Kaleidoscope
Művelődés-, Tudomány- és Orvostörténeti Folyóirat 2016. Vol.7.No.13.
Journal of History of Culture, Science and Medicine **ISSN/EISSN**: 20622597
DOI: 10.17107/KH.2016.13.284-293

ÉLET-TUDOMÁNY-TÖRTÉNET: TUDOMÁNY, INFORMÁCIÓ, MEDIALITÁS

3D-modelling and printing of the heart and great vessels in medical education and clinical practice – a historical review

A szív és a nagyerek háromdimenziós nyomtatása az orvosképzésben és a gyógyításban – történelmi előzmények és eszmetörténeti áttekintés

László Király MD PhD FETCS[1]
laszlokir@gmail.com

Initially submitted October 10, 2016; accepted for publication November 1, 2016

Abstract
Interactivity and hands-on approach is key in modern day medical education, especially in the training of new generations of surgeons. Pediatric cardiac surgery requests detailed pathomorphological knowledge before embarking on any surgical procedure. Morphological archives of cardiac specimens greatly helped that task, however availability of these archives has become limited due to stiffened data protection rules, reduced number of autopsies, natural attrition of specimens and most importantly that patients with congenital heart disease survive. Transfer of morphological specimens on a 3D platform and creation of a virtual museum from clinical data could solve the problem. High-resolution is mandatory to preserve imaging information of delicate valvar structures. Availability of a 3D modelling and a virtual museum offers innumerable opportunities for training and education, presurgical planning and virtual surgery, patient-family education, etc. Inclusion of contour recognition and heart-cycle information may conjoin structure and function in the future. Augmented reality in the form of superimposed optical display of holograms or 3D-models onto the surgical field and/or any can be combined with robotics that may open a new horizon in surgery.

Key words (MeSH): 3D printing, medical illustration, pathological museum, medical education, congenital heart disease

Kulcsszavak: 3D-nyomtatott modellek, orvosi illusztráció, patológiai múzeum, orvosképzés, veleszületett szívbetegség

Introduction
Application of 3D imaging techniques and 3D-printed prototypes may bring back the same intellectual excitement into present-day clinical practice that pioneers of anatomy could have experienced during preparation and studying anatomical specimens. In the 16th century,

[1] Head, Consultant, Pediatric and Congenital Cardiac Surgery, Sheikh Khalifa Medical City managed by Cleveland Clinic, Institute of Cardiac Sciences. POB 51900, Abu Dhabi, United Arab Emirates. Adjunct Staff, Cleveland Clinic Foundation, Cleveland, Ohio, USA. Mobile: +971 50 581 6482, e-mail: laszlokir@gmail.com

2016. Vol.7.No.13.
ISSN/EISSN: 20622597
DOI: 10.17107/KH.2016.13.284-293

anatomy must have been the most popular subject at the European universities. According to contemporary records, there were about 1300 students at University of Padova, *Il Bo*, and all of them wanted to read anatomy [Rippa-Bonati, 2010]. Expansion of medical knowledge between 1500 and 1550 duly compares to the digital revolution in our age around five hundred years later.

Birth of representation of general anatomy, between 1500-1550 CE

Pupils of Renaissance medicine pursued understanding about the structure of the physical body whereas doctorands of theology sought the seat of soul in the body. Anatomy was thus pertinent for both. Artists −wishing to excel with the same accuracy in representation of reality that their predecessors achieved in the antique era − were also pioneering the study of anatomy [O'Malley, 1982]. **Fig 1** and **2** offers an example how closely the antique models were followed. *Vesalius*'s illustration is based on the so-called Belvedere Torso. By using the antique torso as its basic setting, Vesalius (1514− 1564) could have attested enhanced authority for his anatomical presentation.

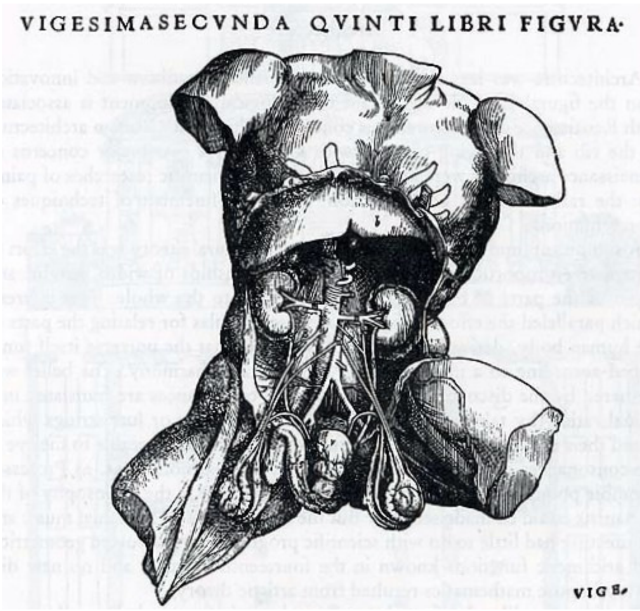

Fig 1: Belvedere Torso attributed to Apollonius of Athens. Marble copy of a Hellenistic sculpture from the 2nd century BCE. Vatican Museum.

Fig 2: Vesalius, Andreas Bruxellensis: Anatomical representation of the male urogenital system. De Humani Corporis Fabrica. Basel, 1543.

This statue also bore such a profound influence on *Michelangelo* (1475–1564), that he portrayed St. Bartholomew (a martyr who was flayed alive) in the same bodily position holding in the hands a flayed skin with Michelangelo's distorted features. **Fig 3**. In other words, he presented his autoportrait in reference to a well-known antique torso and the first step in anatomical dissection: flaying the skin. One could add multiple other examples of the emphasis on anatomy in Michelangelo's oeuvre [Meshberger, 1990], [Suk and Tamargo, 2010].

2016. Vol.7.No.13.
ISSN/EISSN: 20622597
DOI: 10.17107/KH.2016.13.284-293

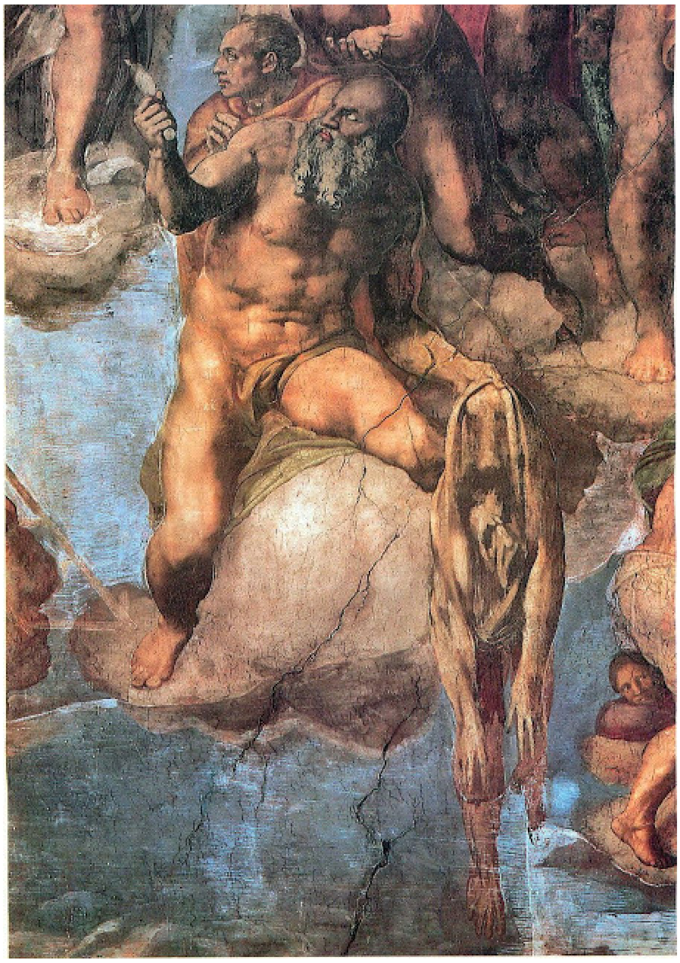

Fig 3: Michelangelo, Buonarroti: St. Batholomew at the Last Judgment. 1536-41, detail, Sistine Chapel, Vatican

It is well documented that artists starting with *Donatello* (1386–1466) commonly studied cadavers and used them to set postures [Tolnay, 1964].

It was the muscles, joints, ligaments and bones that the artists were mostly interested. These were accessible, relatively superficial bodyparts where conjecture about the function could be directly drawn from the structure. Body cavities and visceral organs remained remote for a similar assessment and they also posed technical problems. Rapid decay of cadavers was a universal obstacle as fixation methods (e.g. with formaldehyde) were only discovered centuries later. *Leonardo da Vinci* (1452–1519), the *'most artistically gifted scientist and scientifically acute artist'* as Rifkin put it, was rather unique in his quest that led him deep under the surface [Rifkin, 2006]. He received permission from the Pope to dissect ten cadavers in his search for the seat of the soul [Dolan, 2007]. Having been ambidextrous, Leonardo took notes and diagrams with his left hand while dissecting with the other [Zwijnenberg, 1999]. His famour mirror-writing could well be attributed to his probable dyslexia [Røsstad, 2002]. Leonardo discovered completely new methods of illustration *en route* of his studies: he was the first in applying cross-sectional and 'blown-up' diagrams; he employed models and experiments to test his ideas; he stressed on quantifying his findings and only accepting them when doubly observed; and he was the first known artist/scientist to

2016. Vol.7.No.13.
ISSN/EISSN: 20622597
DOI: 10.17107/KH.2016.13.284-293

assing numerical codes to (facial) features in cataloguing great wealth of data [Doby, 1963]. Truly, Leonardo sought beyond a mere description of his observations, and aspired to understand the working of the structures. His anatomical drawings literally illustrated (from 'lustro' /Lat/=highlight) structure and function and joined them together. Sadly, Leonardo experienced great intellectual loneliness; he was a vanguard in an unexplored territory without fellow travelers [Wells and Crowe, 2004]. His groundbreaking methods and discoveries could not make any impact on science of anatomy as they were hidden from public recognititon from more than two centuries.

Drawing (anatomical) diagrams has always been a personal action that remained under the influence of the period's style [Kemp, 2010]. Dramatic illustration thus became mainly an artistic performance, whereas the scientific method applied depiction and description of the observed structures free from any artistic style [Ghosh, 2015]. A deductive method was employed that abstracted individual features into a general rule and/or presentation (*regressus demonstrativus*). This was the era when the emphasis first started to move from notions of perceived function founded on Galen and Avicenna (*doxa* and *dogma*) towards the description of acute observations. **Fig 4.** Renaissance scientists and artists portrayed themselves as heroes in the battle for knowledge. In this courageous and self-confident era, they all believed that the Creator arranged all things in order and even set a trail for a discoverer to unfold the mysteries of Nature.

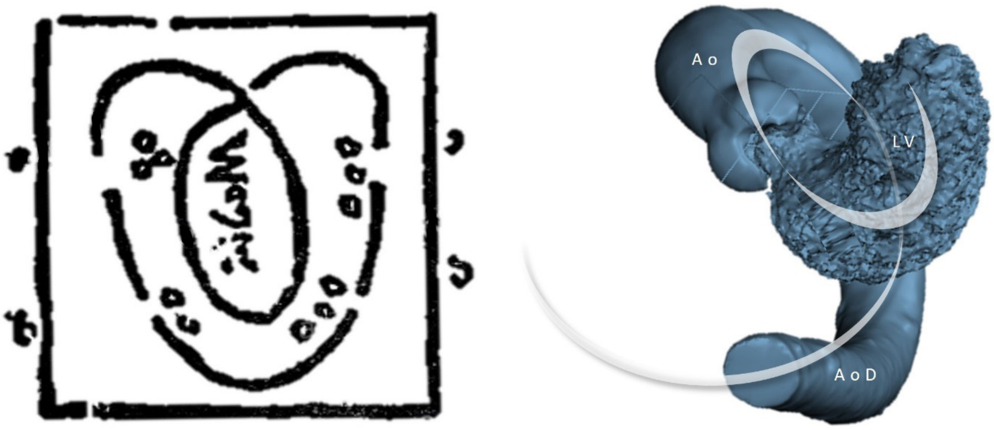

Fig 4: Perceived function v observed structure. Left: Diagram of the heart featuring the Aristotlean concept of the third ventricle in the centre. Industry of the heart represented by a helical lines without correspondence to real anatomical structures. Illustration to *Mondinus*'s (Mondino da Luzzi, 1270–1326) *Anathomia corporis humani*, written in 1316. Right: 3D-reconstruction of a normal left ventricle (LV) to aorta (Ao) to descending aorta (AoD) complex viewed from caudal direction. From this unusual viewpoint, stream of blood takes takes a shape of a helix. ***(Author's segmented model, 2016)***

Personalized imaging and modeling of anatomy in the modern era

Over the centuries, a corpse was the ultimate model that anatomy was studied upon. *Sir William Withey Gull* (1816–1890), an English physician and Governor of Guy's Hospital, London (also a suspect in the Jack-the-Ripper murders) postulated: *'The road to medical knowledge is through the pathological museum and not through an apothecary's shop'* [Gull, 1870]. Generations of physicians and surgeons were educated with the help of morphological archives, especially of cardiac specimens. *Dr. Maude Abbott* (1869-1940), founder of

ISSN/EISSN: 20622597
DOI: 10.17107/KH.2016.13.284-293

pathomorphology for congenital heart disease, began *'museum demonstrations'* in 1904 that had become part of the medical school curriculum [Abbot, 1923]. In recent years, however, availability of these archives has become limited due to stiffened data protection regulations [Smith, 1998], reduced number of autopsies, natural attrition of specimens and most importantly that patients with congenital heart disease survive [Wren and O'Sullivan, 2001]. Source of specimens has dramatically dropped. There are inherent problems with specimens: thay have rigid, friable tissues due to formaldehyde fixation and storage that also lead to shrinking and distorsion; parts are missing and/or open post-autopsy; delicate (valvar) structures are difficult to handle and are vulnerable to injury.
Transfer of morphological specimens on a 3D platform and creation of a virtual museum from clinical data could solve the problem [Mostefa-Kara, 2016]. High-resolution is mandatory to preserve imaging information of delicate valvar structures. First, a specimen is scanned with high-resolution 3D scanner (that only registers surface information), or preferably with micro-computed tomography (it can achieve a resolution of 10 micrometers) [Happel et al, 2010]. Next, digital information is segmented and a 3D virtual model is created. Wall thickness information is rendered accordingly. Availability of a virtual museum offers innumerable opportunities for training and education, presurgical planning and virtual surgery, patient-family education, etc. Inclusion of contour recognition and heart-cycle information may conjoin structure and function in the future. **Fig 5.**

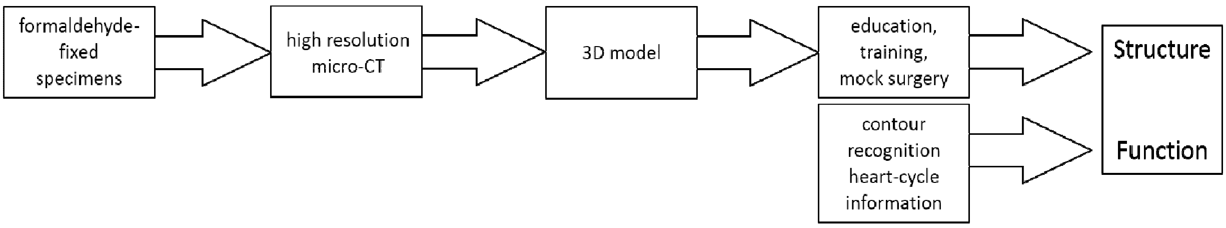

Fig 5: The virtual heart museum project

Interactivity and hands-on approach is key in modern day medical education, especially in training of new generations of surgeons. Apprenticeship in the modern era is a team-based learning, or in other words, it is a structured form of small-group learning. It has gained increasing popularity in medical education as it can be applied in a variety of combinations and permutations across a diversity of settings, learners, and content areas resulting in an overall positive learning experience for all participants [Burgess et al, 2014]. Nurturing professionalism is based on close interaction between educator and student [Mueller, 2015]. Medical education ranges from medical students, trainees, the multidisciplinary clinical team and towards patients/families and the community. Importance of anatomy became grossly increased by modern imaging modalities including computer tomography (CT) and magnetic resonance imaging (MRI). These modalities have created patient-specific demonstration of patho-anatomy hitherto impossible. Compared to traditional anatomical knowledge where – as mentioned - individual features had been abstracted into general knowledge, modern imaging offers individual presentation and promotes personalized surgical plans.
We use pediatric cardiac surgery as example. This discipline requires thorough and detailed pathomorphological knowledge before embarking on any surgical procedure. Simulation-based methods have been invoked by two main aspects: (1) learning curve of any new

2016. Vol.7.No.13.
ISSN/EISSN: 20622597
DOI: 10.17107/KH.2016.13.284-293

procedure has become rather steep; no collateral morbidity/mortality is tolerated; (2) – as mentioned –access to morphological specimens reduced. This prompted the need for 3D-virtual reality models and 3D-printed prototypes.

First, digital data from imaging sources (CT-angio, MRI and echocardiography) are processed by a special 3D software [Mimics, Materialise, Leuven] and a rotatable digital (virtual) 3D model is segmented. Accuracy of segmentation depends on the completeness and clarity of raw data and apprioriate selection of segmentation values. Areas and structures of interest are exposed while others temporarily faded. All this requires intimate knowledge of anatomy, thus involvement of the surgeon; segmentation is time-consuming, laborious and cannot be automated. **Fig 6.**

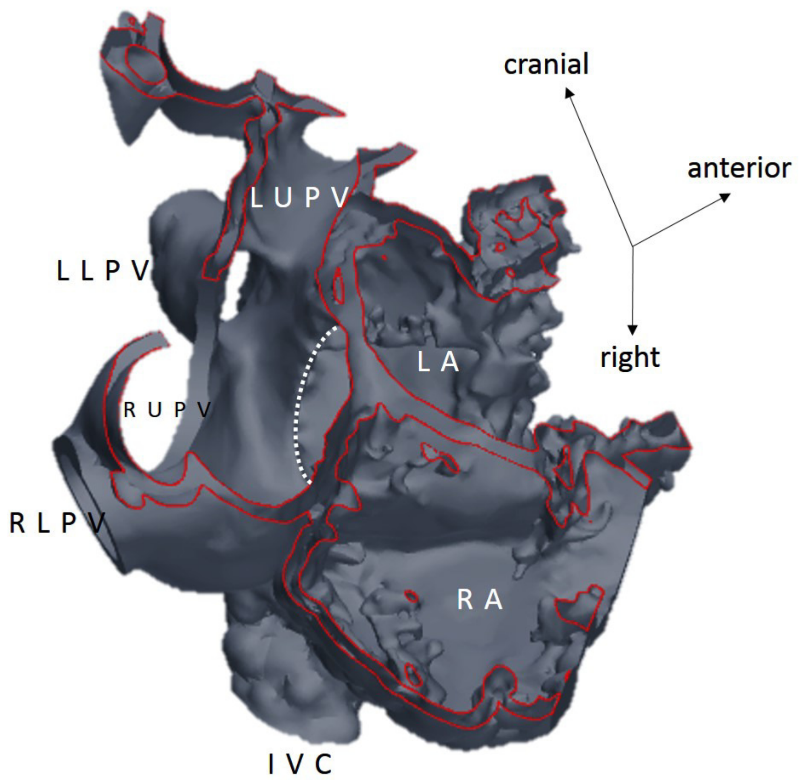

Fig 6: Patient-specific, rotatable, 3D virtual model of a segmented heart. Segments of the ventricles and great arteries are removed from the model. The atria are opened to expose the inflow of the pulmonary veins and the connection (dotted white arc) to the mitral orifice. No other imaging modality could demonstrate the adequacy of this connection. Abbreviations: IVC: inferior vena cava; LA: left atrium; LLPV: left lower pulmonary vein; LUPV: left upper pulmonary vein; RA: right atrium; RLPV: right lower pulmonary vein; RLPV: right lower pulmonary vein

The virtual model (*'.stl' file*) already offers indispensable insight in most instances. The actual printing process involves rapid prototyping and additive manufacturing, building parts layer by layer [Mott-Link et al, 2005]. In our clinical practice two prototypes are 3D-printed: a real life-sized (blood-volume) solid model provides exact dimensions of the structures; another 1.5-3x-magnified hollow model simulates surgical approach and steps of the operation with high-fidelity (virtual surgery) [Kiraly et al, 2016]. **Fig 7.**

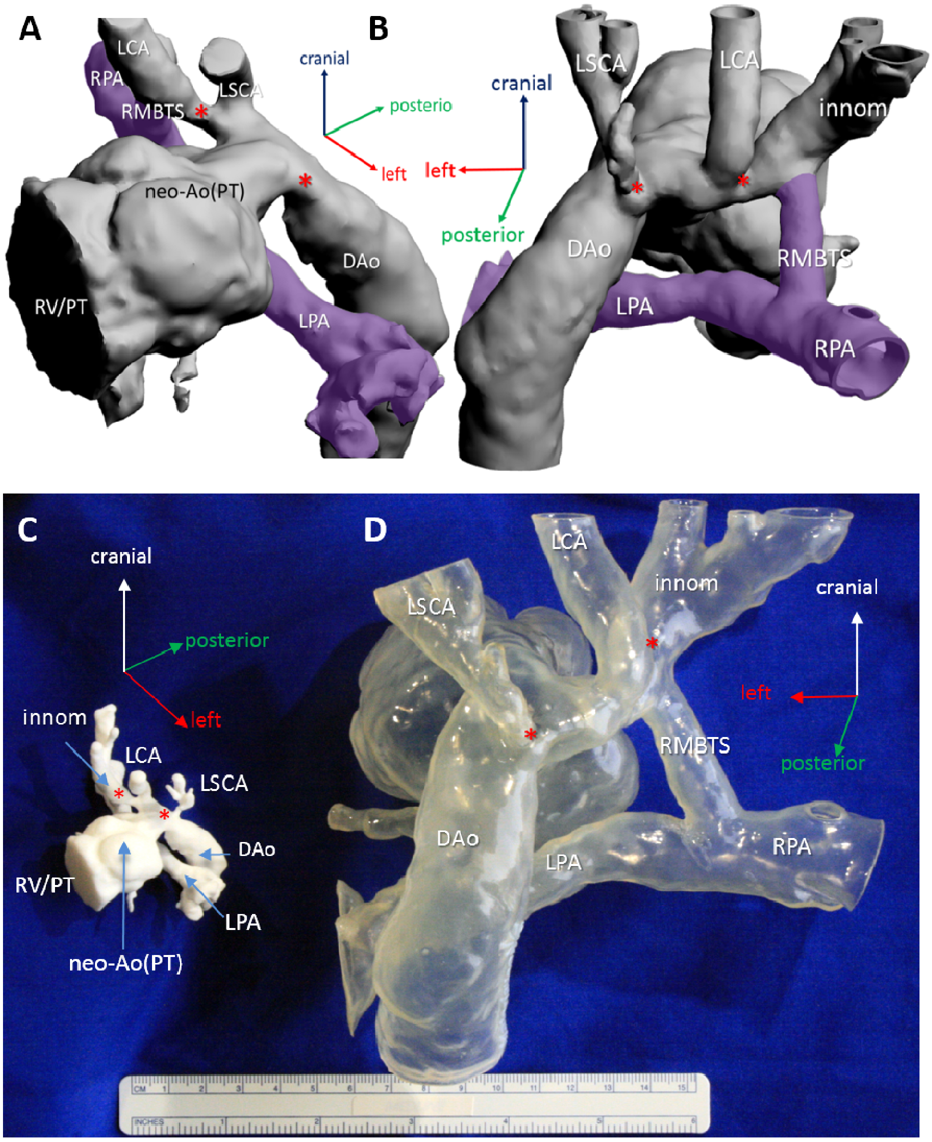

Fig 7: A: Digital 3D model of the aortic arch, its branches and the pulmonary arteries; left anterior oblique lateral view. B: posterior view. C: 3D-printed prototype of the aortic arch, its branches and the pulmonary arteries, life-size solid model; left anterior oblique lateral view. D: 3D-printed prototype of the aortic arch, its branches and the pulmonary arteries, 3x-magnified size, hollow model; posterior view. Sites of obstruction are denoted by *. Abbreviations: DAo: descending aorta, innom: innominate artery, LCA: left common carotid artery, LPA: left pulmonary artery, LSCA: left subclavian artery, neo-Ao(PT): neo-aorta, RCA: right common carotid artery, RMBTS: right modified Blalock-Taussig shunt, RPA: right pulmonary artery, RV/PT: right ventricle to pulmonary trunk junction

Intraoperative assessment confirms anatomic accuracy of 3D models. **Fig 8.** Prototyping contributes to improved patient safety and shortened operating time, successful outcome [Schmauss et al, 2015]. Among the multiple benefits of 3D-printed models are the improved communication within the multidisciplinary clinical team and patient/family education

2016. Vol.7.No.13.
ISSN/EISSN: 20622597
DOI: 10.17107/KH.2016.13.284-293

[Biglino et al, 2015]. Feasibility of new procedures could be experimented with patient-specific morphological characteristics [Schievano et al, 2007].

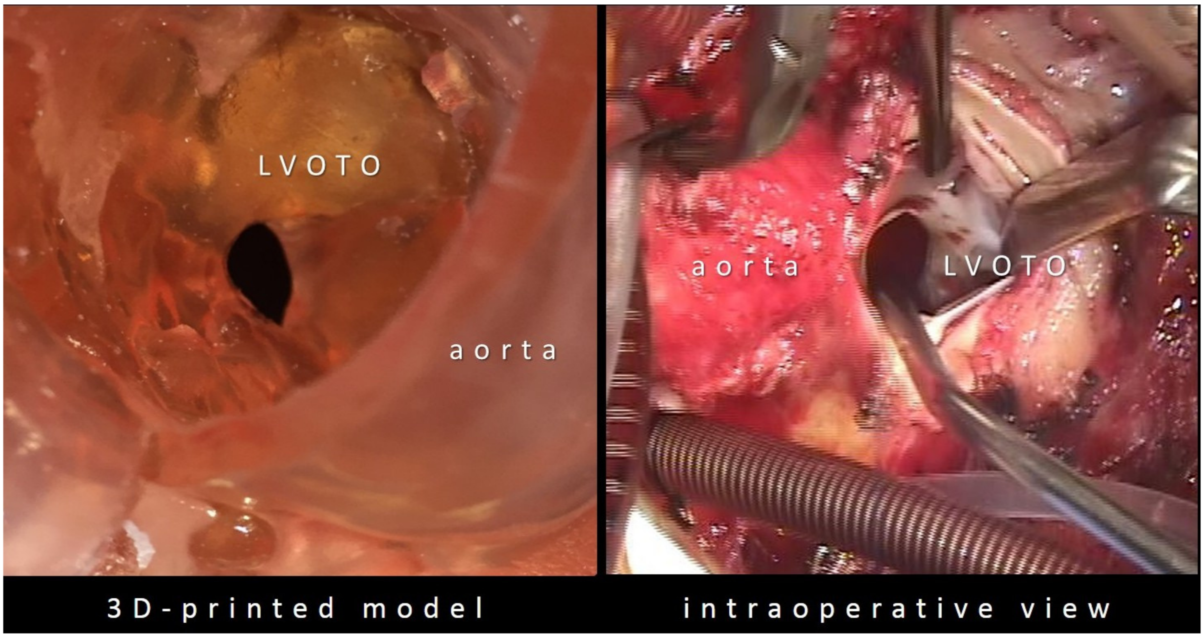

Fig 8: View of the left ventricular outflow tract obstruction (LVOTO) in a 3D-printed model and intraoperatively. Prominent musculature significantly restricts outflow from the ventricle (black opening). Morphology on the model looks identical to the one confirmed by intraoperative exploration.

Virtual surgery can also be performed [Shiraishi et al, 2010]. As with all human endeavors, 3D-printing besides listed advantages, has drawbacks: it presents additional costs, extra work and structuralization (e.g. 3D-printing facility). It is proposed that 3D-printing will have a major role in providing patient-specific (customized) implants and prostheses, especially with evolving techniques of bioprinting [Martelli et al, 2016]. This could help in fulfilling the ultimate goal in cardiac surgery to create an ideal cardiac valve implant.
Another direction of 3D technology is image-guided surgery/augmented reality. With this modality, patient-specific 3D models or holograms projected to a fixed point in space or directly superimposed on the operative area [RealViewHearth, 2013]. In combination with robotics, optical display could revolutionize surgery: it could allow performance of procedures in the heart with preserved perfusion/organ function while being operated. Such prospects revive an intellectual excitement comparable to the one that established anatomy as medical science five hundred years ago.

Bibliography

ABBOTT M: http://www.mcgill.ca/medicalmuseum/introduction/history/physicians/abbott , retrieved on 24 September 2016.
BIGLINO G, CAPELLI C, WRAY J, ET AL BIGLINO G, CAPELLI C, WRAY J, SCHIEVANO S, LEAVER LK, KHAMBADKONE S, GIARDINI A, DERRICK G, JONES A, TAYLOR AM: 3D manufactured patient-specific models of congenital heart defects for communication in clinical practice: feasibility and acceptability. BMJ Open 2015; 5: e007165. http://dx.doi.org/10.1136/bmjopen-2014-007165

2016. Vol.7.No.13.
ISSN/EISSN: 20622597
DOI: 10.17107/KH.2016.13.284-293

BURGESS AW, MCGREGOR DM, MELLIS CM: Applying established guidelines to team-based learning programs in medical schools: a systematic review. Acad Med, 89(2014): 678-88. https://doi.org/10.1097/acm.0000000000000162

DOBY T: Discoverers of blood circulation from Aristotle to the times of Da Vinci and Harvey. London-New York-Toronto, Abelard-Schuman, (1963): 141. http://dx.doi.org/10.7326/0003-4819-59-4-588_2

DOLAN B: Soul searching: a brief history of the mind/body debate in the neurosciences. Neurosurg Focus, 23(2007):E2, 1-7. http://dx.doi.org/10.3171/foc-07/07/e2

GHOSH SK: Evolution of illustrations in anatomy: a study from the classical period in Europe to modern times. Anat Sci Educ, 8(2015): 175-88. http://dx.doi.org/10.1002/ase.1479

HAPPEL CM, KLOSE C, WITTON G, ANGRISANI GL, WIENECKE S, GROOS S, BACH WF, BORMANN D, MÄNNER J, YELBUZ TM: Non-destructive, high-resolution 3-dimensional visualization of a cardiac defect in the chick embryo resembling complex heart defect in humans using micro-computed tomography: double outlet right ventricle with left juxtaposition of atrial appendages. Circulation, 122(2010): e561-e564; http://dx.doi.org/10.1161/circulationaha.110.977884

KEMP M: Style and non-style in anatomical illustration: from Renaissance Humanism to Henry Gray. J. Anat, 216(2010): 192–208. http://dx.doi.org/10.1111/j.1469-7580.2009.01181.x

KIRALY L, TOFEIG M, JHA NK, TALO H: Three-dimensional printed prototypes refine the anatomy of post-modified Norwood-1 complex aortic arch obstruction and allow presurgical simulation of the repair. Interact CardioVasc Thorac Surg, 22(2016): 238–40. http://dx.doi.org/10.1093/icvts/ivv320

MARTELLI N, SERRANO C, VAN DEN BRINK H, PINEAU J, PROGNON P, BORGET I, EL BATTI S: Advantages and disadvantages od 3-dimensional printing in surgery: a systematic review. Surgery, 159(2016): 1485-500. http://dx.doi.org/10.1016/j.surg.2015.12.017

MESHBERGER FL: An Interpretation of Michelangelo's Creation of Adam Based on Neuroanatomy. JAMA, 264(1990): 1837–41. http://dx.doi.org/10.1001/jama.1990.03450140059034

MIMICS, Materialise, Leuven: http://www.materialise.com/ (2010), retrieved on 20 September 2016.

MOSTEFA-KARA M: 3D imaging of heart specimens: a new teaching tool for understanding the anatomy of double outlet right ventricle. (2016) http://www.uni-kiel.de/aepc/aepcAbstractsFinalPrint/O4_6fin.pdf , retrieved on 16 June 2016.

MOTTL-LINK S, BOETTGER T, KRUEGER JJ, RIETDORF U, SCHNACKENBURG B, EWERT P, BERGER F, NAGEL E, MEINZER HP, JURASZEK A, KUEHNE T, WOLF I: Images in cardiovascular medicine. Cast of complex congenital heart malformation in a living patient. Circulation, 112(2005): e356–357.

MUELLER PS: Teaching and assessing professionalism in medical learners and practicing physicians. Rambam Maimonides Med J, 6(2015): http://dx.doi.org/10.5041/rmmj.10195

O'MALLEY CHD, SAUNDERS CM: Leonardo da Vinci on the Human Body. New York, Winks, (1982):11.

REALVIEWHEARTH: Surgery using 3D hologram. (2013) http://www.realviewimaging.com/?page_id=158; https://www.youtube.com/watch?v=K2XesWsL9UY, retrieved on 10 September 2016.

2016. Vol.7.No.13.
ISSN/EISSN: 20622597
DOI: 10.17107/KH.2016.13.284-293

RIFKIN BA: The art of anatomy. In RIFKIN BA, ACKERMAN MJ, FOLKENBERG J: Human anatomy. Depicting the body from the Renaissance to today. London, Thames and Hudson, (2006): 13.
RIPPA-BONATI M: Some traditions regarding the old anatomy theatre of Padua University. (2010) Archivio Antico dell'Università di Padova, Atti dell'Università Artista, Raccolta Minato vol. 28, c. 113r. http://www.unipd.it/esterni/visiteweb/english/pagine/teatro.htm; retrieved 6 May 2016.
RØSSTAD A: Leonardo da Vinci – a dyslectic genius? Tidsskr Nor Laegeforen, 122(2002):2887-90.
SCHIEVANO S, MIGLIAVACCA F, COATS L, KHAMBADKONE S, CARMINATI M, WILSON N, DEANFIELD JE, BONHOEFFER P, TAYLOR AM: Percutaneous pulmonary valve implantation based on rapid prototyping of right ventricular outflow tract and pulmonary trunk from MR data. Radiology, 242(2007): 490-7. http://dx.doi.org/10.1148/radiol.2422051994
SCHMAUSS D, HAEBERLE S, HAGL C, SODIAN R. Three-dimensional printing in cardiac surgery and interventional cardiology: a single-centre experience. Eur J Cardiothorac Surg, 47(2015): 1044-52. http://dx.doi.org/10.1093/ejcts/ezu310
SHIRAISHI I, YAMAGISHI M, HAMAOKA K, FUKUZAWA M, YAGIHARA T: Simulative operation on congenital heart disease using rubber-like urethane stereolithographic biomodels based on 3D datasets of multislice computed tomography. Eur J Cardiothorac Surg, 37(2010):302-6. http://dx.doi.org/10.1016/j.ejcts.2009.07.046
SIR WILLIAM WITHEY GULL: Famous medical quotes. http://izquotes.com/quote/297534; retrieved on 10 January 2015.
SMITH R: All changed, changed utterly. British medicine will be transformed by the Bristol case. BMJ, 316(1998): 1917–8. http://dx.doi.org/10.1136/bmj.316.7149.1917
SUK I, TAMARGO RJ: Concealed neuroanatomy in Michelangelo's separation of light from darkness in the Sistine Chapel. Neurosurgery, 66(2010): 851–861. http://dx.doi.org/10.1227/01.neu.0000368101.34523.e1
TOLNAY, de C: The art and thought of Michelangelo. New York, Pantheon Books, (1964): 111.
WELLS FC, CROWE T: Leonardo da Vinci as a paradigm for modern clinical research. J Thorac Cardiovasc Surg, 127(2004): 929-44. http://dx.doi.org/10.1016/j.jtcvs.2004.02.002
WREN C, O'SULLIVAN JJ: Survival with congenital heart disease and need for follow up in adult life. Heart, 85(2001): 438-443. http://dx.doi.org/10.1136/heart.85.4.438
ZWIJNENBERG R. The writings and drawings of Leonardo da Vinci: order and chaos in early modern thought. Cambridge, Cambridge University Press, (1999): 64.