3D modeling of the vascular system

JF Uhl[*], M Chahim[*], F Cros[**], A Ouchene[**]

[*] URDIA research unit EA4465 (Paris cité Sorbonne University)

[**] Service de Biophysique, Laboratoires Innothera, Arcueil, France

Corresponding author: Prof. Jean François Uhl, jef.uhl@gmail.com

Abstract The 3D modeling of the vascular system could be achieved in different ways: In the **venous location**, the morphological modeling by MSCT venography is used to image the **venous system**: this morphological modeling tool accurately investigates the 3D morphology of the venous network of our patients with chronic venous disease. It is also a fine educational tool for students who learn venous anatomy, the most complex of the human body. Another kind of modeling (mathematical modeling) is used to simulate the venous functions, and virtually tests the efficacy of any proposed treatments. To image the **arterial system**, the aim of 3D modeling is to precisely assess and quantify the arterial morphology. The use of augmented reality before an endovascular procedure allows pre-treatment simulation, assisting in pre-operative planning as well as surgical training. In the special field of **liver surgery**, several 3D modeling software products are available for computer simulations and training purposes and augmented reality.

Keywords 3D reconstruction, vascular modeling, Multislice CT, Angio-CT, Volume rendering (VRT), vectorial modeling, Virtual reality, Simulation, Surgical training, Augmented reality, Educational anatomy

What is vascular modeling and why would we use it? Vascular modeling is a new tool which enhances the knowledge of anatomy and physiology of the vascular system and simplifies the planning of vascular interventions.

Different modalities of vascular modeling

1 - *When considering the VENOUS SYSTEM* the 3D modeling could have several objective:

1.1 The morphological modeling is used for

1.1.1 **Investigation by multislice CT venography** (MSCTV) of patients with chronic venous disease[1-8].

This modeling is very useful in cases of recurrent varicose veins after surgery, especially in the popliteal fossa, in patients with complex venous anatomy and with venous malformations. In all such cases it is essential to obtain additional venous hemodynamic mapping[9] by color Duplex Ultrasound.

But MSCTV provides more accurate morphological 3D information on the whole venous network, in particular of the deep system. Hence we think that MSCTV should be considered as a powerful navigator for varicose vein surgery, providing a complementary road-map for surgery[9,10]. For this purpose, 3D reconstruction is achieved by the means of a volume rendering technique (VRT) with the help of Osirix® software[11].

1.1.2 **For educational venous anatomy**:

3D modeling is a fine educational tool for the students who want to learn venous anatomy, the most complex of the human body[5]. It has a number of applications in the field of morphological sciences, in addition to the classical techniques of anatomical dissection. It is also a new and powerful research tool[6]. In order to develop these new tools and to create partnerships between Universities, we have created in 2015 with Pr Vincent DELMAS (chairman) a UNESCO chair of digital anatomy. For more information see the website: http://www.anatomieunesco.org/. In fact, the best way to build these 3D anatomical databases is by experts in anatomy, not computer graphics.

For this purpose, an anatomical segmentation is necessary before building the 3D vectorial models. This is done with the help of dedicated software programs[12,13] The aim is to build interactive computer atlases of the human body, in particular by the use of anatomical slices[14,15].

The handling of theses realistic 3D models provides a new educational tool for students: the virtual dissection table[16].

For the daily practice of phlebologists and surgeons, Interactive 3D venous atlases are particularly useful in understanding the complexity of venous anatomy, and the huge number of anatomical variations. In practice, improvement of our anatomical knowledge will improve the quality of our venous maps, which is the keystone of decision making and treatment guidelines[9].

1.1.3 Modeling for simulation in liver surgery:

3D modeling of the vessels and reconstruction of the liver segmentation[19] is soon to be introduced into selected surgical disciplines, in particular hepatic surgery

The *aim of* 3D modeling of the liver includes computerized simulations for training purposes, and augmented reality[17,18].

These new computer tools interact with medical images for surgical planning[19,20] and training, to assess surgeons' fitness to practice. 3D models may also guide micro-robots undertaking minimally invasive liver or abdominal interventions.

1.2 Mathematical modeling of the venous system has a totally different objective: to simulate the global venous function[21,23], in order to virtually assess the benefits of proposed treatments[24,25] of the chronic venous disease: it is a software called "venous return simulator" (VRS)

1.3 CAAD (Computer Assisted Anatomical Dissection) is a new research tool enabling a 3D reconstruction of the human embryo's venous system. This technique was originally used to study the anatomy of the pelvic nerves[26-31], but it is very accurate for the embryo's venous system[32-33].

2 - *When considering THE ARTERIAL SYSTEM*;

3D modeling is used to precisely assess and quantify the arterial morphology, particularly the use of augmented reality before endovascular procedures[34,35] Semi-automatic vessel segmentation is now possible with special software packages[36,37]. This provides (makes possible) a simulation of endovascular surgery, aids in pre-operative planning and surgical training[38] and allows for a rehearsal before operations[39].

The Techniques of vascular modeling

1 - <u>Morphological modeling of the vascular tree</u>:

Two different techniques are available for 3D reconstruction: Volume rendering (also called VRT) and vectorial modeling (also called surface rendering)

1.1 - <u>Volume rendering or VRT</u> (using digital data from multislice CT-venography[1-8])

The main steps of direct Volume Rendering (VRT) technique[1-3] are data acquisition, reconstruction, and post-processing: (Figure 1)

Data acquisition: A multislice and multidetector CT scan (64 and now 128 detectors) is used, producing 600 to 1200 slices by series over about 30 seconds.(see Table I for detailed protocol).

The timing of injection is critical: The contrast injection should begin about 40-60 seconds before, and then has to be synchronized with, the acquisition, in order that it finishes at the end of the acquisition.

The patient is lying supine (on his/her back, feet first), with no contact point with the table except for the buttocks and heels: It is important to avoid any compression of the calf and posterior thigh during acquisition time. The patient has to hold perfectly still during this short time and is often asked to do a Valsalva maneuver.
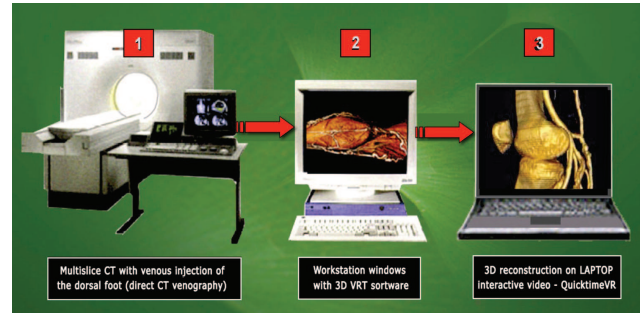

Figure 1 - The 3 main steps of the technique of direct multislice CT venography (MSCTV). 1 - Multislice CT with injection of the dorsal foot (direct CT venography). 2 - Workstation windows with 3D VRT software. 3 - 3D reconstruction on LAPTOP, Interactive video QuickTimeVR.

PROTOCOLS	ACQUISITION	RECONSTRUCTION	POST-PROCESSING	CONTRAST INJECTION
16 Detectors CT : 600 slices in 25 sec	120 kV 150 mAs slice collimation : 16 x 1.5 mm field 512 F.O.V 380 mm	slice width 2 mm slice increment 1.5 mm filter B30 matrix 512x512 zoom factor 1.7	Volume rendering (VRT) fast & automatic with tissues transparencies	- Medrad MSCT injector system. - single-phase injection 20 ml of iodine contrast medium in 180 ml of serum.
64 Detectors MSCT 1000 slices in 20 sec	120 kV 150 mAs	slice width 1 mm slice increment 0.75 mm matrix 512x512 zoom factor 1.7	VRT	- puncture of a vein of the dorsal foot or scarcely the varices of the thigh.
128 Detectors MSCT 1000 slices in 10 sec	100 kVp. slice collimation of 128 × 0.6 mm	Rotation time 300 ms using a continuous helical scan mindose® technique pitch =0.16-0.22	VRT with PC using multi processors Osirix® using fast graphic card	Proximal injection & biphasic injection to visualize pelvic veins.

Table I - Multislice CT protocols. CT=computed tomography MSCT=multislice CT FOV=field of view VRT=volume rendering.

Data reconstruction: Raw data are processed to perform slices reconstruction. See usual protocols on Table I, from 16 to 128 detectors.

Post-processing of the data: 3D reconstruction of the venous system is performed. The data are usually sent by intranet on a dedicated workstation for post-processing using dedicated 3D reconstruction software. Then, the 3D interactive movies could be exported to a laptop.

The principle of VRT technique is to use a look-up table (LUT) establishing a correspondence between the levels of density and the colors (figure 2). A threshold selection makes it possible to isolate some

anatomical elements according to their specific density: skin, adipose tissue, muscles, vessels (injected) and bones.
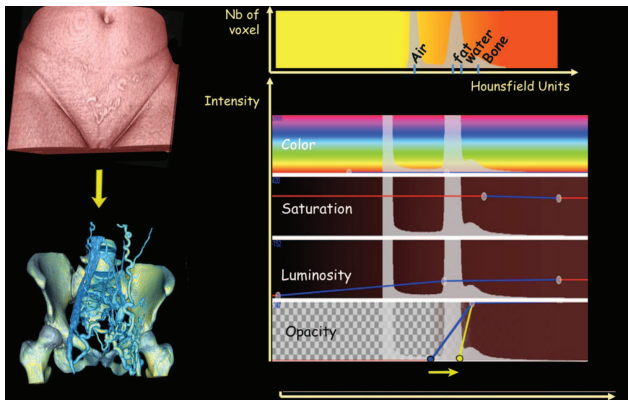

Figure 2 - The principle of Volume rendering technique (VRT) is to select a threshold in order to select a sample of densities in the histogram corresponding to specific anatomical structures. See the arrow on the right modifying the opacity, which makes the skin and muscles transparent (lower image on the left).
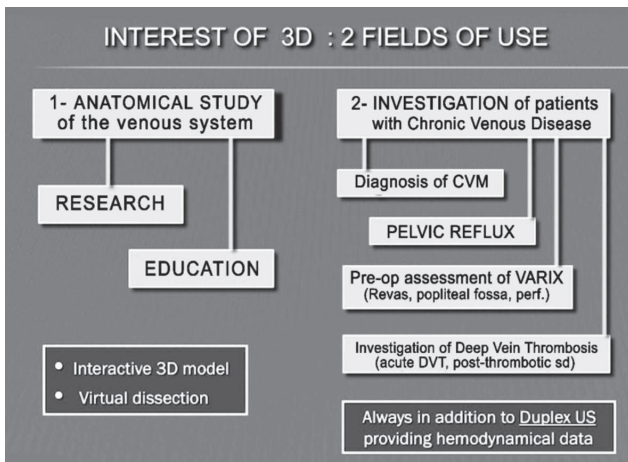

Figure 3 - The 2 fields of use of 3D modeling of the venous system by MSCTV.

Dedicated software can produce a realistic 3D reconstruction of the anatomy: Osirix® for mac computer[11] - Volume wizard, Syngo VRT (Siemens), Voluson 4Dview (GE), Philips, Infinix-i Volume Navigation (Toshiba).

Advantages of VRT are automatic and quick 3D reconstruction with threshold presets and automated vessel segmentation, but it needs powerful computers to handle the huge data sets.

Main indications of MSCTV[3,4] in the chronic venous disease (CVD) are shown on figure 3.

Results[5,8]: an example of 3D reconstruction of the venous network in the case of a patient suffering from pelvic venous reflux (Figure 4)

Figure 4 - CT-venography with 3D reconstruction by VRT. This woman has a pelvic reflux from the obturator vein (6) and a pseudo May-Turner syndrome (2). 1= inferior vena cava 2=imprint of the right common iliac artery 3= internal iliac vein 4=inferior gluteal vein 5=left common femoral vein 6=obturator vein 7=posterior circumflex vein 8=sacral plexus.

1.2 - Vectorial modeling[6] (surface rendering with ray-tracing)

For this we can use analogic data (for example anatomical slices), but a segmentation (by manual or semi-automatic) of the anatomical structures is required.

-Winsurf® software[12] (previously named Surfdriver) could be used to build the vectorial model. An example is given of the software screen during anatomical segmentation of the liver (Figure 5).

-Segmentation with Photoshop® and then use of Mimics® software (http://biomedical.materialise.com) has been used by the team of the Korean Visible man (http://vkh.ajou.ac.kr/#vk)

-Model display uses special CAD software (3Dstudio max® , Cinema4Dxl® , Autocad® , Amira® , Blender® , Maya® …)

-Conversion from winsurf® into Acrobat® 3Dpdf file format[13] enables interactive manipulation of 3D anatomical models.

-Results: creation of educational interactive atlases of anatomy and simulation.

This leads to the use of an interactive virtual dissection table: a computerized table lets the students easily do virtual dissections of the human body. It is a powerful tool for training medical students: a stretcher-sized multi-touch screen of the human body that lets you explore, dissect and understand the body's parts and systems.
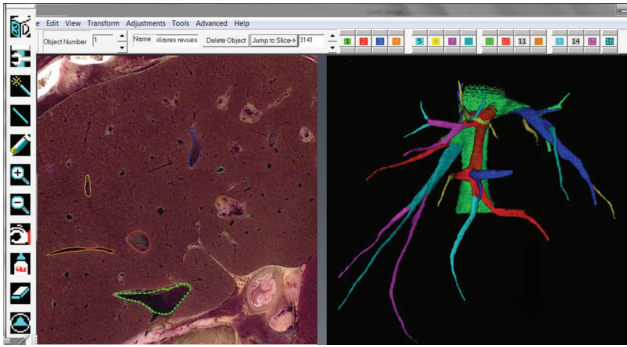
*Figure 5 - Interface window of the **Winsurf® software** showing the colored segmentation of the hepatic veins on the anatomical slice (Korean visible human) using the color channels. The resulting 3d vectorial model is shown on the right (including color channels).*

While Anatomage® (www.Anatomage.com) uses an expensive device and sophisticated software, the virtual dissection could also be achieved with a big touch screen running with Acrobat® 3dpdf models in a simple way[13] (figure 6). The big advantage is that the Acrobat® reader software is available for free on any computer.
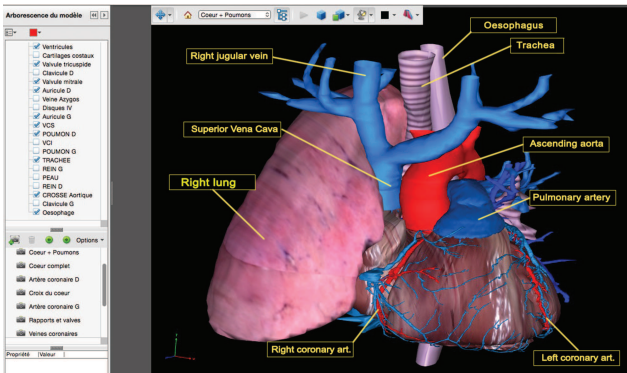

*Figure 6 - Interface window of **the Acrobat® reader software** showing the final 3D model of the heart and lungs which could be handled interactively with the labels. Each anatomical structure (on the left) could be displayed separately.*

1.3 - Vascular modeling for LIVER SURGERY has several useful applications:

-Surgical planning in hepatic surgery[14]

-Augmented reality for minimally invasive liver surgery[15]

-Planning of liver surgery for hepatocellular carcinoma (Figure 7)

-Hepatic transplantation planning.

-Visible patient planning (IRCAD) (Appstore for ipad, iphone)

-VP Planning is a computer software for Mac and PC to help surgical planning (https://www.visiblepatient.com/fr/)
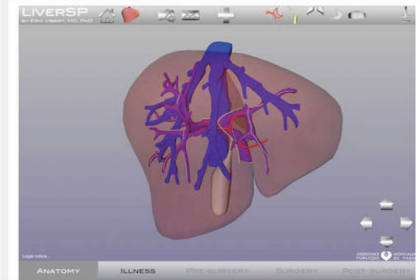

*Figure 7 - Description of **the ipad software "Liver surgery planner®"** (Dr Eric Viber, Paul Brousse hospital, Villejuif).*

2 - Mathematical 3D modeling of the venous network for simulation[16-19]. The aim is to build a virtual model, the venous return simulator[16] (VRS), designed to compute the venous hemodynamic variations when a compression device is applied on the leg.

The Venous return simulator (VRS) is a software package designed to simulate the venous hemodynamic parameters of the lower limbs. It is a virtual (digital) network of the lower extremity that computes in static and dynamic conditions the different variables (flow rate, venous diameter and internal pressure) for a defined external pressure.

It is a mathematical model solving the equations that govern the blood flow, applied to the venous network of the lower limbs.

For this purpose, a simplified model of the venous network is used. (figure 8)

The software takes into account the length and caliber of the veins, their distensibility, the blood viscosity, the valvular function (normal or pathological), the position and activity of the subject (standing, walking, lying) and the external pressure applied to the veins: muscular contraction, wearing of a medical compression stocking.

As a result, the software gives you the caliber, pressure and flow rate for any point of the virtual network.

The setting of the parameters was based on physiological data from the literature and the validation of the VRS software was published17 showing that the distal venous pressure at rest and during exercise are similar to the real pressures measured in vivo on healthy subjects and in different cases of valvular incompetence.

Hence, VRS could be considered as a reliable tool for simulation.

It has been used to assess the effect of the medical compression stockings on the venous return. A study has shown the impact of different levels of compression on (the) distal saphenous vein reflux. Another study was done to simulate the venous edema[19].

In the future, VRS could also be used to predict the hemodynamic consequences of venous surgery and other venous interventions. …
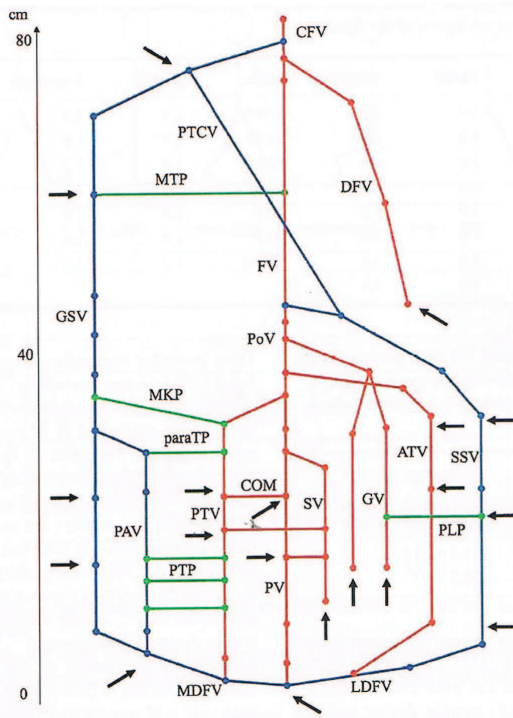

Figure 8 - Two-dimensional representation of the lower limbs venous network used in the model of the **VRS simulation software**[®]. The deep veins are in red, the superficial in blue and the perforators in green. CFV=common femoral vein DFV=deep femoral vein PoV=popliteal vein G=Giacomini PTV=posterior tibial ATV=anterior tibial GV=gastrocnemius vein SV= soleus muscle MDFV=medial dorsal foot LDFV=lateral dorsal foot COM=perforators MTV=medial thigh perforator MKP=medial knee perforator paraTP=paratibial perforator PTP=tibial posterior perforator PLP=posterior leg perforator.

3 - CAAD (Computer Assisted Anatomical Dissection):

Classical anatomical study methods have limitations regarding the micro-anatomy of the location of vessels and nerves. The combination of immuno-histochemical methods and three-dimensional reconstruction could be used to resolve these limitations of morphological sciences.

The technique of computer assisted anatomical dissection (CAAD) is an original method applied in morphological science.

Originally created by Yucel[20,21] to describe the topography of the perineal nerves, the CAAD was first applied in our URDIA research unit by Karam et al. to study the distribution of the nerves of urethra[22,23] and intra-pelvic nerves[24,25], and then also for the whole reconstruction of young human embryo lower limbs[26,27].
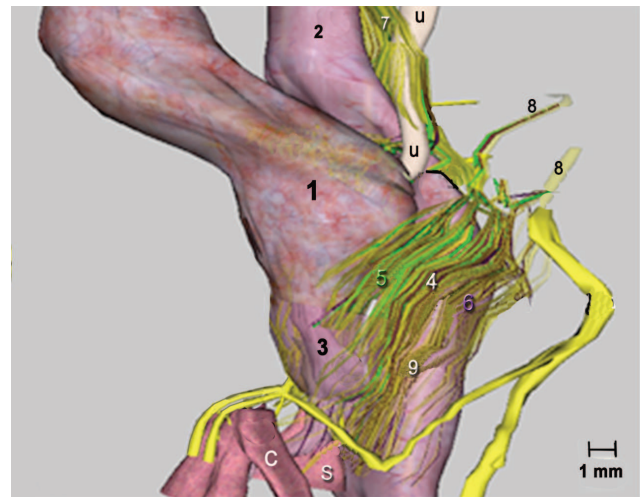

Figure 9 - **Computer-assisted anatomic dissection** of 17-week-old male human fetal pelvis, Lateral view of the **inferior hypogastric plexus (4)**, adrenergic fibers (5) in green and cholinergic fibers (6) in purple, hypogastric nerves (7) and pelvic splanchnic nerves (8) contain both fibers' types, adrenergic fibers mostly situated in the superior portion of the plexus, cholinergic fibers intend to concentrate in inferior portion. 1=bladder 2=Rectum 3=Prostate C=Corpus Cavernosum S= Corpus Spongiosum u=ureter, 9= Cavernous Nerve.

Material and methods:

Serially transverse sections of the embryos' pelvic portion and lower limbs were serially immune-histochemically treated and digitized with high optical resolution scanner. The nerves were stained by Protein S100 immune marker and vessels by D240. The sections were aligned with Photoshop[®] software then a tridimensional reconstruction was achieved by manual segmentation of the anatomical structures using the WinSurf[®] software version 3.5.

Results: This produced a realistic 3D vectorial model of the pelvis and lower limb.

Regarding the pelvis, the three-dimensional reconstruction of serial histological sections stained by immune markers allowed identifying the precise structure and the innervations of the whole intra-pelvic organs with demonstration of the precise location of both adrenergic and cholinergic pathways[24,25]. A virtual dissection could be performed for each of the pelvic structures. We could describe the precise location of the inferior hypogastric plexus as well as the nature and the distribution of its fibers. (figure 9)

The evolution of CAAD confirmed and clarified topographic and surgical anatomy of the intra-pelvic innervations. This technique represents an original method in anatomical research and a great educational tool for surgeons in order to better understand the anatomy of an inaccessible region by conventional techniques.

Regarding the lower limbs, the 3D reconstruction of the whole limbs produces a virtual dissection of the muscles, nerves, vessels which is a precious tool to study the embryogenesis of the nervous and vascular system of the human embryo[26] (figure 10), especially of the venous network. In fact, today, there is no direct observation showing the different steps of the venous organogenesis of the human embryo.
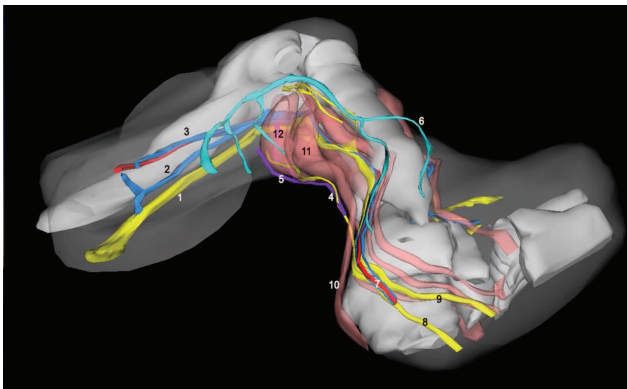

Figure 10 - Three-dimensional reconstruction of a 14 weeks old fetal left lower limb: 1 sciatic nerve, 2 axial vein, 3 femoral vein and artery, 4 sural nerve, 5 small saphenous vein, 6 great saphenous vein, 7 posterior tibial vessels, 8 lateral tibial nerve, 9 medial tibial nerve, 10 Achilles tendon, 11 soleus muscle, 12 medial gastrocnemius muscle.

4 - 3D modeling of the arterial system:

The main use of *3D reconstruction of the arteries* since years is the investigation of 3D arterial reconstruction using CT angiography has traditionally been used for patients suffering peripheral arterial disease. Additional color duplex assessment may better evaluate arterial lesions by quantifying flow in areas of stenosis or dilatation, enabling better choice of treatment options.

More recently, a new field of application of 3D arterial modeling appeared with the onset of endovascular procedures and minimally invasive surgical techniques[28].

New algorithms were developed to improve the quality of the 3D reconstruction and shorten the computing time.

Software's providing functions of segmentation and simulation:

Mevislab is a medical Image Processing and Visualization modular framework downloadable for free at www.mevislab.de. It represents a powerful tool for image processing research and development with a special focus on medical imaging. It allows fast integration and testing of new algorithms and the development of clinical application prototypes.

Vascular modeling tool kit software package[30] (VMTK www.vmtk.org) is a collection of libraries and tools for 3D reconstruction, geometric analysis, mesh generation and surface data analysis for image-based modeling of blood vessels.

3D modeling is a kind of revolution in the management of vascular disease . It is a fantastic new tool which greatly assists the surgeon in surgical planning, simulation, training and augmented reality[29].

Surgical planning

By the use of dedicated simulation software, the preparation for an endovascular procedure is enhanced : it uses the patient's specific CT data the day before operation, and then performs a procedure rehearsal, which is reproducible and reliable.

Simulation and training of endovascular procedures is in fact a new paradigm for vascular trainees. Endovascular simulation improves the quantitative and qualitative performance of general surgery residents performing diagnostic angiography, in a randomized-controlled study[30] (Chaer al. 2006)

Endovascular Simulation has also proved its efficiency and competence in Thoracic Endo-Vascular Aortic Repair (TEVAR) Procedures[31]. Several options of simulation stations and tearing modules are proposed on the internet (endovascular knowledge blog at www.mentice.com)

Augmented reality[32] for minimally invasive and endoscopic surgery. The new technological advances in

optics, instrumentation, robotics, and computer systems provide the surgeon with new possibilities and capabilities : augmented reality technologies now provide guidance and navigation during surgical procedures. In addition, robotic devices[33] can enhance the surgeon's' capabilities in terms of dexterity and accuracy.

Finally, customization of vascular stents has been achieved, in particular for aorta. The customized aortic stent grafts are patient-specific in that they conform to the part of the ascending aorta, aortic arch and/or thoracic aorta. The 3D model of the vascular endoprothesis is based on a 3D image of the patient's anatomy. (patents filed in 2013 : <u>EP2903561A1</u>, <u>US20150209162</u>)

Conclusions

The 3dD modeling of vessels has recently brought us a revolution in the diagnosis and treatment of the vascular diseases:

For veins, the CT venography is a new mapping tool in addition to color duplex ultrasound.

For arteries, it is a true revolution for vascular & endovascular treatments, for surgical planning, training and augmented reality techniques.

It is also a remarkable learning tool for the whole of human anatomy.

References

1) Uhl JF, Gillot C, Verdeille S, Martin-Bouyer Y, Mugel T. Three dimensional CT-Venography: a promising tool to investigate the venous system. Phlebolymphology 2002;38:74-80.

2) Uhl JF, Verdeille S, Martin-Bouyer Y. Three-dimensional spiral CT venography for the pre-operative assessment of varicose patients. VASA 2003;32(2):91-94.

3) Uhl JF, Verdeille S, Martin-Bouyer Y. Pre-operative assessment of varicose patients by veno-CT with 3D reconstruction 3rd International workshop on multislice CT 3D imaging. Springer Verlag Ed Pavone, Debatin (2003) p 51-53.

4) Uhl JF, Caggiati A. In Catalano C, Passariello R. 3D evaluation of the venous system in varicose limbs by multidetector spiral CT Multidetector row CT angiography. (Eds.) Springer 2005 p 199-206.

5) Uhl JF, Gillot C. Embryology and three-dimensional anatomy of the superficial venous system of the lower limbs. Phlebology 2007;22(5):194-206.

6) UHL JF, Plaisant O, Ami O, Delmas V. La modélisation 3D en morphologie: méthodes, interêt et résultats. Morphologie 2006;90:5-20.

7) Uhl JF, Ordureau S. The new computer tools of virtual dissection to study anatomy of the vascular system. Phlebolymphology 2008;15(4):151-55.

8) Uhl JF, Chahim M, Verdeille S, Martin-Bouyer Y. The 3D modeling of the venous system by MSCT venography (CTV): technique, indications and results. Phlebology 2012 ;27:270-288.

9) Uhl JF. The new strategies for the varicose veins surgery (in French) E-mémoires de l'Académie Nationale de Chirurgie, 2009;8(1):12-22.

10) Min SK, Kim SY, Park YJ, Lee W, Jung IM, Lee T, Ha J, Kim SJ. Role of three-dimensional computed tomography venography as a powerful navigator for varicose vein surgery. J Vasc Surg. 2010 Apr;51(4):893-9.

11) Rosset A, Spadola L, Ratib O. OsiriX: An Open-Source Software for Navigating in Multidimensional DICOM Images. Journal of Digital Imaging 2004;17:205-216.

12) Moody D, Lozanoff S. Surfdriver: A practical computer program for generating three-dimensional models of anatomical structures. 14th Annual Meeting of the American Ass. of Clinical Anatomists, July 8-11, 1997. Honolulu, Hawai'i.

13) Dong Sun Shin, Min Suk Chung, Jin Seo Park et al. Portable Document Format File showing the surface models of cadaver whole body. J Korean Med Sci 2012;27:849-856.

14) Soler L, Delingette H, Malandain G et al . An automatic virtual patient reconstruction from CT-scans for hepatic surgical planning. Stud Health Technol Inform 2000;70:316-322.

15) Marescaux J. Augmented reality for minimally invasive liver surgery (VR-planning). Journal of Gastroenterology and Hepatology Research 2013;2(5): 555-560.

16) Fullana J-M, Cros F, Becker F, Ouchene A, Partsch H. The venous return simulator: an effective tool for investigating the effects of external compression on the venous hemodynamics - first results after thigh compression. Vasa 2005;34:19-23. DOI: 10.1024/0301-1526.34.1.19.

17) Chauveau M, Gelade, Cros. The venous return simulator: comparison of simulated with measured ambulatory venous pressure in normal subjects and in venous valve incompetence. Vasa 2011;40:205-217.

18) Chauveau et al. Taille des bas de compression médicale et hémodynamique veineuse. Quelles sont les conséquences d'une taille mal adaptée ? Les produits de série de classe 2 proposés par les fabricants français sont-ils adaptés à la population ? Phlébologie, 2011;64(4):1-8.

19) Chauveau M, Fullana J-M, Gelade P, Vicaut E. Flaud P. Simulation numérique de l'oedème veinolymphatique et des effets de la compression. Journal des maladies vasculaires 2011;36(1):9-15.

20) Yucel S, Baskin LS. Neuroanatomy of the male urethra and perineum. BJU international 2003;92:624-630.

21) Yucel S, Baskin LS. Identification of communicating branches among the dorsal, perineal and cavernous nerves of the penis. J Urol 2003;170(1):153-158.

22) Karam I, Droupy S, Abd-Alsamad I et al. The precise location and nature of the nerves to the male human urethra: histological and immune-histochemical studies with threedimensional reconstruction. Eur Urol (2005) 48(5):858-864.

23) Karam I, Droupy S, Abd-Alsamad I et al. Innervation of the female human urethral sphincter: 3D reconstruction of immune-histochemical studies in the fetus. Eur Urol (2005) 47(5):627-633.

24) Alsaid B, Bessede T, Diallo D, Karam I, Uhl J-F, DelmasV, Droupy S, Benoit G. Computer-assisted anatomic dissection (CAAD): evolution, methodology and application in intra-pelvic innervation study. Surg Radiol Anat October 2012;34(8): 721-729.

25) Balaya V, Uhl JF, Lanore A. et al. Three-dimensional modeling of the female pelvis by Computer-Assisted Anatomical Dissection: Applications and perspectives. J Gynecol Obstet Biol Reprod (Paris). 2016 Feb.

26) Kurobe N, Hakkakian L, Chahim M, Delmas V, Vekemans M, Uhl JF. Three-dimensional reconstruction of the lower limb's venous system in human fetuses using the computer-assisted anatomical dissection (CAAD) technique. SRA 2014 DOI: 10.1007/s00276-014-1350-2.

27) Uhl JF. Focus on embryogenesis of the venous system of the lower limbs. Phlebolymphology 2015;22(2):55-62.

28) Willaert WIM, Aggarwal R, Nestel DF et al. Patient specific simulation for endovascular procedures: qualitative evaluation of the development process. Int J. Med robotics comput assist surg 2010;6:202-10.

29) Rudarakanchana N, Van Herzeele I, Desender L, Cheshire NJ. Virtual reality simulation for the optimization of endovascular procedures: current perspectives. Vascular Health and Risk Management 2015:11 195-202.

30) Chaer R, DeRubertis BG, Lin S et al. Simulation Improves Resident Performance in Catheter-Based Intervention: Results of a Randomized, Controlled Study. Annals of Surgery 2006; 244(3):343-352.

31) Kendrick DE, Gosling AF, Nagavalli A, Kashya VS and Wang JC. Endovascular Simulation Leads to Efficiency and Competence in Thoracic Endovascular Aortic Repair Procedures. Journal of Surgical Education 2015.

32) Lamata P, Ali W, Cano A et al. Augmented Reality for Minimally Invasive Surgery: Overview and Some Recent Advances. In Soha Maad (Ed),Augmented Reality, ISBN 978-953-7619-69-5, pp. 230, January 2010, INTECH, Croatia, downloaded at www.intechopen.com.

33) Antoniou G.A, Riga CV, Mayer EK. Clinical applications of robotic technology in vascular and endovascular surgery. J Vasc Surg 2011;53:493-9.