgical rings*
- Anticipate procedural *complications*
- Create or refine **novel intra-cardiac devices**
- Investigate **intra-cardiac flow** in functional 3D-Printed models
- 3D-Printed models with more **realistic mechanical properties**
- 3D Bioprinting
Conclusions

- 3D Printing is a revolution in personalized medicine
- 3D printed models is a valuable tool for pre-surgical planning
- Patient specific models enhance patient and doctors education
- 3D-Printing is pivotal for the future generations of cardiovascular imagers and clinical cardiologists
Our team