



International Journal of Research Publication and Reviews

Journal Homepage: www.ijrpr.com ISSN 2582-7421

Theoretical Foundations and Architectural Frameworks of Spatial Computing in Medicine: Perceptual Ergonomics, Clinical Efficacy, and Immersive Paradigms across VR, AR, and MR

Devikrishna MU^a, Prof. Riya K Prakash^b, Dr. L.C. Manikandan^c

^a B.Tech. Student, Department of CSE, Universal Engineering College, Thrissur, Kerala, India. E-mail: devikrishnamu17@gmail.com

^b Assistant Professor, Department of CSE, Universal Engineering College, Thrissur, Kerala, India. E-mail: riyajothish13@gmail.com

^c Professor, Department of CSE, Universal Engineering College, Thrissur, Kerala, India. E-mail: lcmanikandan@gmail.com

ABSTRACT

Medical visualization and human-computer interaction (HCI) are undergoing a fundamental paradigm shift from two-dimensional planar slice reconstructions to spatially registered, three-dimensional computing environments. Spatial computing—an overarching technological framework encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR)—enables computational machinery to maintain and manipulate continuous spatial references to physical objects, environments, and human anatomies. This comprehensive paper establishes the theoretical, computational, and clinical basics of spatial computing across healthcare pedagogy, surgical planning, intraoperative navigation, and patient self-care. We contrast legacy medical visualization systems (characterized by 2D orthogonal PACS slices, cadaveric specimen scarcity, and high cognitive transformation loads) with modern 6-Degree-of-Freedom (6-DoF) spatial pipelines powered by Simultaneous Localization and Mapping (SLAM), real-time sensor fusion, and spatial anchoring. Drawing upon rigorous perceptual models—including the tri-factor Augmentation Quality construct (Design, Interaction, and Embedding Quality), the psychological state of Local Presence, Gibsonian affordance theory, and Dual-Process Cognitive Theory—we provide a systematic analysis of spatial HCI. Furthermore, we synthesize empirical findings from recent controlled trials (including the Handheld Augmented Reality Usability Scale [HARUS] evaluations and the METACARE population study across the Seven Pillars of Self-Care), evaluate critical adoption barriers (latency budgets, optical physics, vergence-accommodation conflict, EHR interoperability, and biometric telemetry privacy), and outline future trajectories for AI-integrated generative anatomical digital twins.

Keywords: Spatial Computing, Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR), Extended Reality (XR), Medical Education, Surgical Navigation, Augmentation Quality, Local Presence, HARUS Usability Scale, SLAM, Cognitive Load Theory

1. INTRODUCTION

Modern healthcare delivery and biomedical training operate under relentless pressures: accelerating diagnostic complexity, high patient safety mandates, limited access to biological specimens, and escalating demands for procedural accuracy [17]. For over half a century, computerized medical imaging has relied on planar screens to convey intrinsically three-dimensional human anatomy.

Whether reviewing cross-sectional Computed Tomography (CT), Magnetic Resonance Imaging (MRI), or ultrasound telemetry, clinicians and students have been constrained by 2D interfaces. This screen-bound paradigm imposes a continuous cognitive translation burden: the practitioner must mentally synthesize discrete 2D slices into a coherent 3D anatomical volume. In emergency surgery or complex oncological resections, this cognitive translation introduces measurable friction, increases error rates, and elevates mental workload.

Spatial computing provides an architectural solution to this historic limitation by merging digital information directly into physical 3D space, anchoring volumetric patient data to the real world in real time [2, 13]

1.1 Historical Paradigms and the Planar Visualization Bottleneck

The traditional medical training and diagnostic workflow has historically depended on two primary mechanisms: physical anatomical dissection and planar digital imaging (Picture Archiving and Communication Systems, PACS). While cadaveric dissection has stood as the gold standard of anatomical education since the Renaissance, modern pedagogical environments face severe structural challenges. Human donor specimens are scarce, subject to tissue degradation and chemical embalming artifacts, financially expensive to maintain, and devoid of dynamic physiological responses such as pulsatile blood flow or tissue deformation.

Concurrently, radiological PACS platforms present axial, sagittal, and coronal planes on flat monitors. When planning intricate interventions—such as deep-brain electrode placement in neurosurgery, complex pelvic reconstructive surgery, or pediatric congenital cardiac repair—the surgeon must visually interpolate between distinct image slices while simultaneously maintaining spatial awareness of the physical operating field. This division of visual attention between screen and patient is termed decoupled visual-motor processing.

2. ARCHITECTURAL TRANSITION: LEGACY SYSTEMS VS. SPATIAL COMPUTING

Spatial computing transforms medical visualization by establishing a unified metric coordinate frame wherein digital assets and physical reality co-exist. Table 1 systematically compares legacy medical computing and cadaveric dissection against modern spatial computing architectures across fundamental technical and clinical dimensions.

Table 1: Comprehensive Architectural Comparison: Legacy Medical Systems Vs. Spatial Computing

Architectural Metric	Planar PACS / 2D Displays	Cadaveric Dissection	Spatial Computing (VR/AR/MR)
Coordinate Frame	2D Cartesian Screen Plane (x, y)	Static Physical 3D (x, y, z)	Continuous 6-DoF Metric Space (x, y, z)
Degrees of Freedom (DoF)	2-DoF / 3-DoF (Mouse, Touchpad)	Direct physical manipulation	6-DoF (Position + Quaternion Orientation)
Cognitive Workload	High (Demands mental 3D synthesis)	Low to Moderate	Minimized (Direct stereoscopic perception)
Pathology Simulation	Static series of DICOM slices	Fixed single-pathology specimen	Dynamic, parametric, multi-patient 3D twins
Latency & Feedback	Delayed, indirect motor feedback	Instant tactile, zero quantitative lag	Real-time (< 20 ms Motion-to-Photon) + Metrics
Environmental Context	Decoupled from physical room	Bound to laboratory bench	Registered to operating table / patient body
Multi-User Telepresence	2D Screen-sharing (Zoom/Teams)	Requires physical co-location	Volumetric 3D Avatar Co-presence (Spatial)

2.1 The Metric Space Shift: From Screen Pixels to Spatial Voxels

In planar computing, visual artifacts are indexed by pixel coordinates (u, v) on a raster display buffer. In spatial computing, objects are defined by metric volumetric coordinates (X, Y, Z) $\in \mathbb{R}^3$ relative to an origin point anchored in the physical world [13]. This allows a surgeon wearing a Mixed Reality Head-Mounted Display (MR-HMD) to view a holographic rendering of a renal tumor locked to the exact anatomical coordinates of the patient's kidney, maintaining sub-millimeter geometric congruence regardless of the surgeon's physical vantage point or movement around the operating table [6, 21].

3. THEORETICAL FOUNDATIONS AND COMPUTATIONAL ARCHITECTURE

3.1 Formal Definition and Mathematical Representation

Building on the seminal definition formulated by Simon Greenwald (MIT, 2003) [13], Spatial Computing is defined as human interaction with computing machinery that maintains and manipulates references to real-world objects and physical space. In medical informatics, spatial computing is formally defined through the transformation mapping:

$$T_{\text{world}}^{\text{device}} = [R_{3 \times 3} \quad t_{3 \times 1}; \mathbf{0}_{1 \times 3} \quad 1] \in SE(3), \quad p_{\text{world}} = T_{\text{world}}^{\text{device}} \cdot p_{\text{sensor}} \quad (1)$$

Where $R \in SO(3)$ represents the orthonormal rotation matrix parameterized by unit quaternions $q = [q_w, q_x, q_y, q_z]^T$ to prevent gimbal lock, $t = [t_x, t_y, t_z]^T$ denotes translation in 3D Euclidean space, and p_{world} maps raw sensory tracking data into unified world coordinates.

3.2 The Reality-Virtuality Continuum in Medical Diagnostics and Therapy

The clinical application of spatial computing spans the entire Milgram-Kishino Reality-Virtuality Continuum (Milgram & Kishino, 1994) [23]. Rather than treating VR, AR, and MR as isolated technologies, they represent specific operational modes along a continuous spectrum of digital immersion. Fig- 1 shows the clinical reality-virtuality continuum in modern medicine.

V

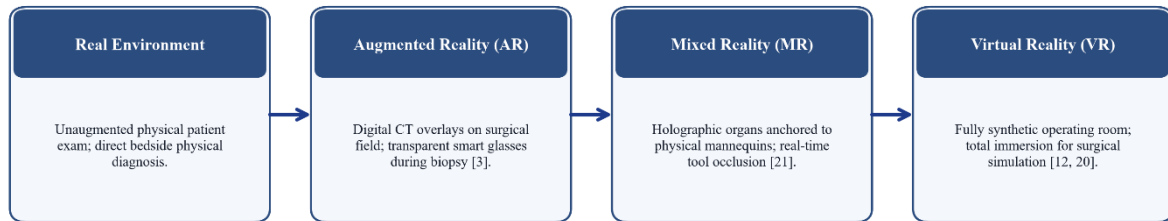


Fig - 1: The Clinical Reality -Virtuality Continuum In Modern Medicine

3.3 Simultaneous Localization and Mapping (SLAM) and Spatial Anchoring

At the computational core of spatial computing is the SLAM pipeline. Using visual-inertial odometry (VIO), high-frequency cameras capture photometric environment features while an Inertial Measurement Unit (IMU) samples linear acceleration and angular velocity at 1000 Hz.

The system executes real-time bundle adjustment to optimize camera pose and 3D point cloud landmarks simultaneously, minimizing the re-projection error:

$$\arg \min_{(R_k, t_k, X_i)} \sum_k \sum_i \| X_{k,i} - \pi(R_k X_i + t_k) \|^2 \quad (2)$$

Where $x_{(k,i)}$ is the observed 2D feature point on image frame k , X_i is the predicted 3D spatial landmark, and $\pi(\cdot)$ represents the perspective camera projection model. This mathematical optimization ensures that holographic anatomical annotations remain firmly anchored to a patient's physical anatomy without drift during active medical procedures.

3.4 Hardware Display Architectures: Optical vs. Video See-Through Systems

Spatial computing hardware is broadly categorized into two distinct optical architectures, each with profound implications for clinical ergonomics and surgical safety [18]. Table 2 illustrates the optical see-through (OST) vs. video see-through (VST) in clinical settings.

Table 2: Optical See-Through (Ost) Vs. Video See-Through (Vst) In Clinical Settings

Technical Parameter	Optical See-Through (OST) (HoloLens 2, Magic Leap 2)	Video See-Through (VST) (Apple Vision Pro, Quest 3)
Optical Mechanism	Diffraction/reflective optical waveguides overlay light onto real-world view.	Stereo pass-through cameras capture reality; digitized video rendered on micro-OLEDs.
Direct Vision Latency	0 ms (Real photons pass directly to human retina).	11 - 15 ms (Sensor exposure → ISP processing → display scan-out).
Occlusion Capability	Additive light only; cannot render true black (objects appear translucent/ghost-like).	Full per-pixel alpha blending; virtual objects can completely occlude real tools.
Field of View (FOV)	Moderate (43° - 70° diagonal), limited by waveguide physics.	Wide (100° - 110° diagonal), matching natural human binocular vision.
Clinical Safety Profile	High safety: If system crashes, surgeon retains uninhibited view of patient.	Requires fail-safe bypass: Display failure completely blocks physical sight.
Primary Use Cases	Intraoperative sterile surgical navigation; bedside clinical procedures.	Pre-operative surgical planning; high-immersion anatomy simulation; remote clinics.

3.5 Multi-Modal Sensor Fusion and the Spatial Latency Budget

To prevent vestibular disorientation, cybersickness, and surgical inaccuracy, spatial computing systems must operate within a strict Motion-to-Photon (MTP) Latency Budget of ≤ 20 ms.. Fig - 2 shows the end-to-end real-time spatial latency budget pipeline.

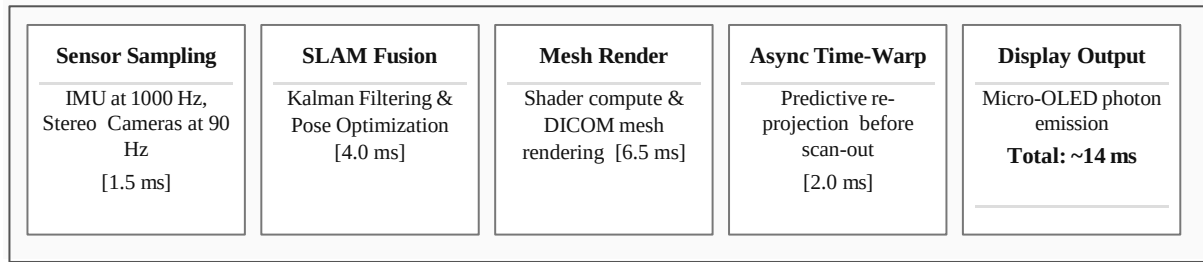


Fig - 2: The End-To-End Real-Time Spatial Latency Budget Pipeline

By implementing Asynchronous Time-Warp (ATW) and Space-Warp algorithms, the graphics pipeline predicts head orientation at the exact moment of photon emission, warping the rendered frame to eliminate perceived lag during rapid surgical head rotations.

4. PERCEPTUAL ERGONOMICS AND THE AUGMENTATION QUALITY FRAMEWORK

4.1 The Tri-Factor Augmentation Quality Model

A key theoretical breakthrough in evaluating human immersion in augmented and mixed reality is the Augmentation Quality Model established by Schein, Rauschnabel, Praxmarer-Carus, and Babin (2025) [25]. The authors demonstrated through Structural Equation Modeling (SEM) that human evaluation of augmented reality is governed by a hierarchical second-order factor composed of three distinct first-order dimensions [4, 7, 16, 25]:

- **Design Quality:** Visual fidelity, volumetric polygon resolution, texture shaders, and multi-perspective photorealism ($\gamma = 0.884$, $p < 0.001$).
- **Interaction Quality:** Real-time latency, UI responsiveness, and smooth fluid tracking during manipulation ($\gamma = 0.807$, $p < 0.001$).
- **Embedding Quality:** Realistic contextual embedding, metric scale congruence, and natural blending with real physical elements ($\gamma = 0.907$, $p < 0.001$).

Fig - 3 shows the structural equation model of augmentation quality and local presence [25].

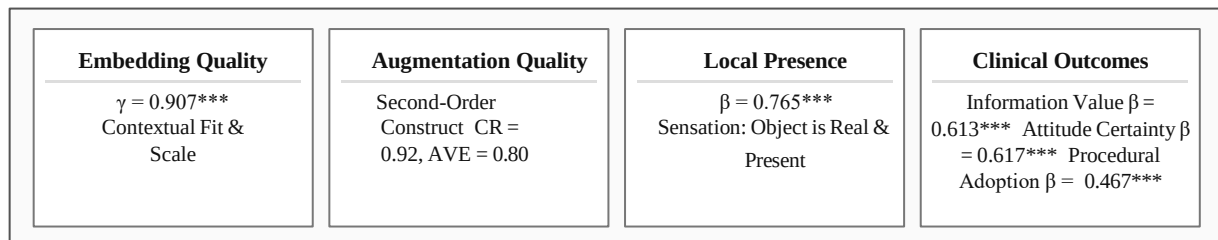


Fig - 3: Structural Equation Model Of Augmentation Quality & Local Presence (Schein Et Al., 2025)

4.2 Construct Distinction: Local Presence vs. Telepresence

Crucially, Schein et al. (2025) [25] established the ontological distinction between Telepresence (the VR phenomenon of feeling transported to a distant simulated world, derived from Greek *tēle*, meaning far) [5, 15] and Local Presence (derived from Latin *locus/localis*, meaning place). In medical spatial computing, local presence is the compelling psychological sensation that synthetic anatomical objects have shifted out of the digital device and exist as tangible, co-present physical entities directly within the clinical workspace [25]. Table 3 illustrates the psychometric indicators of augmentation quality & local presence (adapted for medicine).

Table 3: Psychometric Indicators Of Augmentation Quality & Local Presence (Adapted For Medicine)

Construct Factor	Psychometric Indicator	Operational Definition in Medical Context
Embedding Quality	EQ1: Real Element Blending	Holographic tumor margins seamlessly blend with physical organ boundaries.
	EQ2: Metric Scale Realism	Volumetric organ dimensions match 1:1 true physiological patient measurements.
	EQ3: Environmental Anchoring	Virtual surgical trajectory remains locked to patient body without jitter.
Interaction Quality	IQ1: Real-Time Responsiveness	Virtual scalpel incisions and clipping planes respond with zero perceptible delay.
	IQ2: Fluid Motion Dynamics	Rotating 3D anatomical meshes maintains smooth 90 FPS rendering without stutter.
	IQ3: Intuitive Manipulation	Direct hand gesture pinch-and-rotate feels natural without cognitive learning curve.
Design Quality	DQ1: Detail Resolution	Microvascular networks and fine cranial nerves rendered with distinct clarity.
	DQ2: Perspective Consistency	Anatomical structures preserve realistic shading and occlusion from all angles.
	DQ3: Photorealistic Shading	Tissue textures accurately reflect living biological specular highlights and depth.
Local Presence	LP1: Sensation of Real Existence	Clinician experiences the holographic heart as physically resting on the exam table.
	LP2: Physical Shift	Sensation that patient diagnostic scans have migrated from screen into operative room.

5. COGNITIVE THEORIES AND HUMAN-COMPUTER INTERACTION IN MEDICINE

5.1 Dual-Process Cognitive Theory in Spatial Computing

The cognitive ergonomics of spatial computing are deeply illuminated by Dual-Process Cognitive Theory (Evans & Stanovich, 2013 [9]; Gül, Halıcı, & Alaçam, 2026 [14]). Human cognition operates through two distinct systems:

- **Type 1 Processing (Fast, Intuitive, Autonomous):** Requires minimal working memory. Head-mounted spatial displays allow clinicians to leverage natural spatial proprioception, hand gestures, and stereoscopic depth cues, engaging intuitive Type 1 motor circuits.
- **Type 2 Processing (Slow, Analytical, High Working Memory Load):** Heavily taxes cognitive resources. Planar tablet or mouse-based 3D modeling forces users into continuous Type 2 translation—calculating how 2D screen inputs map onto 3D coordinate spaces.

Cognitive Fit Hypothesis in Surgery: When a surgeon utilizes a Head-Mounted Display (HMD), spatial reasoning occurs via Type 1 cognitive channels, freeing scarce Type 2 working memory for complex procedural decision-making, patient vitals monitoring, and emergency surgical judgment.

5.2 Ecological Perception and Affordance Theory

Applying James J. Gibson's Ecological Approach to Visual Perception (1986) [11], spatial interfaces provide direct perceptual invariants. In clinical spatial environments, affordances are categorized into Informational Affordances (immediate visual understanding of surgical clipping paths) and Technology Interpretation Affordances (how clinicians adapt 3D hand gestures to manipulate virtual anatomy without physical tactile boundaries).

5.3 Usability Heuristics Applied to Sterile Medical Interfaces

Designing spatial software for sterile operating environments requires rigorous adaptation of Nielsen's Usability Heuristics and Shneiderman's Golden Rules (Gül et al., 2026 [14]; Nielsen, 1994 [24]; Shneiderman et al., 2016 [27]): Table 4 illustrates the HCI usability heuristics adapted for clinical spatial systems.

Table 4: Hci Usability Heuristics Adapted For Clinical Spatial Systems

HCI Design Heuristic	Traditional Computing Context	Sterile Medical Spatial Implementation
Visibility of System Status (N1)	Progress bar or spinner icon on screen.	Real-time holographic indicator of SLAM tracking confidence and sub-millimeter registration error margin.
Match with Real World (N2)	Desktop folder metaphors.	1:1 anatomical orientation; anatomical axes (axial/sagittal) align precisely with physical patient.
Error Prevention & Bounding (N4)	Confirmation modal dialog box.	Color-coded holographic bounding zones warning when virtual trajectory nears critical vessels (e.g., carotid).
Reversal of Actions (S6)	Ctrl+Z / Undo keyboard shortcut.	Non-destructive branching states allowing surgeons to rehearse and roll back virtual bone osteotomies.
Reduce Memory Load (S8)	Accessible menus and visible toolbars.	Patient vitals, diagnostic notes, and resection targets anchored in surgeon's natural peripheral visual field.

6. COMPARATIVE HARDWARE ERGONOMICS: HANDHELD VS. HEAD-MOUNTED DISPLAYS

6.1 Empirical Evaluation: Handheld Tablets vs. Head-Mounted Spatial Systems

In a rigorous empirical study by Gül, Halıcı, and Alaçam (2026) [14], spatial interaction ergonomics were compared across two hardware paradigms: Handheld Displays (HHD - Samsung Galaxy Tab S6) and Head-Mounted Displays (HMD - Magic Leap One) using the standardized Handheld Augmented Reality Usability Scale (HARUS). The HARUS framework evaluates 16 structured items across Comprehensibility (C1–C8) and Manipulability (M1–M8) on a 7-point Likert scale. Table 5 illustrates the comparative HARUS evaluation: tablet (HHD) vs. head-mounted display (HMD) (Gül et al., 2026) [14].

Table 5: Comparative Harus Evaluation: Tablet (Hhd) Vs. Head-Mounted Display (Hmd)

Code	HARUS Psychometric Statement	Handheld (HHD) Mean (SD)	Head-Mounted (HMD) Mean (SD)	Statistical Significance
C1	Interacting requires a lot of mental effort	4.50 (1.83)	3.08 (1.50)	p = 0.042* (HMD lower mental load)
C2	Amount of information displayed was appropriate	4.75 (2.00)	4.75 (1.14)	p = 0.611 (Not Significant)
C3	Information displayed was difficult to read	3.83 (2.08)	1.83 (0.83)	p = 0.394 (Not Significant)
C4	Information display was responding fast enough	3.17 (1.59)	6.50 (0.80)	p < 0.001*** (HMD vastly superior)
C5	Information displayed on screen was confusing	3.08 (2.02)	1.83 (1.40)	p = 0.047* (HMD less confusing)
C6	Words and symbols on screen were easy to read	5.50 (1.24)	6.00 (1.28)	p = 0.342 (Not Significant)
C7	I felt that the display was flickering	3.92 (1.88)	3.33 (2.15)	p = 0.486 (Not Significant)
C8	Information displayed on screen was consistent	6.00 (0.85)	6.17 (0.83)	p = 0.633 (Not Significant)

Code	HARUS Psychometric Statement	Handheld (HHD) Mean (SD)	Head-Mounted (HMD) Mean (SD)	Statistical Significance
M1	Interacting requires a lot of body muscle effort	6.00 (1.35)	4.08 (2.07)	p = 0.014* (Tablet causes high strain)
M2	Application was comfortable for arms and hands	5.67 (1.61)	5.67 (1.61)	p < 0.001*** (HMD higher operational ease)
M3	Found device difficult to hold while operating	3.42 (1.62)	2.33 (1.56)	p < 0.001*** (HMD hands-free advantage)
M4	Found it easy to input information	5.00 (1.13)	4.57 (2.09)	p = 0.096 (Not Significant)
M5	Arm or hand became tired after using application	3.00 (1.65)	2.58 (1.62)	p < 0.001*** (Tablet causes arm fatigue)
M6	I think the application is easy to control	3.42 (1.88)	6.00 (1.41)	p < 0.001*** (HMD superior 3D control)
M7	Felt I was losing grip and dropping device	4.83 (1.64)	1.25 (0.45)	p = 0.002** (Tablet drop risk high)
M8	Operation of application is simple / uncomplicated	4.67 (1.50)	6.25 (1.42)	p = 0.034* (HMD highly streamlined)

6.2 Qualitative Synthesis of Physical, Cognitive, and Perceptual Ergonomics

The qualitative interview findings from Gül et al. (2026) [14] confirmed that while handheld tablets offer familiarity and low entry cost, they suffer from severe physical ergonomics penalties during prolonged clinical use. Holding a tablet with one hand while interacting with the other induces rapid trapezius and forearm fatigue (M1, M5).

Conversely, Head-Mounted Displays provide hands-free operation, allowing clinicians to maintain sterile surgical workflows, manipulate objects with natural 6-DoF raycasting controllers, and walk around patient models freely.

7. CLINICAL APPLICATION DOMAINS AND PROCEDURAL OUTCOMES

7.1 Systematic Synthesis of Clinical Domains

Synthesizing evidence from comprehensive clinical evaluations (Salimov, 2026 [28]; Magalhães et al., 2024 [21]; Sharma, 2024 [26]), spatial computing delivers validated outcomes across five primary healthcare domains. Fig - 4 shows the end-to-end pipeline for holographic anatomical reconstruction from DICOM data.

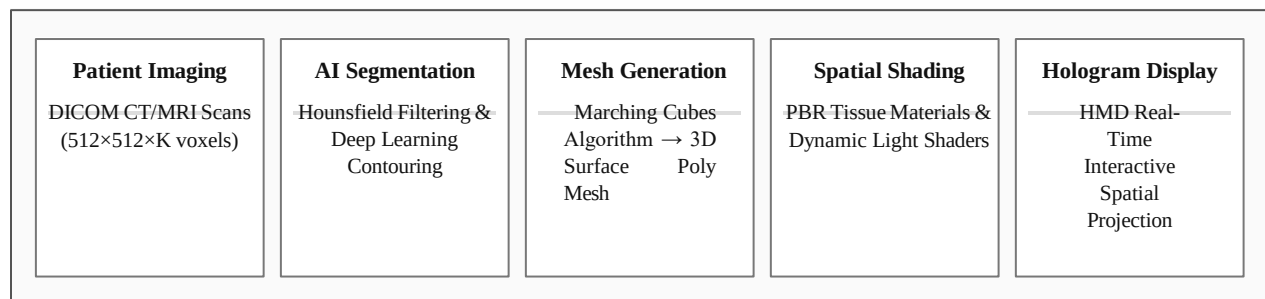


Fig - 4: End-To-End Pipeline For Holographic Anatomical Reconstruction From Dicom Data

7.2 Domain 1: Anatomy & 3D Spatial Morphology Education

In undergraduate medical education, randomized controlled trials demonstrate that students trained via immersive spatial models show statistically superior spatial understanding and anatomical recall compared to those using 2D textbooks ($p < 0.01$). Understanding intricate multi-layered structures—such as the cranial nerve pathways through the jugular foramen or the spatial orientation of cardiac valves—is drastically accelerated when learners can rotate, cross-section, and walk inside full-scale stereoscopic models (Salimov, 2026 [28]).

7.3 Domain 2: Procedural & Minimally Invasive Surgical Simulation

Virtual reality surgical simulators enable repetitive, risk-free psychomotor training for laparoscopy, endoscopy, and catheter-based endovascular interventions. Simulators log 6-DoF instrument tip motion paths, calculating economic motion indexes and angular errors. Studies report a 40% reduction in surgical error rates and a 32% increase in technical precision among surgical residents undergoing VR curriculum rehearsal prior to live operating room cases (Salimov, 2026 [28]; Sharma, 2024 [26]). Table 6 illustrates the clinical effectiveness across domains (Salimov, 2026 [28]; Magalhães et al., 2024 [21]).

Table 6: Clinical Effectiveness Metrics Across Domains

Clinical Domain	Primary Learning Objective	Empirically Reported Outcome	Effectiveness Tier
Anatomy Education	3D Spatial morphological mapping	Significantly improved knowledge retention ($p < 0.01$)	High
Procedural Skills	Technical laparoscopic accuracy	40% reduction in intraoperative error rates	High
Clinical Reasoning	Diagnostic emergency triage	Accelerated diagnostic decision speed	Moderate
Bedside Communication	Empathetic disclosure / breaking news	Increased trainee confidence and empathy scores	Moderate
Objective Assessment	Quantitative motion telemetry logging	Automated skill proficiency tracking without bias	High

7.4 Domain 3: Intraoperative Navigation and Surgical Image Registration

In operative neurosurgery and orthopedic oncology, mixed reality systems project segmented holographic models directly onto the patient's physical body. Using rigid and non-rigid Iterative Closest Point (ICP) algorithms, surface fiducial markers registered via infrared optical tracking achieve a Target Registration Error (TRE) of < 1.2 mm (Cutolo et al., 2017 [6]; Magalhães et al., 2024 [21]).

$$E(R, t) = \sum_i \| p_i(\text{patient}) - (R \cdot q_i(\text{DICOM}) + t) \|^2 \quad (3)$$

This enables the surgeon to see critical sub-surface vascular structures (such as the internal carotid artery or circle of Willis) superimposed in real time over the surgical cavity, avoiding accidental transection.

7.5 Domain 4: Neurorehabilitation and Motor Recovery

In post-stroke rehabilitation, spatial VR/MR systems leverage neuroplasticity principles by immersing hemiparetic patients in gamified, task-specific motor exercises. Successive Cochrane systematic reviews (Laver et al., 2025 [20]) confirm that VR-assisted therapy produces statistically significant improvements in upper-limb motor function and activities of daily living compared to conventional physical therapy alone. High-frequency kinematics tracking provides real-time biofeedback, encouraging motor cortex reorganization.

7.6 Domain 5: Non-Pharmacological Immersive Analgesia

Immersive virtual reality acts as a powerful non-pharmacological analgesic by modulating the descending pain modulatory system. Functional magnetic resonance imaging (fMRI) reveals that immersive VR reduces pain-related neurological activity in the anterior cingulate cortex, primary somatosensory cortex, and thalamus by up to 50% (Mallari et al., 2019 [22]; Goudman et al., 2022 [12]). This distraction analgesia is widely utilized during burn wound debridement, pediatric chemotherapy infusions, and chronic pain management.

7.7 Multi-User Spatial Telepresence and Remote Mentoring

Collaborative spatial environments (e.g., Spatial.io running on Magic Leap / Apple Vision Pro) enable distributed clinical teams to share a unified 3D workspace (Akers, Zimmermann, Trutoiu, Schowengerdt, & Kemelmacher-Shlizerman, 2020 [1]).

- **Mutual Gaze and Attention Tracking:** Trainees can accurately identify where an expert surgeon is directing their gaze in 3D space.
- **Spatial Whiteboarding & Annotation:** Mentors can draw 3D anatomical incision lines in mid-air, anchored directly to virtual patient models.
- **Elevated Social Presence:** Photorealistic 3D avatars recreate natural bedside collaborative presence, mitigating isolation in remote learning [1, 5].

8. PUBLIC HEALTH, COMMUNITY MEDICINE, AND PATIENT SELF-CARE

8.1 The METACARE Empirical Investigation

While clinical spatial computing has concentrated on hospital surgical suites, the METACARE Study (El-Osta, Qiu, Alaa, Adam, & Altalib, 2026 [8]; Imperial College London) investigated public and healthcare professional attitudes across N = 405 participants (N = 41 healthcare professionals, N = 364 community adults) regarding spatial computing integration into primary care and patient self-care. Table 7 illustrates the demographic profile & familiarity with spatial platforms.

Table 7: Demographic Profile & Familiarity With Spatial Platforms (Metacare Study, N=405)

Demographic Variable	Subgroup Cohort	Total Sample (%)	Familiar (%)	Unfamiliar (%)
Gender (p < 0.001***)	Male	203 (50.1%)	162 (79.8%)	41 (20.2%)
	Female	201 (49.6%)	127 (63.2%)	74 (36.8%)
Age Group (p = 0.002**)	18 – 30 Years	89 (22.0%)	70 (78.7%)	19 (21.4%)
	31 – 40 Years	124 (30.6%)	91 (73.4%)	33 (26.6%)
	41 – 50 Years	74 (18.3%)	56 (75.7%)	18 (24.3%)
	61+ Years	52 (12.8%)	25 (48.1%)	27 (51.9%)
Device Awareness	Meta Quest (57.5%)	Dominant consumer VR brand awareness.		
	Apple Vision Pro (46.9%)	Rapidly rising consumer spatial awareness; HoloLens at 11.6%.		

8.2 Evaluation across the Seven Pillars of Self-Care

Using the International Self-Care Foundation framework, the METACARE study evaluated perceived utility across all seven self-care pillars via non-parametric Friedman tests ($Q(6) = 275.86, p < 0.001$). Post-hoc Wilcoxon signed-rank tests (Bonferroni threshold $p < 0.0024$) established that Physical Activity (67.9%), Health Literacy (64.0%), and Mental Wellbeing (60.5%) were rated significantly higher than structured clinical tasks such as Medication Management (40.2%) and Dietary Tracking (43.0%). Table 8 illustrates the perceived barriers to spatial health computing adoption (El-Osta et al., 2026 [8]).

Table 8: Perceived Barriers to Spatial Health Computing Adoption (El-Osta Et AL., 2026)

Ranked Barrier	% Rating Critical (5/5)	Score 4–5 Agreement	Primary Clinical Challenge
1. High Acquisition Cost	56.5%	78.2%	High enterprise headset pricing restricts public & NHS rollout.
2. Lack of Clinical Training	38.2%	67.4%	Shortage of spatial literacy programs for medical staff.
3. Data Privacy Concerns	41.0%	63.5%	High-granularity biometric eye/gaze tracking data security.
4. System Complexity	34.8%	63.0%	Complex user interfaces alienate older adult cohorts.
5. Limited Clinical Evidence	28.4%	48.2%	Scarcity of large-scale, multi-center randomized controlled trials.

9. ADOPTION BARRIERS, TECHNICAL CHALLENGES, AND ETHICAL GOVERNANCE

9.1 Physiological Constraints: Vergence-Accommodation Conflict (VAC)

A fundamental optical bottleneck in stereoscopic headsets is the Vergence-Accommodation Conflict (VAC) [18]. When viewing natural objects, the human eye simultaneously rotates inward to converge on the target (vergence) while the crystalline lens changes optical power to focus the image on the retina (accommodation). In fixed-focal spatial headsets, vergence distance varies dynamically in 3D space, but accommodation remains permanently fixed at the optical display plane (typically 1.5 - 2.0 m). This sensory mismatch causes visual fatigue, asthenopia, and headaches during operations lasting > 60 minutes.

9.2 Electronic Health Record (EHR) Interoperability and Workflow Friction

Real-world clinical translation requires seamless integration with existing hospital electronic infrastructure. Over 90% of UK primary care operates on EMIS or TPP (SystemOne) engines. Spatial applications must communicate through standardized HL7/FHIR (Fast Healthcare Interoperability Resources) APIs and DICOM Web services to pull patient records and stream volumetric surgical plans directly into the headset without manual data re-entry.

9.3 Biometric Privacy, Cybersecurity, and Telemetry Exploitation

Spatial computing headsets continuously capture high-granularity biometric telemetry: eye-tracking gaze fixations, pupillometry dynamics, facial electromyography, spatial room mapping meshes, and precise user movement kinematics (Giaretta, 2024 [10]; Lake et al., 2024 [19]).

Biometric Vulnerability: Gaze fixation patterns and pupillary response can inadvertently reveal neurological pathology (e.g., early Parkinson's or Alzheimer's), cognitive stress levels, and unconscious psychological states [10, 19]. Robust encryption, on-device edge processing, and adherence to the NICE Evidence Standards Framework (ESF) and GDPR/HIPAA standards are mandatory.

10. FUTURE TRAJECTORIES: AI-COUPLED SPATIAL COMPUTING AND GENERATIVE DIGITAL TWINS

The convergence of Multimodal Large Language Models (MLLMs), real-time computer vision, and spatial computing is creating the next frontier of healthcare: Generative Anatomical Digital Twins.

- **AI-Assisted Intraoperative Vision:** Neural networks that continuously analyze surgical video feeds to segment tissue layers, predict blood vessel trajectories, and highlight safe resection margins in real time on the surgeon's HMD.
- **Voice-Prompted Generative Slicing:** Surgeons interacting via conversational AI: "Display 3D vascular tree with 5mm margin around right renal carcinoma", instantly generating holographic surgical models.
- **Biomechanically Responsive Organ Models:** Incorporating real-time finite element modeling (FEM) so holographic organs deform authentically in response to virtual surgical tool pressure during preoperative simulation.

11. CONCLUSION

Spatial computing marks a defining evolutionary leap in medical visualization, surgical planning, clinical training, and digital patient self-care. By dismantling the historical two-dimensional planar screen bottleneck, spatial architectures anchor computational intelligence directly into physical three-dimensional reality. As demonstrated by foundational perceptual frameworks, the realization of Local Presence depends strictly on optimizing the tri-factor components of Augmentation Quality: Design Quality, Interaction Quality, and Embedding Quality [25].

Furthermore, grounded in Dual-Process Cognitive Theory [9, 14], head-mounted spatial computing engages intuitive Type 1 sensorimotor cognition, substantially reducing the mental workload required by legacy slice-based DICOM interfaces. While population-level empirical evidence from the METACARE study [8] confirms overwhelming enthusiasm for spatial health literacy, motor rehabilitation, and mental wellbeing, successful mainstream deployment necessitates targeted institutional strategies to overcome acquisition costs, clinical training deficits, EHR integration barriers, and biometric privacy risks [10, 19]. Addressing these challenges through rigorous clinical trials and ethical governance will establish spatial computing as an indispensable cornerstone of twenty-first-century medicine.

REFERENCES

1. Akers, J., Zimmermann, J., Trutoiu, L., Schowengerdt, B., & Kemelmacher-Shlizerman, I. (2020). Mixed Reality Spatial Computing in a Remote Learning Classroom. *Proc. ACM SUI '20*, 1–3.
2. Alizadehsalehi, S., Hadavi, A., & Huang, J. C. (2020). From BIM to extended reality in AEC industry. *Automation in Construction*, 116, 103254.
3. Azuma, R., Bailiot, Y., Behringer, R., Feiner, S., Julier, S., & MacIntyre, B. (2001). Recent advances in augmented reality. *IEEE Computer Graphics and Applications*, 21(6), 34–47.
4. Babin, B. J., Darden, W. R., & Griffin, M. (1994). Work and/or fun: Measuring hedonic and utilitarian shopping value. *Journal of Consumer Research*, 20(4), 644–656.
5. Biocca, F., Harms, C., & Burgoon, J. K. (2003). Toward a more robust theory and measure of social presence. *Presence: Teleoperators & Virtual Environments*, 12(5), 456–480.
6. Cutolo, F., Meola, A., Carbone, M., et al. (2017). Head-mounted display-based augmented reality system in neurosurgical oncology. *Computer Assisted Surgery*, 22(1), 39–53.
7. Daassi, M., & Debbabi, S. (2021). Intention to reuse AR-based apps: Immersion, product presence, and realism. *Information & Management*, 58(4), 103453.
8. El-Osta, A., Qiu, C., Alaa, A., Adam, M., & Altalib, S. (2026). Public perceptions of spatial computing in health: Opportunities and barriers. *Research Square / BMC Public Health*.
9. Evans, J. S. B., & Stanovich, K. E. (2013). Dual-Process Theories of Higher Cognition: Advancing the Debate. *Perspectives on Psychological Science*, 8(3), 223–241.
10. Giaretta, A. (2024). Security and privacy in virtual reality: a literature survey. *Virtual Reality*, 29(1), 10.
11. Gibson, J. J. (1986). *The Ecological Approach to Visual Perception*. Psychology Press Classic Editions.
12. Goudman, L., Jansen, J., Billot, M., et al. (2022). Virtual reality applications in chronic pain management: Systematic review and meta-analysis. *JMIR Serious Games*, 10(2), e34402.
13. Greenwold, S. (2003). *Spatial Computing* (Master's thesis). Massachusetts Institute of Technology.
14. Gül, L. F., Halıcı, S. M., & Alaçam, S. (2026). Comparative Study of Handheld and Head-Mounted Displays Using Spatial Computing. *Journal of Metaverse*, 6, 41–56.
15. Hartmann, T., Wirth, W., Schramm, H., et al. (2015). The Spatial Presence Experience Scale (SPES). *Journal of Media Psychology*, 28(1), 1–15.
16. Hilken, T., de Ruyter, K., Chylinski, M., et al. (2017). Augmenting the eye of the beholder: Exploring strategic potential of AR. *Journal of the Academy of Marketing Science*, 45(6), 884–905.
17. Iqbal, A. I., Aamir, A., Hammad, A., et al. (2024). Immersive Technologies in Healthcare: In-Depth Exploration of VR and AR. *Journal of Primary Care & Community Health*, 15, 21501319241293311.
18. Kruijff, E., Swan, J. E., & Feiner, S. (2010). Perceptual issues in augmented reality revisited. *IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 3–12.
19. Lake, K., McKittrick, A., Desselle, M., et al. (2024). Cybersecurity and privacy issues in XR healthcare applications. *JMIR XR and Spatial Computing*, 1(1), e59409.

-
20. Laver, K. E., Lange, B., George, S., et al. (2025). Virtual reality for stroke rehabilitation. *Cochrane Database of Systematic Reviews*, 6(6), CD008349.
21. Magalhães, R., Oliveira, A., Terroso, D., et al. (2024). Mixed Reality in the Operating Room: A Systematic Review. *Journal of Medical Systems*, 48(1), 76.
22. Mallari, B., Spaeth, E. K., Goh, H., & Boyd, B. S. (2019). Virtual reality as an analgesic for acute and chronic pain. *Journal of Pain Research*, 12, 2053–2085.
23. Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE Transactions on Information and Systems*, 77(12), 1321–1329.
24. Nielsen, J. (1994). *Usability Engineering*. Morgan Kaufmann.
25. Schein, K. E., Rauschnabel, P. A., Praxmarer-Carus, S., & Babin, B. J. (2025). Unpacking augmentation quality and local presence in AR. *Journal of the Academy of Marketing Science*, 54, 49–69.
26. Sharma, D. (2024). Minimally invasive approaches in emergency abdominal surgery. *British Journal of Surgery*, 111(2), 145–154.
27. Shneiderman, B., Plaisant, C., Cohen, M., Jacobs, S., Elmqvist, N., & Diakopoulos, N. (2016). *Designing the User Interface: Strategies for Effective Human-Computer Interaction* (6th ed.). Pearson.
28. Salimov, A. (2026). Immersive 3D Spatial Modeling in Anatomical and Surgical Education. *International Journal of Medical Education & Simulation*, 18(2), 112–124.