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EDITORIAL

3D printing: From digital to real in modern personalized medicine

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In the vast universe of medical sciences, the quest for understanding the human body and its pathologies has historically been comparable to the journey of a cave explorer. Looking through the lens of the present, we could liken these initial exploratory endeavours to stepping, without a lantern, into an unknown cavern shrouded in profound darkness.

One of the primary exploratory methods was surgery, an invasive approach in an era when the inner workings of the body were largely a mystery. Surgeons made incisions and dissections to physically examine internal organs and tissues, aiming to visualize and analyze physiological mechanisms "live". This approach, although straightforward, was fraught with risks, including infections, especially since this practice was carried out in a period prior to the emergence of disinfectants and the techniques of asepsis and antisepsis. It was equivalent to dynamiting the cavern, for exploratory purposes.

At the end of the 19th century, the first "cave explorer" emerges, bringing with him the first flashlight, the first glimmer of light in the previously impenetrable darkness.

In 1895, the accidental discovery of X-rays by Wilhelm Conrad Röntgen marked a crucial moment in the history of medicine. With a first picture, that has entered the eternal annals of medical history - a picture of his wife's hand - Röntgen transformed the once opaque and enigmatic interior of the human body into a visible tableau in shades of black, white and gray (Figure 1). The scientific impact of this discovery lay not only in its ability to visualize what is concealed, but also in its rapid adoption and adaptation. Within weeks of Röntgen's announcement, doctors worldwide were using X-rays to diagnose bone fractures and locate bullets in wounded soldiers. It was a breakthrough in trauma care, fundamentally changing the approach to emergency medicine[1]. As technology has evolved, so have its applications. The development of contrast agents in the 1920s allowed for the visualization and individualization of soft anatomical structures such as the gastrointestinal tract, kidneys, or gall bladder, expanding diagnostic capabilities beyond the skeletal system and deepening the understanding of the complexity of the human body[3].

Nevertheless, this pioneering technology was not without limitations. The initial excitement gave way to the acknowledgment of certain inherent constraints. One of the significant limitations of traditional X-rays was, and continues to be, their two-dimensional nature. Similar to a shadow projected on a wall, X-rays provided a flat representation of three-dimensional anatomical structures. This often led to the overlapping images of organs and bones, resembling a palimpsest where multiple layers of text are superimposed, making individual layers difficult to read. Such overlap obscured critical details and made it difficult to establish a precise diagnosis, especially in complex anatomical areas. X-rays were better at visualizing dense structures, such as bones, but less effective in distinguishing between different types of soft tissue. Subtle nuances between muscles, organs and other soft tissues often remained hidden in the ambiguity of the grayscale in X-ray images[4].

The cavern continued to demonstrate its complexity, concealing its web of corners and crevices. A simple flashlight was no longer sufficient.

The next significant step occurred in 1970, facilitated by Sir Godfrey Hounsfield, an English electrical engineer and physicist employed at EMI Laboratories in Great Britain, and Dr. Allan Cormack, a physicist of South African origin at Tufts University in the United States. Although developed independently, their contributions laid the foundation for this revolutionary invention – computed tomography. In 1971, Hounsfield built the first prototype of a CT scanner and performed the first successful CT scan on a human patient. This inaugural scan was of a patient's brain, and was carried out at

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Figure 1. Hand mit Ringen (Hand with Ring): a print of one of the first radiographs taken by Wilhelm Röntgen (1845-1923) of the left hand of his wife, Anna Bertha Ludwig (Wikipedia[2]).

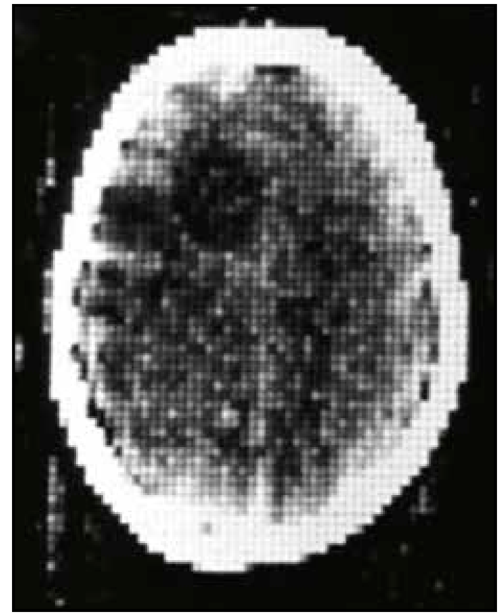

Figure 2. The first clinical computed tomography, performed in October 1971 at the Atkinson Morley Hospital in London (Taubmann et al.[6]).

the Atkinson Morley Hospital in London[5]. The 80x80 pixel image of an astrocytoma required 2 days of repeated scans, a journey through the city with the magnetic tapes, 2.5 hours of data processing on a central supercomputer at EMI headquarters, and capturing the image using a Polaroid camera before returning to the hospital[6] (Figure 2).

The computed tomography represented the necessary qualitative step in the field of medical imaging, overcoming many limitations of traditional X-rays. The CT scanner, which basically uses the same X-ray technology, generates multiple cross-sectional images, essentially slicing the area to be investigated into slices. These slices were then reconstructed using complex computer algorithms, creating a three-dimensional model of the body's internal structures. This transition from two to three dimensions was revolutionary. It was as if the flat and enigmatic map of the human body visualized through radiography had been transformed into a tangible and explorable landscape. Unfortunately, however, one of the main limitations of computerized tomography remained the continued presentation of images in two-dimensional slices. While these cross-sectional images provided a more detailed view than traditional X-rays, they still presented a fragmented picture of the internal structures of the body. Doctors had to mentally reconstruct these slices to form a comprehensive understanding of three-dimensional anatomical relationships. We brought volume to the human body, but we were still looking at it through two-dimensional slices.

It is difficult to estimate the depth of a cavern by looking only at pictures of it.

The next breakthrough came with the advent of 3D reconstruction techniques. These techniques involve the use of advanced algorithms to digitally compile two-dimensional CT slices into three-dimensional images. Through digital methods, overlaying CT images and selecting areas of interest enabled the creation of the first truly three-dimensional models of patients' anatomy (Figure 3). This innovation has allowed for a more holistic and intuitive visualization of internal structures, providing a more natural and accurate representation[7,8]. 3D reconstructions have also improved the diagnostic capabilities of CT scans. Advances in computer processing power and imaging technology have further refined 3D reconstructions. High-resolution scans could now be processed rapidly, reducing scan time and improving patient comfort. This has also led to a reduction in motion artifacts, resulting in clearer and more precise images[9].

Now is the perfect time to bring the digital back to the real.

3D printing, an already ubiquitous term in so many industries and articles, has found profound applications in the medical field, overcoming limitations and opening new horizons in patient care. 3D printing, at its core, is the process of creating three-dimensional objects from a digital file, bringing digital imaging, with all the information it has accumulated in the past, into the hands of doctors in a tangible, physical form.

3D printing allows surgeons to hold and interact with accurate 1:1 scale models of organs, bones or other anatomical structures based on digital reconstructions[10,11] (Figure 4). Surgeons can now practice and plan complex procedures on patient-specific models, reducing surgical time and improving surgical outcomes. Another area where 3D printing has a profound impact is in the creation of customized guides, prostheses and implants. Traditional prostheses and implants come in standardized sizes and shapes, often requiring adjust-

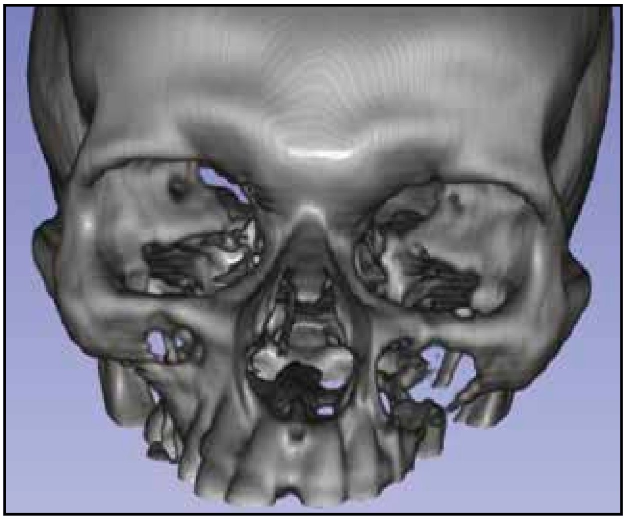

Figure 3. An example of a simple 3D reconstruction using Volume Rendering (3D Printing Laboratory, Innovation and e-Health Center , "Carol Davila" University of Medicine and Pharmacy, Bucharest, Romania).

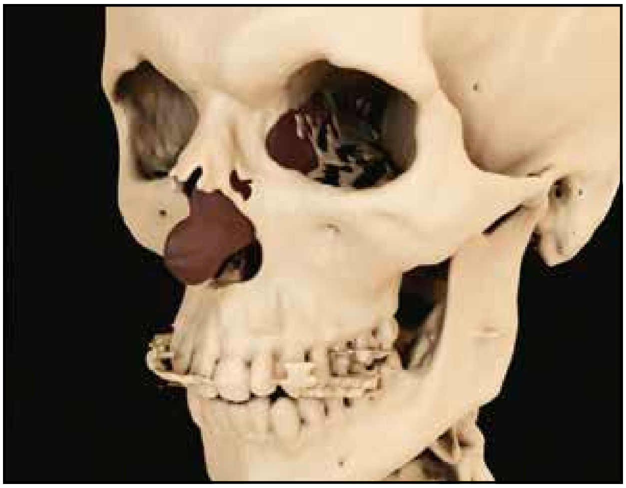

Figure 4. 3D printable reconstruction using modern segmentation methods of a rhinosinusal tumor - Esthesineuroblastoma (3D Printing Laboratory, Innovation and e-Health Center , "Carol Davila" University of Medicine and Pharmacy, Bucharest, Romania).

ments to fit individual patient pathologies. On the other hand, 3D printing, allows for the creation of medical devices that are custom-made to fit each patient's unique anatomy[12-15]. In education, 3D printing provides the opportunity to reproduce pathologies and create customized simulators for various types of pathologies and surgical situations identical to real ones.

Through this latest technological leap from digital models to physical ones, the "cave explorer" no longer visualizes just a simple map of the cave, nor sees only pictures, but explores it safely and comfortably, thoroughly analyzing it. Later, with "the homework done", he can venture, as always, into the darkness.

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