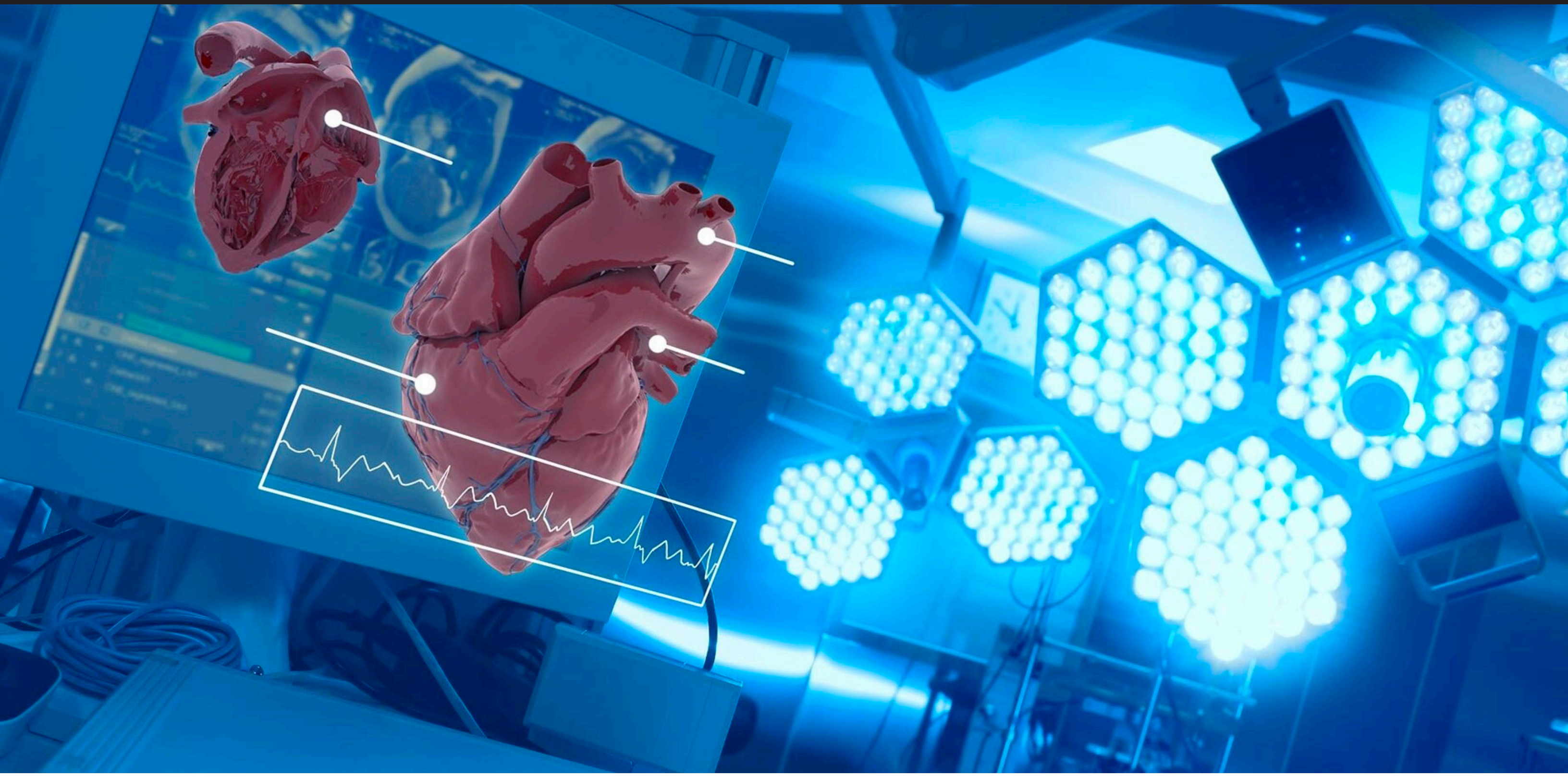
HOLOGRAPHIC VISUALIZATION IN THE PRACTICE OF MEDICINE

PART 1



AVALON HOLOGRAPHICS

Executive Summary

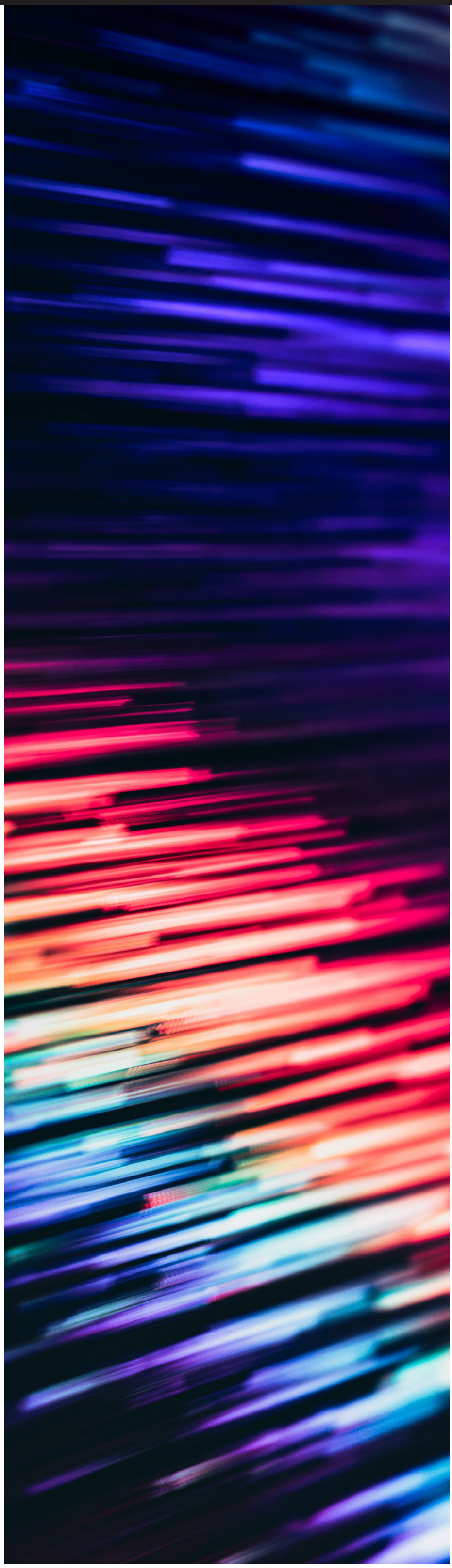
Medical imaging is on the threshold of an enormous step forward in visualizing the body, both in sickness and in health. Today, images of structure and function in radiology workflows are usually viewed as two-dimensional (2D) slices of the body, and only rarely as volumetric renderings. Many acquisition modalities provide information about the structure and function of the body that is critical to planning and therapy. Sadly, much of this information is trapped in decades-old 2D-display visualization tools.

The advent of holographic displays and rendering, however, is launching a new paradigm, bringing natural, naked-eye views of breathtaking realism to clinicians, surgeons, and patients. This new capability stands to enhance multidimensional image review and surgical planning. With extensions into the operating room itself, intraoperative imaging, gathered by dedicated scanners and commonplace in interventional and laparoscopic surgeries, can now move into the third (3D) and fourth (4D) dimensions, improving the safety and speed of surgeries.

This whitepaper reviews some basics of medical imaging visualization and explores the benefits that extending them to holographic visualization will bring to the practice of medicine. A future update will incorporate additional data from studies in progress or already completed.

THIS NEW CAPABILITY STANDS TO ENHANCE MULTIDIMENSIONAL IMAGE REVIEW AND SURGICAL PLANNING. WITH EXTENSIONS INTO THE OPERATING ROOM ITSELF, INTRAOPERATIVE IMAGING, GATHERED BY DEDICATED SCANNERS AND COMMONPLACE IN INTERVENTIONAL AND LAPAROSCOPIC SURGERIES, CAN NOW MOVE INTO THE THIRD (3D) AND FOURTH (4D) DIMENSIONS, IMPROVING THE SAFETY AND SPEED OF SURGERIES.

Advanced visualization in medical imaging has grown from a diagnostic service to a preoperative planning tool



Medical imaging modalities enable healthcare teams to see within the body and plan surgery before making the first incision. Medical imaging has rapidly leveraged many different forms of energy to reveal pathology.

Transmission X-Ray (XR) first allowed doctors to "see" bones and the shadows of organs and thereby diagnose everything from obviously broken or fractured bones to subtle changes in size, shape, or location of soft-tissue organs. When it evolved through digital radiography (DR) and computed radiography (CR) into computed tomography (CT), XR moved from 2D to 3D, allowing for optimal visualization of objects oriented outside the anatomical planes by reorientation.[1] It also enabled the creation of segmented volumetric images of specific features, removing the "overburden" of uninvolved anatomy by rendering only the critical pathology and its key anatomical landmarks.[2] The addition of injectable contrast agents enabled the differentiation of fine vessels (CT angiography, CTA) and hollow organs, as well as the pulse-chase and time-series imaging that is critical for cardiology.[3]

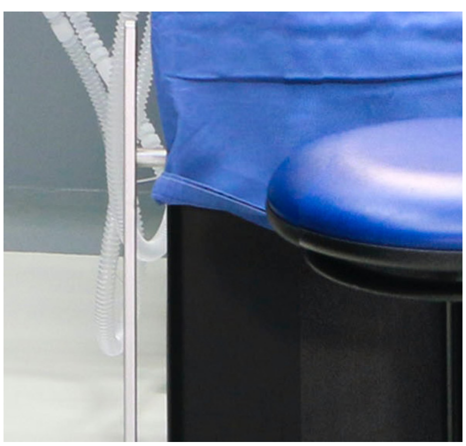
WHEN IT EVOLVED THROUGH DIGITAL RADIOGRAPHY (DR) AND COMPUTED RADIOGRAPHY (CR) INTO COMPUTED TOMOGRAPHY (CT), XR MOVED FROM 2D TO 3D, ALLOWING FOR OPTIMAL VISUALIZATION OF OBJECTS ORIENTED OUTSIDE THE ANATOMICAL PLANES BY REORIENTATION.

Magnetic resonance imaging (MRI) introduced contrasting pulse sequences (e.g., T1, T2, PD, etc.) which, unlike XR and CT, can highlight specific soft tissues and histological components.[4] Positron emission tomography (PET, PT) and nuclear medicine (SPECT, NM) meanwhile provided insight into the metabolic activities of sugar and other chemical substrates of cellular function.[5] With the advent of ultrasound (US), the ease of imaging utilization improved massively while its cost was drastically reduced, causing usage to explode.[6]

Over the last couple of decades, the combination of these various modalities has provided simultaneous structural, dynamic, and functional imaging (e.g., PET/CT, PET/MR, CTA, 4D-US) with reduced ionizing radiation dosage, increasing benefits to patient care, particularly in oncology,[7] as well as easing fundamental clinical research. In particular, the advent of three-dimensional visualization has taken imaging modules from purely diagnostic uses. Surgical planning, intraoperative and postoperative follow-up, and even patient communication are all now possible. Without years of specialized training, only 3D viewing makes organs and bones immediately recognizable.[8]

The extension of these viewing modes, from 3D on a 2D screen to fully holographic will no doubt expand patients' comprehension of their personal pathology and surgical plans, options, and risks, given their exposure to very futuristic medical-imaging simulations in the mass media.

Intraoperative imaging has become a mainstay of advanced surgical technology



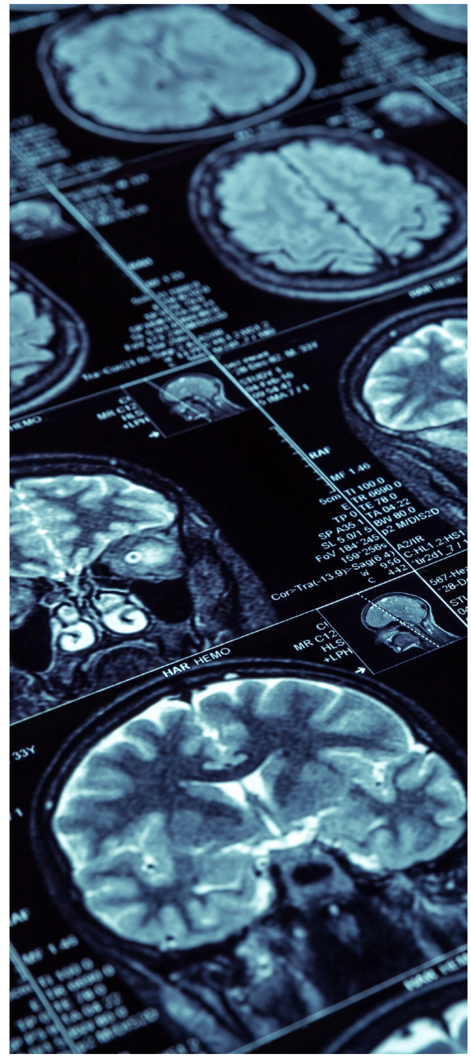
A common imaging workflow for patient work-up includes initial XR imaging, progression to CT (and sometimes PET/CT), and tissue differentiation with MRI, with US chosen, as required and where appropriate, for its ease of use and exquisite dynamic cardiac and endovascular internal imaging capabilities. An entire practice of medicine has evolved from these diagnostic and planning workflows to image-guided surgery, interventional radiology, and intraoperative imaging, even including MRI and CT.[9]

Each of these approaches require the acquisition of imagery during a surgical procedure, be it open surgery or interventional (intravascular). Surgeons use the intraoperative imagery to confirm their approach by identifying target anatomies, their positions, and optimal tool routes in the surgical field.[10] Furthermore, intraoperative US can help identify donor structures such as veins or arteries, and intraoperative fluoroscopy helps the interventionalist guide catheters through the vasculature itself, in real time.

REAL-TIME VIDEO IS A KEY COMPONENT OF MINIMALLY INVASIVE SURGERY. THE NEXT STEP IS REAL-TIME HOLOGRAPHY.

Minimally invasive (MIS), endoscopic, laparoscopic, and robotic surgeries have revolutionized many high-volume surgical procedures. They depend on hardware thin enough to be inserted through small holes in the skin and surrounding tissues that can capture and transport video signals.[11] Commonly stereoscopic, these video signals allow surgeons to see what their tools are doing inside the surgical field, which may be insufflated for visibility and accessibility. Stereoscopic methods partially restore depth perception, but the imagery still presents a single viewpoint to the surgeon and team. Looking "behind" structures requires pausing the procedure to realign the camera(s). Further, stereoscopic presentation induces known physiological side effects, as discussed further below.

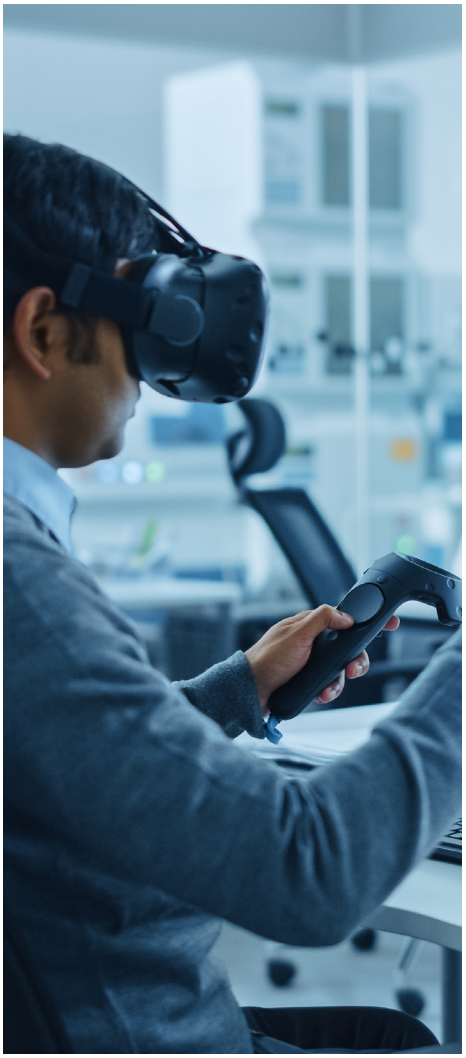
The great majority of medical visualization, even for these advanced intraoperative uses, is presented as two-dimensional images interleaved as a stereo pair on a single two-dimensional display. In MIS, these are two videos that simulate an intraocular distance by capturing two views of the operative field, either by splitting a single source of imagery from one camera or by using two separate optic devices within the catheter(s). For volumetric renderings, beginning with shaded surfaces of segmented structures and, more recently, ray-traced volume rendering from pre-operative imaging, the most common display system is still a single 2D monitor. These systems capture or generate left and right eye views, then present them to the respective eye using a variety of techniques – from shuttered glasses, color filtering, high-speed switching of the views, or, more recently, dedicated head mounted displays (AR, VR headgear).[12] Collectively, they're known as stereoscopic displays.



These displays present stereo-paired images either simultaneously (in which case filters are used to reveal a left image to the left eye and right to the right) or in sequential presentations, where signal-locked glasses (e.g., polarized) are switched to pass each image to its corresponding eye. While these systems have been around for more than 20 years, they have not been adopted widely in medical visualization, least of all in radiology. While the high-quality (in terms of resolution, contrast, calibration, and fidelity) radiology monitors are capable of fast-switching for stereo, this capability just doesn't seem to be relevant to daily workflows due to radiologists' highly trained expertise reading 2D-slice images. It is, however, deployed for surgical suites,[13] where the practitioners rely on both vision and touch to build up a mental representation of a patient's anatomy.

Spatial depth perception in these systems is enhanced by both monocular and binocular depth cues. Monocular cues include the shadowing and shading of geometry and linear perspective (the convergence of parallel lines and decrease of size of renderings into the distance) and blurring of distant objects, but the greatest feeling of depth arises from motion

of the rendered object. When rotating about the Y axis, for instance, deep components pass behind more superficial components and are therefore obscured. But to achieve these effects in MIS requires the camera(s) to be moved, and most of these cues are still effective on 2D displays, particularly when motion is incorporated. Binocular disparity (also known as binocular parallax) is the primary additional benefit of adding a second camera and stereo image pairs when using stereoscopic display technologies. But the disparity between the point of focus on the display system and the vergence of the viewer's eyes often leads to some viewers suffering headaches and nausea.[14]



Within advanced research establishments, the small form-factor stereo display systems are replaced with immersive displays, in the form of wraparound floor-to-ceiling screens or cubical arrangements of large screens like the Cave Automatic Virtual Environment (CAVE).[15] These CAVEs are used for immersive interaction, with volumetric renderings derived from clinical studies and research imaging, as well as simulations ranging from molecules to whole anatomies. The combination of expensive projectors, various types of head, hand, and eye tracking, and the need for dedicated spaces to contain the large screens make these systems unsuitable for surgical usage, but they have been tried for surgical simulation in teaching and research.[16]

For ease of deployment, surgical-suite simulations have moved from CAVEs to head-mounted Virtual Reality and Augmented Reality displays. One important difference between VR and AR in the medical space is that VR uses entirely machine-generated imagery for environmental simulation, whereas AR combines computer-generated images with active video of real furnishings and objects. In AR, preoperative imagery is often recombined with real-time surface imagery from the headgear's video stream, such as by painting imaged deep-anatomy onto a patient's skin.[17] The spatial location of the respective body part may be gathered optically from cameras on the headset and/or mapped with other sensors that generate a depth field. Dynamic registration, or alignment, of the volumes and scenery is necessary for these tools to function.

The combination of video signal augmentation with multimodality preoperative and potentially intraoperative imaging is the next horizon and demands enhanced capability to facilitate group exploration and planning in 4D. Novel holographic-visualization systems, where the form factor is a key determinant of the team size that can collaborate simultaneously, can meet that demand. This capability can be particularly beneficial for difficult surgeries.

For example, the anatomy, pathology, and imaging characteristics of the spine make spinal surgeries particularly challenging.[18] As many as 15% of spinal surgeons experience a wrong-site surgery in their career, with a prevalence of 1:3110 procedures, an issue that stems in part from incomplete, or inaccurate, communication between surgical team members.[19] Avoiding wrong-site spinal surgery involves using intraoperative imaging and taking extra precautions such as preoperative placement of fiducials and intraoperative consultations,[20] which can delay procedures and extend their duration.

Extending visualization capability to team holographic systems can mitigate these difficulties. In planning, the availability of a holographic system supports better understanding of a particular patient's anatomy through life-sized presentation of the pre-op imagery, facilitating discussion of the surgical approach and identification of landmarks by the whole team. Superimposition of the various modalities of both 2D (XR) and 3D (CT, MR) could help to identify the risk of inaccurate exposure or procedure and mitigate these outcomes. An OR-ready display which makes these views easy to explore in depth, without the complications of headgear or glasses, may greatly facilitate the mental mapping of the surgical field onto the pre-op imagery. Incorporation by registration of any intraoperative imagery can improve the team's confidence and optimize the input of multiple experienced members by allowing simultaneous visualization of the holograms.

Team holographic visualization improves the accessibility and comprehension of medical imagery in advanced surgical situations

IN THE PARLANCE OF EXTENDED REALITY TECHNOLOGIES SUCH AS VR AND AR, THIS TECHNOLOGY CAN BE DESCRIBED AS DISPLAYED REALITY (DR), REPRESENTING A SIMPLE, NATURAL 3D-EXPERIENCE ON A FAMILIAR PHYSICAL DISPLAY SCREEN.

Presenting medical imagery as space-filling holograms is at the forefront of medical visualization. With holography, a display system projects a set of intersecting rays that represent the medical model(s), in the same way real 3D objects reflect rays from various light sources. When each of the team members in the viewing session moves their head or eyes within this field of view, they perceive the viewing volume from different viewpoints. This coordination of the presentation of multiple points of view with the natural movement of the viewers' head and eyes simulates "looking around" the models, all without the need to wear any special glasses or headgear. The medical imaging data are thereby visually explored intuitively, in the same manner as a physical object: The holographic visualization system provides an experience as though the viewers are seeing natural light reflecting from a physical object. This technology is enabled by:

- The exponential increase of graphics computational power
- Increase in resolution of display systems and associated optical equipment
- Decrease in cost of these now-commodity components
- Innovation in the design and management of the simultaneous rendering and presentation of holograms

"In the parlance of eXtended Reality technologies such as VR and AR, this technology can be described as Displayed Reality (DR), representing a simple, natural 3D-experience on a familiar physical display screen."

Avalon Holographics has developed a holographic team-visualization system of particular interest for surgical teams, as it allows many people to inspect the rendering at the same time. Decades of experience in CAVEs and with Augmented and Virtual Reality systems reveals that when teams view the same data at the same time, their conversations change from describing what they are seeing to talking directly about the consequences and ramifications of the information they are seeing. The primary benefits of holographic team-visualization systems for medicine derive from this enhanced learning, understanding, and communication within the team. It is not just surgical teams who can receive these benefits, however. Individual practitioners can also benefit, and patient satisfaction and case retention improve when using virtual reality in surgeon-patient briefing.[21]

The data input to this device can be as simple as the now-ubiquitous system of exporting geometric surfaces from automated segmentations used by all the leading advanced-visualization postprocessing tools. It can also be a combination of these model surfaces with slices or volume renderings of the native grayscale imagery. The combination of these structures is the normal mode of viewing for the advanced visualization tools commonly available to radiologists, who are usually sequestered on dedicated workstations in their reading rooms, separate from the operating room or planning suites.

With the current automated segmentation times coming in at well under a minute, intraoperative imaging can be combined with leading-edge holographic technology for team exploration of the anatomical situation. This is particularly convenient for robotic surgical systems, since the operator console is segregated from the sterile area, leaving room for a team to gather. This ability to view complex combinations of pre- and intra-operative imaging in remote settings allows for only the patient to be exposed to intraoperative CT scanning. It also supports highly specialized remote surgery and/or consultation. With the hologram standing off the surface of the display, the visualization can also be brought right into the OR itself for immediate consultation in particularly tricky situations, without requiring the viewers to don headgear or glasses. Providing complex anatomical information in a natural display will speed comprehension, thereby enriching communication, increasing confidence, reducing OR time, and improving patient outcomes.

Better planning and group consensus leads to safer, shorter, and less expensive surgeries

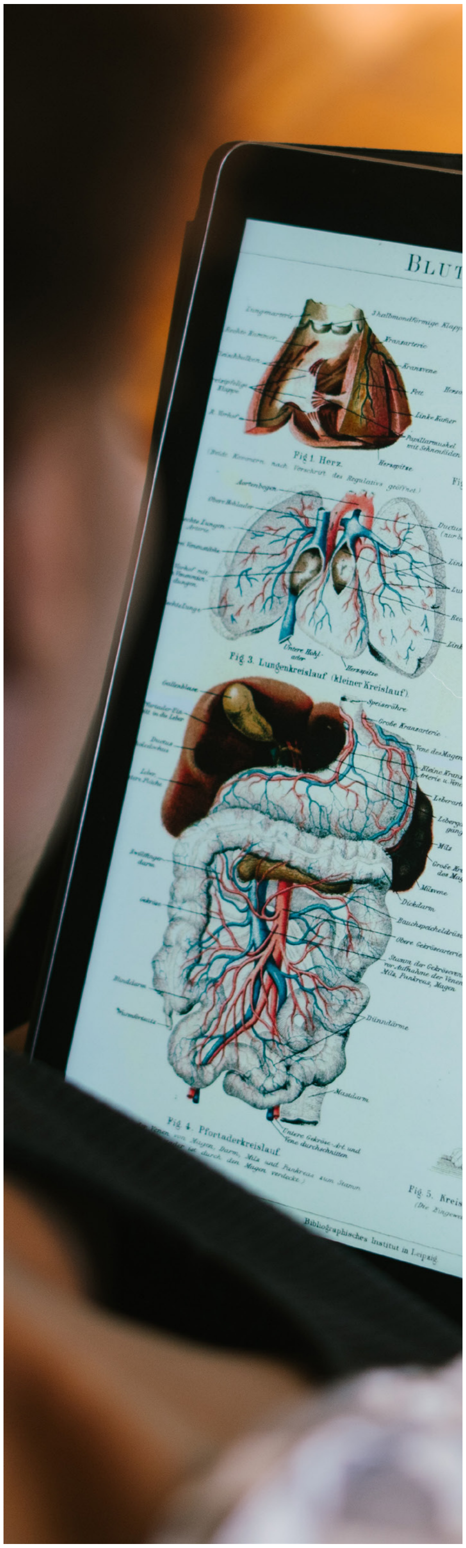
Just as employing more advanced visualization techniques enhances surgical resident learning and retention,[22] providing surgical teams access to these views, with the addition of true depth perception, should enhance the planning and execution of the operations. When people are looking at the same object, or rendering thereof, the conversation changes from "describing what is being seen" to "describing the implications of what is being seen." This is the key to better outcomes such as reduced OR time, with its associated reduced anesthesia time and OR cost.

For example, one of the most frequently performed surgeries, laparoscopic cholecystectomy, requires careful identification of the ducts and vessels before resection. Holographic presentation of the pre-op imagery for study by the team could help plan for the three-dimensional identification of the ducts, without requiring additional imaging or delays during the procedure. During the operation, the fast registration and fusion of real-time intraoperative video from the surgical robotic system, with pre-op and potentially volumetric modalities such as intraoperative CT, could enable the team's deeper involvement and confirmation of the surgeon's selection of where to cut. Working fully three-dimensionally, the team could inspect the positioning of tools versus anatomy from all angles. The surgeon is restricted to the camera point of view within the navigation system but is equally able to benefit from the holographic fusion with a simple turn of the head when holography is available.

Similarly, the use of team holographics could benefit prostate procedures. Providing real-time team visual input could reduce complications and improve outcomes by avoiding damage to the sensitive and very fine nerves in the region of the prostate, which are at risk during partial or complete prostatectomy and/or placement of thermal lesions or radioactive seeds.

Even complex procedures, such as partial nephrectomy for renal-cell carcinoma or renal transplant donor preparation, can reduce costs with better visualization.

DURING THE OPERATION, THE FAST REGISTRATION AND FUSION OF REAL-TIME INTRAOPERATIVE VIDEO FROM THE SURGICAL ROBOTIC SYSTEM, WITH PRE-OP AND POTENTIALLY VOLUMETRIC MODALITIES SUCH AS INTRAOPERATIVE CT, COULD ENABLE THE TEAM'S DEEPER INVOLVEMENT AND CONFIRMATION OF THE SURGEON'S SELECTION OF WHERE TO CUT.



For example, it's becoming more common for surgical teams to request 3D-printed models of the kidney and associated vasculature for these procedures. Surgeons recognize that these tools allow for different surgical path selection and reduce OR table times, therefore improving outcomes.[23] However, 3D printing requires dedicated staff and space, specific expertise, and can take days or even weeks to produce a suitable model for each patient's individual procedure. Due to the delays inherent to the process (time for 3D model preparation, the printing itself, and postprocessing, such as curing, cleaning, and coloring, depending upon the printer available), 3D printing is not something that can be done in an emergent timeframe.

Team holographic presentation, however, can greatly reduce or even remove these delays and costs. Intraoperative imagery has the immediacy required to have an impact in the timeframe of the procedure itself. These cutting-edge methods can leverage all the benefits of the full team in the shortest possible time.

Avalon Holographics technology is poised to deliver the premiere solution for today's most advanced surgical applications

Medical-imaging modalities now offer routine acquisition of structure and function and generate multidimensional time-varying data sets. The presentation of these data has evolved from 2D images to fully 3D visualizations, which makes the information more accessible to non-radiologists.

Avalon Holographics' holographic visualization technology dramatically expands these capabilities by enabling the natural perception of form, without requiring headgear or eyewear. Many types of complex surgical procedures are set to benefit from this new capability, especially where they involve complex anatomies, intertwined pathology, confirmation of the operating site, or which structures are to be corrected. Even simple procedures can benefit when it is important for patient satisfaction that the specialist's plans are communicated clearly and comprehensively.

As the team holographic visualization system does not restrict the view to a single person, it enables simultaneous visual comprehension, enabling discussions and decisions to be based on immediately available pre- and intra-operative imagery. Where clear, quick, and comprehensive communication between team members is at the heart of improved patient outcomes, the best visualizations are those that show natural, easily perceived 3D visuals simultaneously to a group of experts. When the technology is sufficient to present life-sized, dynamic anatomies combining pre-, intra-, and post-op acquisitions for the whole surgical team, everyone's expertise can contribute to improving the outcome. Putting the best data in front of the full surgical team helps ensure optimal patient outcomes from each procedure.

GLOSSARY

AUGMENTED REALITY (AR)	An optical system in which light from real world objects passes through a lens displaying computer-generated imagery to combine them into a coherent scene.
ENDOSCOPIC	A surgical procedure in which an optical system, usually fibre optics combined with one or more cannulas in a protective tube, is passed into a hollow organ for visualization. For instance, bronchoscopy, colonoscopy.
HOLOGRAPHY	An optical system that generates many unique renderings for display such that a person can move their eyes or head to observe a point or an object computed to represent the way light would reflect from a real scene, from the perspective and location of the viewer. By generating and presenting these various views, the observer experiences depth perception and different aspects of the model scene (i.e., true 3D), in contrast to standard volume renderings in which only one perspective is offered (i.e., 3D on a 2D screen), regardless of the position of the viewer. Not to be confused with "Laser Holography," which is a specific technical implementation of still-image holograms using lasers and diffractive effects in a substrate (similar to how both CRTs and LCDs were used to make "television").
LAPAROSCOPIC	A surgical procedure using endoscope(s) passed through the abdominal wall into insufflated space in which a variety of procedures can be affected on the liver, gall bladder, stomach, intestines, kidney, etc.
MIXED REALITY	An optical system in which an augmented or virtual reality system is extended by sensors such that real-world objects are mapped into the computational space within which they can be combined with the CGI and their appearance manipulated.
EXTENDED REALITY (XR)	An umbrella term covering the full spectrum of real and virtual environments, including VR, AR, MR, DR, and future immersive technologies. Not to be confused with Transmission X-Ray, also known as XR.
DISPLAYED REALITY (DR)	An optical system that presents holograms naturally from a simple display surface, which can be perceived in natural 3D by all viewers in a viewing region without wearables, eye tracking, or other limitations.
MODALITY	One of several medical imaging devices using a specific medium (e.g., x-ray, magnetic resonance, emission, sonography) to create a series of images representing the anatomy and/or metabolic function of the body.
NEPHRECTOMY	A surgical procedure in which some or all of the kidney is removed, often for cancer treatment.
RENAL-CELL CARCINOMA	The most common form of kidney cancer found in adults.
RADIOLOGY	Using ionizing radiation to generate images of internal bodily structures for analysis and diagnosis.
TOMOGRAPHY	An x-ray technique whereby the shadows of structures superimposed over the image are blurred out by moving the x-ray tube.

BINOCULAR PARALLAX	The difference in image location from the left and right that the brain uses to generate depth perception.
REGISTRATION	The spatial alignment of two or more series of medical images to facilitate comparison within or between subjects. For instance, to observe changes over time, or between health and disease, or to combine structural and functional images from different modalities.
SEGMENTATION	Manual, semi-, or fully automated identification of differing structures, such as bones, tissues, or organs, in medical imaging. For multidimensional imaging, often the surface of segmented structures is rendered as geometry (triangles) in visualization software, versus volumetric imaging of the raw imaging data itself to provide faster interaction or a basis for combination of multimodality data.
STEREOSCOPIC	Pertaining to the provision of a left and right eye view to engage the binocular depth perception capability of the human visual system.
VIRTUAL REALITY	An optical system that completely obscures the visual system and replaces it with display of computer-generated imagery of simulated spaces and objects. "Pass through" video may be provided and is often pasted onto surfaces within the virtual world as a "video feed." While external sensors may be provided to map the real-world space in which the operator moves (to limit bumping into walls, for example) and to track hand gestures, the virtual world is generally self-contained and complete.

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NOTES:

Visualizations that show images appearing outside of, or "breaking," the frame on a display from certain angles are simulations of a user's perspective for demonstration purposes and not intended to imply certain viewing angles.