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3D Printed Model of Human Anatomy for Training Nursing Students: Skeletal, Respiratory and Circulatory Systems

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Abstract

This paper presents the development of a full-scale, realistic 3D printed model of the human anatomy for training nursing students using simulation based learning experiences (SBLEs). SBLEs are structured activities that represent actual or potential situations in nursing practice. These activities allow nursing students to develop knowledge and skills to analyze and respond to realistic situations in a simulated environment. The 3D printed model of the human body is currently being integrated into several SBLEs in the College of Nursing at UAH. The 3D printed model of the human body includes rib cage, spine, pelvis, clavicles, scapulas, lungs, trachea, heart and aorta. Various diameters of silicone rubber cord were used to simulate the pulmonary arteries and veins to the lungs. The left subclavian branch and the brachiocephalic trunk were designed using CAD and 3D printed. Assembly issues were many including stiffness of organs causing excessive voids, maintaining full scale organs, fastening organs in correct locations and fusing silicone rubber cord to the 3D printed models. Small sleeves were designed using CAD and 3D printed for connecting the silicone rubber cord and as supports for fusing the PLA.

Keywords: 3D printed models, human body, lungs, heart, aorta.

1. Introduction

3D printing is increasingly being used in healthcare and especially in healthcare education. Michalski and Ross (2014) call it "the shape of things to come." Detailed 3D printed models are being made of the organs of the human body as an alternative to cadaveric dissection in teaching anatomy (Yuen, 2020).

The Systems Management and Production Center at The University of Alabama in Huntsville (UAH) has been working closely with the College of Nursing (CoN) in developing 3D printed models for teaching anatomy. The next logical step was to assemble these various models of the human anatomy into one model of the human body.

A two phase approach has been developed for constructing the 3D printed model. The objective of Phase I (discussed in this paper) was to develop a 3D printed model of the human anatomy that included the skeletal system, respiratory system and circulatory system. Specific elements of the model were spine, pelvis, rib cage, clavicles, scapulas, lungs and trachea, heart, aortic arch and the major arteries. Principle design goals were realism, correct location and size of organs and addition of major arteries. The end use of the 3D printed model will be the integration into the simulation based learning experiences (SBLEs) for training nursing students in the College of Nursing at.

Phase II will consist of adding the following organs to the 3D printed model of the human body: liver, stomach, kidneys, gallbladder, spleen, pancreas, intestines and bladder.

Section 2 briefly discusses augmented reality and an overview of the human body. Section 3 discusses the 3D printed models of the skeletal, respiratory and circulatory systems. Section 4 presents the completed 3D model of the body along with the arteries supplying blood from the heart to the lungs and other locations. Section 5 summarizes the feedback from the nursing faculty, the lung and heart trainer that has resulted from the nursing feedback and the integration of the model into the College of Nursing's student training.

2. State of the Art

Two recent and novel advances in healthcare education are the Anatomage Table and augmented reality (AR). The Anatomage Table (Fenske, 2020) is an interactive anatomy and physiology learning approach through virtual dissection. The virtual dissection table is a fully segmented human 3D anatomy system. Students can see the anatomy exactly as they would on a cadaver and can stuy human arterial, vascular, muscular, and nervous and vein systems, as well as organs and bones. This technology is resulting in a debate over the need for cadavers. A dissection table can cost over $70,000. However, just one cadaver can cost over $20,000 and requires costly ventilation systems (Hawryluk, 2020).

Augmented reality consists of superimposing computer generated content over a live view of the world. AR apps overlay digital information and audio onto human body structures (such as 3D printed models) in real time to assist students to learn names of bones and arteries. AR is becoming more accessible and affordable for medical education and nursing education.

An example of a very elementary and inexpensive application of AR is the Virtual Tee (Curiscope, 2021) that allows students to explore the circulatory, respiratory and digestive systems with fully immersive 360 video. An app is downloaded and the mobile device camera is focused on a set of QR (quick response) codes on a tee-shirt. By tapping the screen the student can peel back layers of the body. The app even works in a selfie mode. The Virtual Tee sells for less than $50.

Figure 1 is an overview of the human body and includes the major organs (Villa-Forte, 2019). The respiratory system brings air into and out of the lungs to absorb oxygen and remove carbon dioxide. The circulatory system circulates blood around the body via the heart, arteries and veins. The digestive system breaks down food into smaller and smaller components until it can be absorbed and assimilated into the body. The excretory system removes excess and unnecessary materials from body fluids. The urinary system (urinary tract) is the body's drainage system for the eventual removal of urine.

The thorax, or chest, is the part of the body between the neck and the abdomen and contains the organs of the circulation and respiration systems, namely the lungs and heart. The abdomen (belly) is the body space between the thorax and pelvis. The abdomen contains the organs of the digestive system and urinary system, namely the stomach, liver, gallbladder, pancreas, spleen, small and large intestines.

The diaphragm is a thin sheet of muscle that separates the thorax from the abdomen and performs an important function in respiration (Figure 1). As the diaphragm contracts the volume of the thoracic cavity increases and creates a negative pressure which draws air into the lungs (Alila Medical Media, 2021).

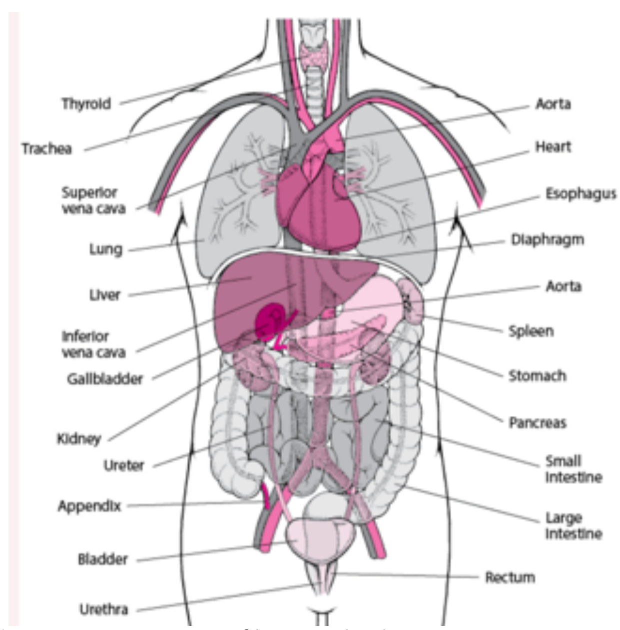

Figure 1. Front view of human body.

3. Materials and Methods

Phase I of this project consisted of starting with a 3D printed model of the spine/chest/pelvis as the frame and then placing the 3D printed models of the lungs and heart in the correct locations within the frame. All the models were originally made from CT (computed tomography) scans and converted to STL (stereolithography) files for 3D printing.

The following fused deposition modeling (FDM) 3D printers were used in the project: Prusa-i3 MK3S and MakerBot-Replicator+. The approximate print times were 18 hours for half of the ribs T1-T11, 12 hours for heart and 18 hours for one lung.

Two types of filament were used to print the models. The PLA (polylactic) filament was used for the spine/chest/pelvis model and selected organs that required rigidity. The TPU (thermoplastic polyurethane) filament was used for the organs and parts that required flexibility.

Silicone rubber o-ring cord was used extensively for simulating the arteries. The cord comes in a variety of diameters from 4-20mm. An adhesive was located for bonding the silicone rubber cord. However, the adhesive had a tendency to break loose where there was considerable movement in the model. Therefore, small sleeves were designed using CAD (computer assisted design) and 3D printed using PLA for connecting the silicone rubber cord to the 3D printed model. The cords were super glued into the sleeves and the sleeves then fused to the PLA filament with a soldering iron.

The following sections briefly describe the elements in Phase I of the 3D printed model of the body.

3.1. Spine/Chest/Pelvis

The STL files of the spine chest and pelvis were obtained from Embodi3D and developed by Ahmad Fares. The dimensions of the model were 34.8x17.7x59.1cm. A person with a 38 inch chest has an anterior rib cage diameter of 30cm. A 40 inch chest has a rib cage diameter of 32cm and a 42 inch chest a rib cage diameter of 34cm. Consequently, the 3D printed model represents a 42 inch chest.

Several iterations of the rib cage were printed because of the weakness of the rib connections to the vertebrae. The solution was to modify the STL file and add filament at the base of each rib for more rigidity. The "script mode" in the Blender software has a variety of sculpting tools that were used to deform and inflate potentially weak segments of the rib cage.

The original rib cage and spine model was divided into seven segments (two halves of T1-T11, two halves of T12-L3, L4 and two halves of the pelvis with L5) to fit within the print volume of the 3D printer. After 3D printing these segments were glued back together using super glue. Magnets were used to fasten the pelvis segment to the L4 vertebra.

The clavicle (collarbone) is a six inch bone that serves as a strut between the scapulas (shoulder blade) and the sternum. There are two clavicles, one on each side and rest on top of the rib cage. Each clavicle/scapulas assembly was 3D printed separately.

Figure 2 is the 3D printed model of only the spine, pelvis and rib cage. The STL file of the sternum was obtained from Embodi3D and developed by Cheick Sissoko. The clavicle/scapulas assemblies were fused to the rib cage with a soldering iron.

The STL files of the cervical spine segment and intervertebral discs were obtained from Embodi3D and developed by Fbonel. The 3D printed model of the cervical spine segment consisted of individual C1-C7 vertebrae and was fused to the thoracic T1 vertebra. Silicone rubber cord was inserted through the spinal canal to simulate the spinal cord.

3.2. Lungs

The lungs are a pair of spongy, air-filled organs that are located on either side of the thorax. Oxygen in the lungs is moved into the bloodstream and carried throughout the body. At each cell in the body oxygen is exchanged for a waste gas, carbon dioxide. The bloodstream then carries the waste gas back to the lungs where it is removed from the bloodstream and exhaled (American Lung Association, 2021). Deoxygenated blood leaves the heart through the pulmonary valves, into the pulmonary arteries and to the lungs. Oxygenated blood is returned to the heart through the pulmonary veins.

The height of a normal adult lung is 24cm during normal breathing (D'Angeles and Ryan, 2011). The trachea (windpipe) diameter is between 15-25mm and 10-12cm long. The trachea starts under the larynx (voice box) at cervical vertebra C6 and goes down behind the sternum. The trachea then divides into two bronchi tubes, one for each lung.

The STL files of the lungs and trachea were obtained from Embodi3D and developed by Selami. Figure 3 is the 3D printed model of the lungs that measured 25.0 x 22.6 x 37.6cm. This height included the trachea and larynx. The 3D printed model of only one lung measured approximately 23cm in height.

The trachea and larynx were 3D printed as separate assemblies. A soldering iron was used to fuse the bronchi tubes to the lungs. The trachea was fused to the vertebral column. Individual ribs were also fused to lungs for strengthening the overall 3D printed model.

Figure 2. 3D printed model of spine, pelvis and rib cage.

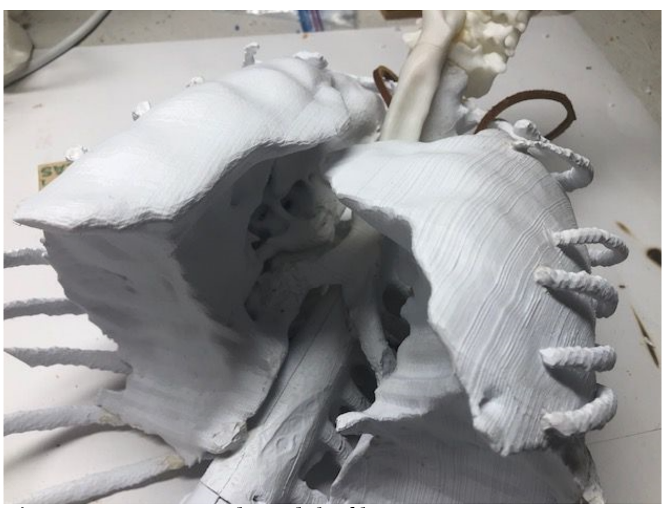

Figure 3. 3D printed model of lungs.

3.3. Heart

The heart is a muscular organ that pumps blood through the blood vessels. The blood carries oxygen and nutrients to the body while carrying waste such as carbon dioxide to the lungs. The heart is located in the middle of chest, behind and slightly to left of sternum and between the thoracic vertebrae T6-T9 when standing and between T5-T8 when sitting

The heart is a little larger than a closed fist. An adult heart is about 9cm wide at the base (widest and uppermost part), 13cm from the base to the apex (pointed lower end) and 6cm from anterior to posterior at the thickest point (Saladin, 2018). The heart weighs approximately 300g.

The STL file of the heart was obtained from Embodi3D and developed by Marco Vettorello, MD, an anesthesiologist and intensive care physician in Italy. Figure 4 is the 3D printed model of the heart that measured 8.8 x 12.1 x 8.2cm. The left and right coronary arteries that surround and supply blood to the heart were 3D printed onto the heart. The left subclavian trunk and the brachiocephalic trunk were CAD designed and 3D printed (Figure 4).

The wall thicknesses of the artery openings of the 3D printed model were thin and subject to breaking when inserting the silicone rubber arteries. Therefore, the wall thicknesses were increased by utilizing the "solidify" modifier within the Blender software on the entire heart model.

Various diameters of silicone rubber o-ring cord were used to simulate 1) the left pulmonary artery (two branches), 2) the two left pulmonary veins, 3) the right pulmonary artery (two branches) and 4) the two right pulmonary veins from the heart to the lungs. The cords kept the heart correctly positioned. Consequently, the heart floated freely in the rib cage.

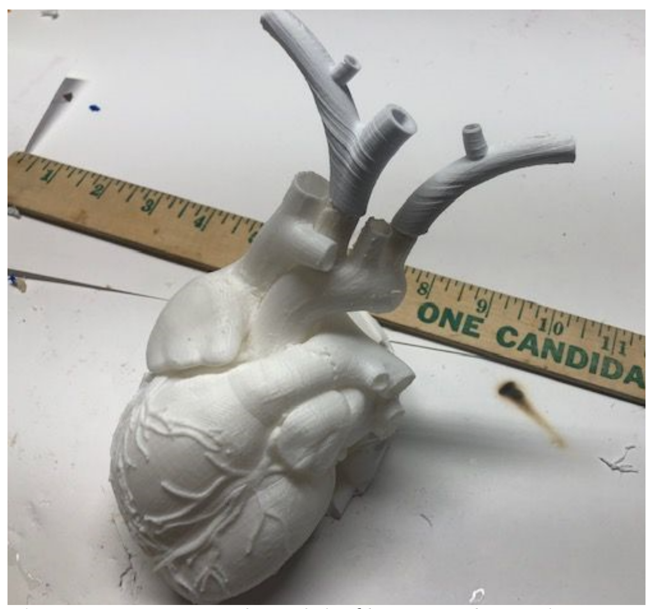

Figure 4. 3D printed model of heart with trunks.

Solid Edge CAD software was used to design a 4-10mm diameter sleeves that were 3D printed. One end of the silicone rubber was glued into a sleeve and the sleeve then fused to the interior walls of the lungs.

Some of the cord lengths for the arteries were long and had to be connected in the model to maintain correct location. In these instances the sleeves served as support for the o-ring cord. A soldering iron was used to fuse the sleeves to the 3D printed model and the silicone rubber cord inserted through the sleeves.

3.4. Aorta

The aorta is the large artery that carries oxygen-rich blood from the left ventricle of the heart to other parts of the body. The thoracic aorta begins at the aortic valve and goes to the diaphragm. The abdominal aortic section extends from the diaphragm through the abdomen. The aortic arch is a portion of the main artery that leaves the heart and ascends and then descends back to create the arch. The aorta distributes blood from the left ventricle of the heart throughout the body (Editorial Team, 2018).

The three major branches from the aortic arch are:

- Left subclavian artery (trunk) that supplies blood to the left arm.
- Left common carotid artery that supplies blood to the left side of head and neck.
- Brachiocephalic trunk that supplies blood to the right side of head and neck and the right arm.

The left common carotid artery arises directly from the aortic arch. The right common carotid artery is a branch of the brachiocephalic trunk on the right. The common carotid arteries supply blood to the head and neck and divide in the neck to form the external and internal carotid arteries (Manbachi etal., 2011).

The left vertebral artery rises from the left subclavian artery. The right vertebral artery rises from the brachiocephalic trunk. These two vertebral arteries ascend through the foramina (openings) of the transverse processes of the cervical spine segment usually starting at the C6 vertebra. These arteries are the major arteries of the neck that originate from the subclavian arteries. They merge within the skull to form the basilar artery. The vertebral arteries supply blood to the upper spinal cord, brain stem, cerebellum and the posterior part of the brain (Standing etal., 2008).

Models were designed using Solid Edge CAD software of the left subclavian artery (trunk) and the brachiocephalic trunk. The CAD files were then converted to STL and 3D printed (Figure 4).

Various diameters of silicone rubber o-ring cord were used to simulate the major arteries from the left brachial artery (trunk) and the brachiocephalic trunk. The descending aorta is part of the aorta which is the largest artery that runs from the heart down through the abdomen and ends by splitting into two large arteries, the common iliac arteries. A large diameter silicone rubber o-ring cord was used to simulate the descending aorta.

No veins were simulated in the 3D printed model. However, short lengths of o-ring cord were inserted into the superior vena cava and the inferior vena cava rather than have openings in the 3D printed model.

4. Results and Discussion

Table 1 gives the diameters from the literature of the major arteries and several veins and the corresponding diameters of the silicone rubber o-ring cord that were used in the model. In most instances either the mean diameters were used in the model or the values were dictated by the artery openings in the 3D printed heart model. It should be noted that there are many references with different artery mean diameters. Also these means vary with sex and age.

Figure 5 is the completed 3D printed model of the human body with the skeletal, respiratory and circulatory systems.

Figure 5. Completed 3D model.

Table 1. Diameters of arteries and veins.

Artery	Mean diameter from literature (mm)	Diameter of silicone rubber cord in model
Left subclavian artery (trunk)	9-12 (Rigberg etal., 2006)	8
Left vertebral artery	3-5 (Weerakkody and Gillard, 2021)	4
Left subclavian artery to left brachial artery	3.93+-0.49 (Tomiyama, 2015)	5
Left common carotid artery	4.3-7.7 (Limbu, 2006)	6
Brachiocephalic artery (trunk)	12.1+-1.6 (Sheikh and Oliver, 2021)	8
Right common carotid artery	4.3-7.7 (Limbu, 2006)	6
Right vertebral artery	3-5 (Weerakkody and Gillard, 2021)	4
Right subclavian artery	6.38 (Kaki etal., 2018)	5
Left pulmonary artery	19.74+-2.35 (Gokoglan etal., 2014)	10
Left pulmonary artery (smaller)	-	5
Left superior pulmonary vein	9.6-10.5 (Kim, 2005)	5
Left inferior pulmonary vein	9.0-9.9 (Kim, 2005)	6
Right pulmonary artery	19.24+-2.43 (Gokoglan etal., 2014)	10
Right pulmonary artery (smaller)	-	5
Right superior pulmonary vein	12.3-13.1 (Kim, 2005)	5
Right inferior pulmonary vein	11.4-12.4 (Kim, 2005)	6
Superior vena cava	14-28 (Sonavane etal., 2015)	-
Left brachiocephalic vein	-	7
Right brachiocephalic vein	-	10
Inferior vena cava	12-17 (Mookadam, 2011)	16
Ascending aorta	30.9+-4.1 (Hager etal., 2002)	19mm printed on model
Descending aorta at diaphragm	24.3+-3.5 (Hager etal., 2002)	20mm printed on model Inserted 14mm o-ring cord

5. Conclusions

Simulation based learning experiences (SBLEs) are structured activities that represent actual or potential situations in practice. These activities allow nursing students to develop and enhance their knowledge and skills to analyze and respond to realistic situations in a simulated environment. SBLEs are conducted in a laboratory where nursing students come to engage in activities specifically designed around a set of learning objectives. These activities are developed into simulation cases with realistic patient scenarios.

A simulation scenario contains the learning objectives, performance measures, patient's clinical information (background, current condition and medications), actor scripts, timeline for the unfolding of the scenario, cues needed by the facilitator to progress the learner's actions and other information to ensure that the SBLE is robust, immersive and successful.

The College of Nursing at UAH has developed over one-hundred SBLEs (Moeller etal., 2015). Each simulated clinical experience is documented in detail and placed in a binder with specific objectives, a detailed set up sheet and pictures for standardized repetition.

Figure 6 is the schematic of the simulation environment for training nursing students. Once a SBLE has been selected the patient examining room

Figure 7 is configured and the initial conditions established for the simulation. The facilitator control room and the patient examining room are set-up for the scenario. The simulation is recorded for both participant and facilitator reflection. The simulation may also be transmitted live to the faculty/student debriefing room or classroom to expand the learning for broader participation or for peer review.

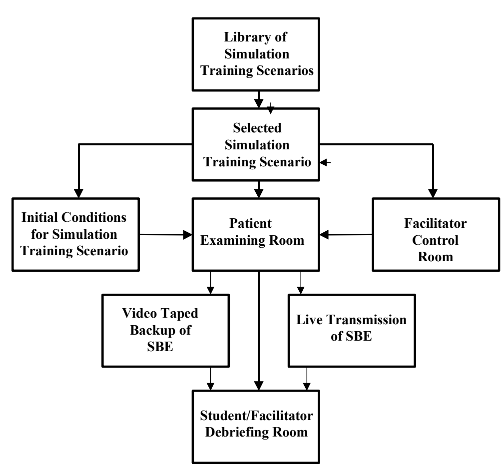

Figure 6. SBLE environment.

Figure 7. College of Nursing examining rooms.

The 3D printed model of the human body is currently being integrated into the SBLEs related to teaching human anatomy and physiology. The steps in adding the model into a SBLE consist of 1) reviewing and adding to the learning objectives and scope of the SBLE, 2) rewriting the simulation scenario and 3) updating the performance measures.

The 3D printed model is providing an excellent assistant for nursing students to visualize and study 1) the human anatomy or structure of the body (organ size, location and relationships to other organs) and 2) the human physiology (mechanical, physical and biochemical) functions of the human body. The AR application Virtual-Tee (Curiscope, 2020) is also being evaluated as an additional education tool.

The faculty had suggested that the 3D printed model have the flexibility to remove the heart and lungs which were permanently fastened to the spine and vertebrae. The suggestion was satisfied by constructing a separate trainer. Figure 8 is the resulting SBLE trainer of the heart and lung that shows the arteries supplying blood from the heart to the lungs. All the arteries from the aortic arch were included in the trainer. Short lengths of silicone rubber were inserted in the heart openings to simulate the arteries. The trainer included a 14mm descending aorta, a 10mm diameter superior vena cava and a 16mm inferior vena cava.

The heart and lung trainer also included a schematic of the layout of the arteries, the names of the arteries, the diameters of the arteries from the literature and the diameters of the o-ring cord used in the model (see Table 1).

Based on the initial feedback it appeared that the heart and lung trainer was of significant value to nursing students in visualizing and tracing the routing of the arteries and in learning and remembering artery names.

Figure 8. SBLE trainer of heart and lung.

Upon the completion of Phase II all the 3D printed organs will be included in the body model. At that time a more detailed student evaluation will be conducted.

It is estimated that less than three reels of 1kg PLA (polylactic acid) filament were used to 3D print the Phase I model (less than $100). Several of the models such as the ribs had thirty-percent waste because of the many PLA support structures required during printing.

An undergraduate senior engineering student and a high school junior intern were used to modify, print and assemble the 3D models and the heart and lung trainer. Both students had CAD and 3D printing experience. The project took two months and approximately 200 student hours. The majority of the student hours were redesigning and sizing the models and making the STL files suitable for 3D printing. UAH faculty served as advisors on the project.

In summary the following conclusions are made relevant to the fabrication of the 3D printed model:

- The diameters of the arteries from the heart vary considerably in the reported literature. Therefore, the diameters of the arteries were controlled by the diameters of the openings in the 3D printed heart model.
- Securing the arteries to the organs was a problem since the organs were printed in PLA and the arteries were made of silicone rubber. The problem was solved with CAD designed and 3D printed sleeves. The o-ring cord was glued into the sleeves and the sleeves then fused with a soldering gun to the organs.
- Since the 3D printed organs were rigid and not flexible like real organs, extra volume was necessary to install the organs.
- Silicone rubber o-ring cord was very satisfactory in simulating arteries.
- The connection of the ribs to the spine in the 3D printed model was fragile and prone to

breaking. Consequently, the thickness of the base at each rib was strengthened within the STL file.

- The PLA waste during the 3D printing from the support structures made an excellent material for fusing the PLA models and sleeves. These waste PLA structures were thin and became soft quickly with a soldering iron.

Acknowledgements

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