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> To form a mental 3D image of the body and the underlying anatomy is not that easy, specifically with the heart

Q1 You have been at the forefront of integrating 3D printing into medical education, such as the '3D-Printed Forearm Trainer', and the '3D-Printed Human Heart'. How can 3D-printed anatomical models enhance the learning experience for students, and address gaps in medical training?

Starting off with the 3D-printed human heart, what triggered it was that it's really hard to imagine the heart in its t3D projections. The heart has two atria and two ventricles, positioned in a specific way within the body and chest, making it difficult to imagine how it sits and where each chamber is located. For anatomy in general, to be able to form a mental 3D image of the body and the underlying anatomy is not that easy, specifically with the heart.

I teach ultrasound, and I got into this around 8 years ago. Together with some colleagues in emergency medicine, we developed a 'special topics' course. A basic heart ultrasound is a very important part of point-of-care ultrasound and for the Focused Assessment with Sonography in Trauma (FAST) exam. However, it is difficult to imagine the plane that you are intersecting the heart because when you place the ultrasound probe on someone's chest, you see a greyscale image, 256 shades of grey, which you then have to interpret. I asked myself: 'How can I teach it better to help students understand something like the parasternal long axis view? How do I teach it?' So, I thought: 'Well, we've got a 3D printer.'

I went online, and I found the model of the heart on the National Institute of Health (NIH) database, and we 3D-printed a scaled-down model of it. For the first prototype, I simply cut it into two halves with a saw so it could be opened up, and I thought: 'Wow, that's not bad.'

Then I had to teach myself how to use the 3D editing software, which was a steep learning curve. I learnt how to use the editing software to make the slices in the software to print out two different halves, so it was possible to print the parts of the heart in a way that would mimic the projection that you see on the ultrasound screen. So, when you hold the model of the heart, you can open it up. I also put magnets in between, so you can just click it apart and easily show the students the left ventricle and the left atrium, the right ventricle and the right atrium, and then you can put it back together. This allowed me to explain to students that by turning the ultrasound probe 90 degrees, they are now intersecting the heart with a beam perpendicular to the previous plane. So, having that side by side when you are teaching ultrasound on standardised patients, for instance, helps a lot. The students who've been able to use the 3D-printed hearts have really enjoyed it and have said that it is much easier to learn. For neuroscience, we 3D-printed smaller, scaled-down versions of the brain, or a hemisected brain, which you can then colour yourself, and this is really useful.

Q2 What initially drew you to the field of anatomical sciences, and what sparked your particular focus on ultrasound technology and 3D printing in medical education?

The first person to get a 3D printer in my department was a colleague of mine, Dr Barger, and he got the 3D printer for a different project. Once he completed that work, he kindly allowed me to use the printer. In the anatomy lab, we have anatomical donors, they are very valuable, and we dissect them. While we do have some anatomical models, these tend to be quite expensive. Even a skeleton model of a hand or foot can range from dozens of dollars to hundreds, depending on how complex they are. So, I thought we must be able to create something cheaper, like print them ourselves. Over the past 10 years, the database for readily printable 3D models of medical education-relevant structures has grown tremendously. It is possible to make a 3D model from a CT scan of an abnormally formed heart, for instance, and that's really useful for surgical planning, allowing surgeons to evaluate the feasibility of their approach before performing the operation.

The heart was one of the first 3D-printed projects I worked on a couple of years ago. We also did a 3D-printed finger. First, we 3D-printed the inside skeleton, then I made an alginate mould using my own finger to form the outer shape of the model. We then used ballistic gelatin around the 3D-printed bone pieces. We added some tendons made out of a monofilament line, and we used this model to practice joint injections. That sparked the idea to make trainers, also known as phantoms, that will help aspiring physicians and people who are already physicians and residents to learn procedures fast, and provide better and safer patient care with less negative outcomes.

Q3 Can you tell us about some of the projects you've worked on over the years?

We wanted to print a forearm with the cubital fossa, a region with a big vein, so students could practice drawing blood. However, there was no mould for 3D printing the whole forearm, so one of my ingenious students came up with the idea to 3D-print it so they could practice drawing blood from patients.

I bought a 3D scanner and scanned the forearm of my student. We used ballistic gelatin; this can either be synthetic, which is oil-based, or organic, made from real gelatin, which means it will go bad, but it's very cheap. It has a similar density to body tissue, so it's very useful. We filled the mould with ballistic gelatin and put in latex tubes that were connected in a way to match the standard branching pattern of the vessels in the forearm. We then filled the vessels with water that had either blue or red food colouring. Of course, we do not believe that arterial blood is red and venous blood is blue, but it's just useful to help reinforce the concept effectively.

We also 3D-printed a model of the brachial plexus in the axilla, a complex network of nerves. It's essential to learn where they go, what spinal levels the different nerves are derived from, what the signs and symptoms are if you

have lesions in the articular nerve, etc. So, we printed it and put little magnets in between the different branches, allowing the branches to be detached and rearranged. We also made it possible to colour-code the branches to indicate which spinal level they come from. It's like a big puzzle. I think it's much easier for people who are multi-modal learners, which I believe a lot of people are; it's helpful to be able to hold a model and study with that.

We also did a 3D-printed knee, embedded in ballistics gelatin, and practiced ultrasound-guided injections into the knee and ultrasound-guided aspiration of fluid out of the knee. I have to give credit to all my students who work with me, because they have great ideas, and they are right there at the forefront of learning and innovation. I'm just the fortunate one who can try and harvest the glory.

Q4 Are there any new materials you've come across that are even closer to mimicking human tissue?

We've experimented with all sorts of unconventional ideas. For the 'Special Topics' course, which is a week-long boot camp, I've embedded pork butts. We've placed the tip of a 9 mm handgun bullet into a pork butt. When we scanned it, the muscle striations were clearly visible and closely resembled human muscle. You could even see the projectile lodged within the tissue, and gunshot wounds are a common issue faced by physicians in Birmingham, Alabama, USA.

The possibilities with ultrasound gel or with ballistics gel are pretty vast. Ballistics gel is similar to human body tissue. It is non-toxic and very easy to prepare. You

dissolve the powder in water, boil it, add some deformer, and cast it. It is like making jelly, only that jelly tastes much better.

We also have an oil-based gel that melts at a much higher temperature. For that, I use a crock pot to melt blocks of gels, as it remains stable at room temperature and only melts at temperatures exceeding 100 °C. This makes the gel gooey and sticky, which then can be poured into different shapes. Its main advantage is its longevity; it doesn't spoil. However, it comes with two significant drawbacks: its high cost, around 50 USD per pound, and its higher melting temperature. So, you have to be a little cautious if you're embedding something. Care is needed to let the gel cool sufficiently, otherwise they might melt.

Some people add antimicrobials that dissolve well to organic gelatin to prevent it from spoiling. But I like the idea of not working with toxic substances. When I make phantoms from the organic gel, I don't add any preservatives to it. I would be a hypocrite to get my biweekly agriculture box, which is all organic and green, and then put formaldehyde in everything. Instead, when we're done with our session, we can either re-melt and then re-use them, or we can toss them.

Q5 How do you see the integration of ultrasound in the medical curriculum evolving over the next few years, and what innovations do you think will drive this field forward?

It is incredible how much technology has advanced. One thing that I think is great is that technology is becoming much more affordable. One of the caveats of ultrasound is that the

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machines can be very expensive, but now you can get a handheld device for about 2,000 USD, or sometimes even less. That brings them into the reach of medical education, and not just for the people who are privileged enough or have a grant at university. These handheld devices can even connect to your phone. So, if you are a physician doing rounds in the hospital, you could have your ultrasound probe in one pocket of your lab coat and use it for bedside scanning on the spot. I have a wireless one; on one side, it has a probe that you can use for superficial scanning, you can use that for vascular access, and on the other end, it has a transducer that can scan deeper, like the heart, liver, and kidneys. These models are a bit more expensive, but they're still far more practical than the massive machines that used to take up an entire room.

Technology is advancing with machine learning and AI. Several companies are working on using machine learning algorithms to interpret the ultrasound images. It's great because it means you could scan someone with an ultrasound probe, and even if you're not an expert, the system could help you identify what you're looking at. Since these algorithms are powered by vast databases, it will be able to compare the picture that you have with 1,000s of images in a database and tell you if the image is similar to a normal one, or if it is similar to a pathological one, and what type of pathology it is. It would be used as a diagnostic tool. It's really amazing how we're going to be able to use machine learning to help interpret ultrasound images and use it in general for training.

In rural settings, having a portable ultrasound means that the patients don't have to

travel far. With these devices, you can perform exams on the spot, potentially sparing patients unnecessary procedures and significantly reducing costs. Furthermore, with machine learning, or even with telemedicine, you can do these scans even if you're not an expert. Usually, to become a trained stenographer here in the USA, you have to go to sonography school, which takes at least 2 years, and then you have to specialise, which takes even more time. Instead, someone could use the technology that's built into the portable ultrasound device to interpret the image. If further clarification is needed, the images can be wirelessly transmitted to a remote expert for assistance.

Q6 Looking ahead, are there any upcoming projects or research initiatives that you are particularly excited about?

A former student of mine, now in her OB-GYN residency in New Orleans, Ochsner, USA, identified a challenge in locating the cervix. As a man, I didn't realise the complexity of it. I thought, as an anatomist, it was simply straight ahead at the end, but it's actually not that straightforward. The cervix can be positioned in different ways, it might be angled in various directions, making it difficult for physicians performing procedures like pap smears. So, she and I actually made a model for pap smears. The model consists of the external female genitalia, with the introitus, the vaginal canal, and up to the cervix. We designed it so the cervix could be placed in different positions. This allows clinicians to practice using a speculum and accurately locating the cervix before performing the procedure. Because for a patient, it's a very uncomfortable procedure. When

the physician is less experienced, practicing with a 3D-printed model could really help minimise the trial and error of locating the cervix, ultimately improving patient comfort and outcomes with better-trained clinicians.

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