

CARE - Clinician Augmented Reality Environment: Developing an Apple Vision Pro Framework for Image-guided Surgeries

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Abstract

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In the evolving landscape of surgical specialties, the shift toward minimally invasive procedures has become increasingly prominent, with most surgeries now being guided by imaging techniques such as laparoscopy, endoscopy, and fluoroscopy. Monitors have become essential for these procedures, yet their placement and visibility present significant challenges in terms of user experience and ergonomics, contributing to musculoskeletal disorders affecting 50-85% of practicing surgeons. Operating room staff continually seek innovations that simplify the environment, improve the surgical experience, and improve patient outcomes. Augmented Reality (AR) tools offer a promising solution by allowing optimal placement of virtual monitors, reducing the physical constraints and ergonomic challenges of traditional monitor placement. We are developing the Clinician Augmented Reality Environment (CARE) platform, a wireless streaming platform paired with an Apple Vision Pro AR headset software application, to enable wireless casting of any video source directly into the surgeon's field of view. Our implementation achieved streaming latencies under 71 milliseconds for 1080p video, meeting established requirements for real-time surgical applications. This thesis establishes a user-centered design methodology grounded in comprehensive interviews with 23 clinical and engineering stakeholders, analyzes the technical performance of our platform in surgical contexts, and evaluates the potential for clinical deployment and commercialization of AR-based surgical technologies.

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A market-focused project would not be possible without a proper understanding of the product commer-

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DEDICATION

My heart goes out to my family for their love, support, and patience throughout my last six years at the UW.

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Chapter 1

Introduction

The research aims to be the latest stage in a decade-long endeavor to find suitable applications of augmented reality (AR) in healthcare and surgical settings. Our initial proposal was a decade-later continuation to the works of Liebert et al. and Aalami, who, over 2013-2016, investigated the feasibility and potential utility of head-mounted displays for real-time wireless vital sign monitoring during surgical procedures using a custom streaming platform which they had developed for the original Google Glass platform [1, 2]. Over the decade, advancements in AR technology, such as higher processing power, higher resolution, more intuitive controls, and longer battery life, have redefined the AR landscape. This thesis aims to be a 2025-era update re-examining the feasibility and utility of Augmented Reality (AR) in surgery using the Apple Vision Pro towards the overarching goal of simplifying the operating room to enhance procedural situational awareness.

Throughout the initial technical scoping stage and the user study process, we were able to define the exact scope of the thesis better. AR platforms, such as the Apple Vision Pro, offer a vast range of features and capabilities [3]. This thesis focuses entirely on the specific problem space of virtual monitors for image-guided surgeries.

This thesis delves into the user study and the development of the proposed CARE platform, presenting our journey of delivering a user-centric design and implementing it on the Vision Pro headset. This thesis also delves into our proposed plans to further validate the CARE implementation through clinical testing, future feature additions to the CARE platform, and current and future steps towards commercializing the

CARE platform, as well as anticipated challenges along the path to bridge technical implementations with product commercialization. We aim to answer the overarching question of “How can Augmented Reality human-computer-interaction methods be used to simplify the operating room to improve clinician and patient outcomes?”

1.1 The Rise of Image-guided Surgery

In the evolving landscape of surgical specialties, the shift toward minimally invasive procedures has become increasingly prominent, with most surgeries now being guided by imaging techniques such as laparoscopy, endoscopy, or radiography (fluoroscopy) [2], which Aalami detailed in their 2017 seminar in Appendix 5. Since the first laparoscopic appendectomy was performed in 1983 [4], surgeons have rapidly adopted minimally invasive surgical (MIS) techniques for an expanding range of applications. This transformation represents one of the most significant paradigm shifts in modern surgery, with laparoscopic procedures showing a dramatic 462% increase among general surgery residents between 2000 and 2018, and overall minimally invasive case volumes increasing by 111% from 2003 to 2019 [5].

Compelling clinical advantages have driven this shift toward minimally invasive techniques. Patients experience reduced postoperative pain, shorter hospital stays, faster recovery times, improved cosmetic outcomes, and lower infection rates compared to traditional open procedures [6, 7, 8]. From an economic perspective, minimally invasive approaches often result in cost savings through reduced hospital length of stay and faster return to work, despite higher initial equipment costs [9].

Monitors have become essential for these procedures, as shown in Fig. 1.1, yet their placement and visibility present significant challenges in terms of user experience and ergonomics. These challenges have become increasingly recognized as limiting factors in surgical performance and surgeon wellness, with studies revealing that 50-85% of practicing surgeons worldwide experience regular musculoskeletal discomfort in the neck, shoulders, and back [10].

Specific monitor placement issues include suboptimal positioning that forces surgeons to adopt awkward postures during procedures. Research has established that monitors are frequently positioned too high and too far away from surgeons [12], forcing them to crane their necks upward and lean forward to maintain adequate visualization. Ergonomic guidelines recommend that monitors should be positioned 80-120



Figure 1.1: An image-guided surgery in-session. Notice the gazes of attention from all three clinicians at the operating site, directed at the three physical monitors suspended from support arms [11].

centimeters from the surgeon's eyes [13] and placed 10-25 degrees below the horizontal plane of the eye to promote neutral cervical spine positioning [10]. However, many operating rooms utilize fixed-height tower systems that cannot accommodate these optimal positioning requirements for surgeons of varying heights [13].

1.2 The Potential of Augmented Reality (AR)

Augmented Reality (AR) headsets offer a promising solution by allowing the virtual placement of these critical monitors in optimal locations, thereby enhancing ergonomics and surgeon comfort. AR devices with strong passthrough capabilities allow computer graphics to be rendered directly in the wearer's field of vision, effectively integrating a 3-dimensional television into the wearer's field of view without seriously disrupting the wearer's organic vision [14]. Combined with novel methods of user input from the AR hardware, such as eye, hands, and body tracking, AR technology allows hands-free control of high-resolution content merged into reality with minimal middle-processing between the wearer's senses and their input-

output to reality, effectively allowing clinicians to freely move, resize, create, and delete virtual monitors from their field of view simply by waving their hands and fingers around or using other methods of hands-free control, such as voice commands [15, 16]. These powerful capabilities make AR an ideal candidate to face the challenge of simplifying the operating room to enhance procedural situational awareness, improve ergonomics, and surgeon comfort [17]. Fig. 1.2 compares the original example of a current image-guided surgery setup shown previously in Fig. 1.1 with a concept image of a hypothetical implementation of an AR headset-based virtual monitor setup from the point of view of the right-most clinician.

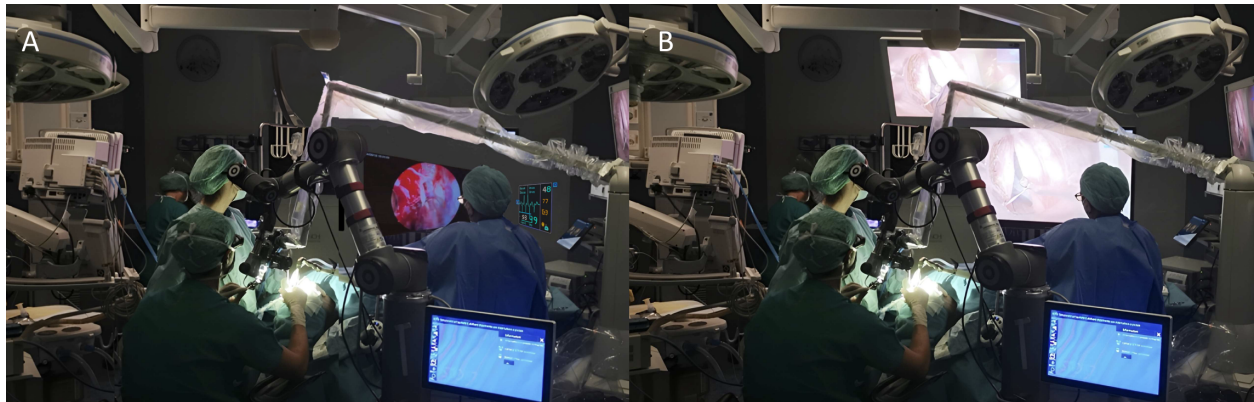


Figure 1.2: The concept image above compares the operating room with (B) and without (A) the use of the CARE virtual monitor interface, edited with Adobe Photoshop. Note that image (A) only shows the virtual displays from the perspective of the right-most surgeon. The other two surgeons would each have their own customized virtual display layouts, which are exclusively visible to them [11, 18].

Although AR-healthcare research published in the 2013-2016 era, which leveraged the Google Glass, as shown in Fig. 1.3, as a platform for hosting AR interactions, surfaced several limitations of AR technology at the time, they still demonstrated that AR technology has fundamental compatible points with medical practices, and expressed optimism of an increase in compatibility as AR technology grows more mature and robust while suggesting that the testing of AR devices in surgical settings should continue and increase in scale and reach to assess its feasibility potential larger-scale deployments further [1, 2, 19, 20, 21, 22].

The field of Augmented Reality (AR) has seen steady growth in the past decade. The Microsoft HoloLens 2 [23] turned four years old in 2023, and the Meta Quest 3 was released in October 2023 [24]. The Apple Vision Pro, as shown in Fig. 1.4, was released in February 2024 [25]. The release of these current-generation devices suggests that the AR field is steadily maturing and could deliver on its promise to usher in a new era of spatial computing.



Figure 1.3: The Google Glass, released in 2013 [26].



Figure 1.4: The Apple Vision Pro, announced in 2023 and released in 2024 [27].

The introduction of the Apple Vision Pro in 2023 marked a significant breakthrough in AR technology. Leveraging spatial computing, the headset projects digital content directly onto high-resolution displays, enabling applications and interfaces to appear seamlessly overlaid in three-dimensional space onto the real world [25]. The Vision Pro is also the first commercial AR headset to use eye-tracking and hand-tracking as part of its native user-interface input methods for cursor control and navigation, in contrast to earlier devices which included these features but did not leverage them for native user input, such as the 2019 HTC Vive Pro Eye that used eye tracking for rendering and analytics only [28], and the Meta Quest 2's 2019 hand-tracking feature that served as an optional input method on top of its central navigation theme using physical controllers [29]. Fig. 1.5 demonstrates the Vision Pro's native user interface in action, where scrolling through a text document could be done by pinching and dragging directly with the user's hands. Items could be selected throughout the space simply by turning the user's head.

The Apple Vision Pro can provide surgeons with real-time information directly within their view, minimizing the need to shift their gaze during a procedure away from the operating site. By seamlessly overlaying diagnostic imaging, anatomical models, and critical patient data onto the surgeon's immediate field of view, these emerging technologies promise to potentially improve patient outcomes across complex medical interventions [3]. Building on these new capabilities, which far outpace the capabilities of the 2013 Google Glass's role as a wearable heads-up-display [1], we see a strong incentive for another thorough investigation of the feasibility of augmented reality in a clinical setting, both as a feasibility assessment and demonstration of the growing maturity of the field of augmented reality.

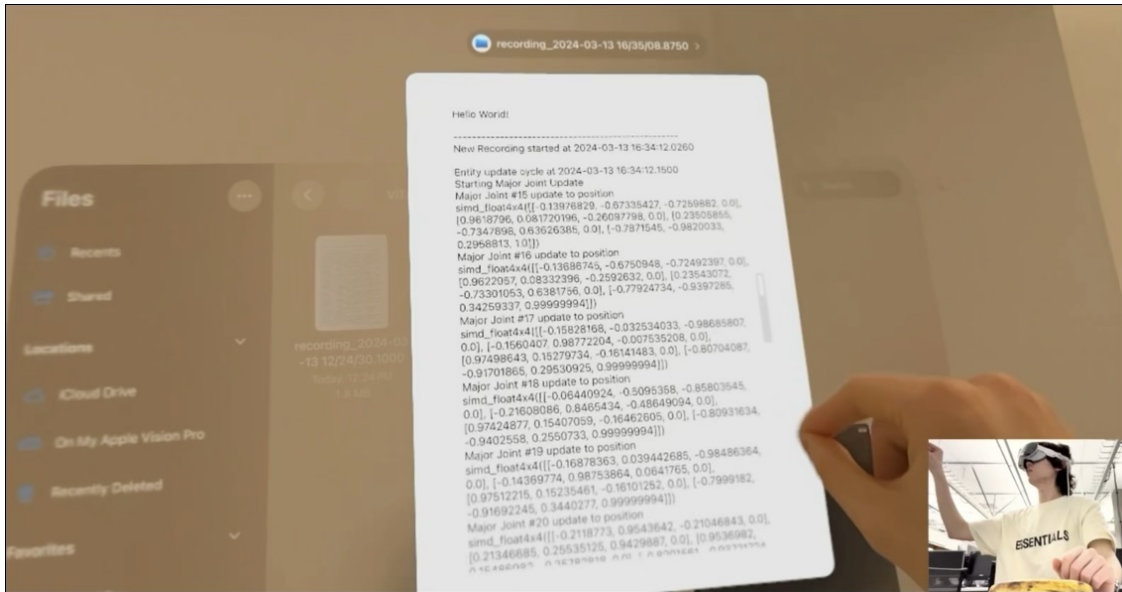


Figure 1.5: Author testing CARE system hand gesture functionality.

Lastly, although Apple’s presence in the AR space far predates the release of the Vision Pro in 2024, with the first iOS AR apps being built with camera-based software frameworks since the mid-2010s [30, 31] and Apple’s official release of its ARKit framework for iOS in 2017 [32], the Vision Pro marks Apple’s first entry into the dedicated AR hardware space and its first product with AR as the primarily and only method of user interaction. Therefore, literature and investigation into the capabilities of the Apple Vision Pro is much more sparse [33] than that of other AR devices and platforms, such as the Microsoft HoloLens, with hundreds of published literature investigating its use and effectiveness in surgical settings [34]. This gap in existing literature represents an additional incentive to focus this thesis on the Apple Vision Pro.

1.3 Scope of the Thesis

The scope of this thesis primarily encompasses the design and development of the Clinician Augmented Reality Environment (CARE) platform, as illustrated in Fig. 1.6, as well as our proposed plans for future clinical testing and potential commercialization. The detailed boundaries of the scope of this thesis are outlined below to show the precise area of investigation that this thesis project encompasses, and which are deemed to be out of scope for the time and resources available.

User-Centered Design Research: A significant portion of this research is dedicated to understanding

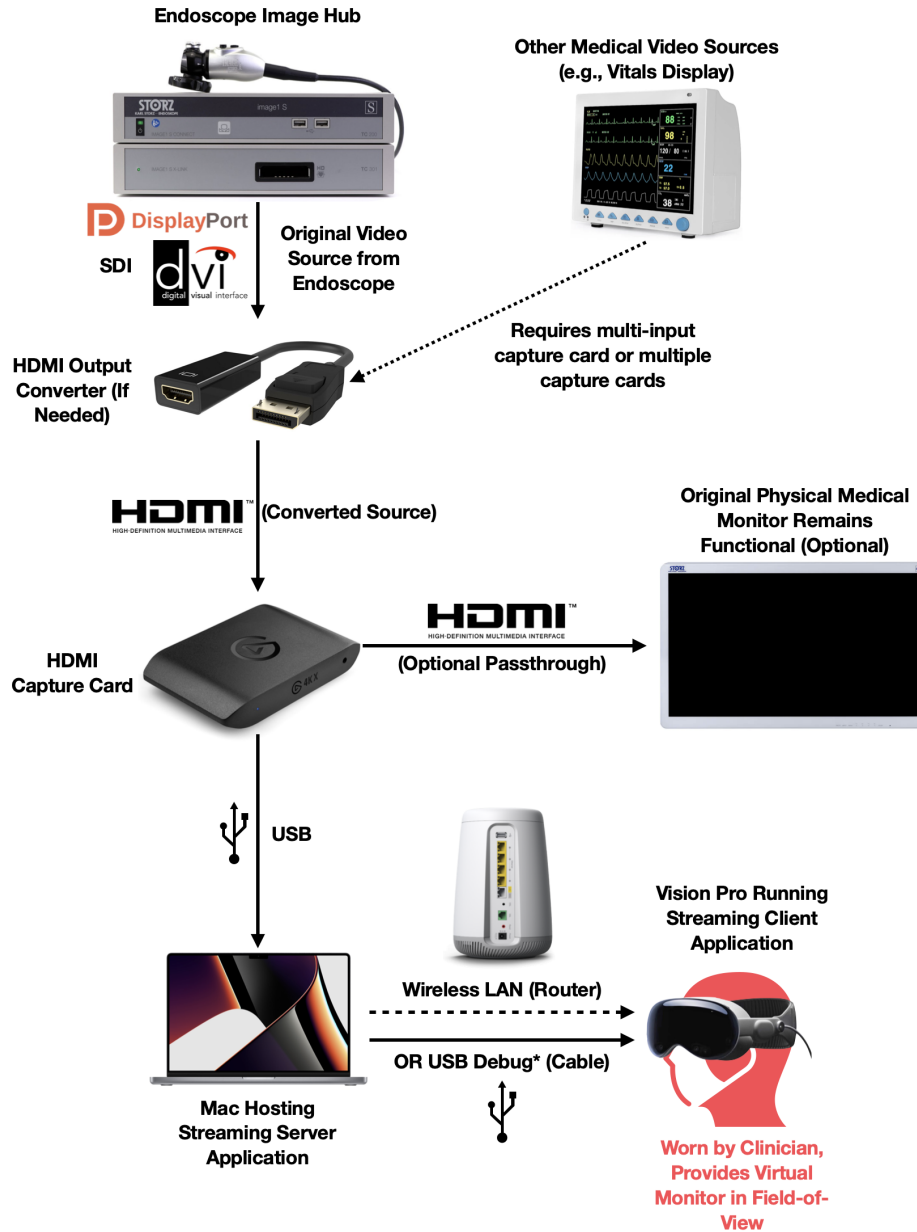


Figure 1.6: CARE system architecture showing the video streaming workflow from endoscope to Apple Vision Pro. Product images courtesy of their respective manufacturers. Note*: The Apple Vision Pro does not have a user-facing USB connection; wired USB casting requires the Vision Pro Developer Toolkit.

the clinical problem space through comprehensive stakeholder interviews. The scope encompasses qualitative research with 23 participants, including 9 anesthesiologists and 5 surgeons, to identify specific pain points in current image-guided surgical workflows. This user study directly informs the design requirements and feature prioritization of the CARE platform, ensuring that the technological solution addresses

real clinical needs.

Technical Implementation Scope: The CARE system, as shown in Fig. 1.6, integrates a local area network (LAN) video streaming architecture paired with a native Apple Vision Pro application, paired with a native macOS server application to enable wireless or wired casting of surgical video feeds directly into the surgeon's field-of-view. The technical scope encompasses the development and optimization of the streaming framework, aiming to achieve sub-100-millisecond latencies for 1080p video content. It also includes latency measurement methodologies and the implementation of intuitive hand gesture and eye tracking interfaces designed explicitly for sterile surgical environments. The CARE platform enables the capture of any compatible video output signals from medical devices using a capture card, allowing them to be streamed into a Mac hosting the streaming server. Multiple medical devices can stream their video feeds into the Mac streaming server using multi-input capture cards or by connecting multiple capture cards directly to the server. Lastly, the input passthrough feature, which is present on most mid and high range capture cards on the market today, allows the original video input to be still routed to the original physical monitor, potentially serving as a back up display without the added latency of the capture card and the streaming server; this allows the CARE system to strictly add functionality to the source-to-monitor pipeline without compromising the existing clinical workflow.

Clinical Application Focus: While AR technology offers broad applications in healthcare, this thesis deliberately focuses on the specific use case of virtual monitor placement for image-guided surgeries such as laparoscopy, endoscopy, and fluoroscopy procedures. The scope includes ergonomic analysis of current monitor placement challenges and the development of solutions that enhance surgeon comfort while maintaining or improving surgical precision. Other features that could be enabled by the same Vision Pro headset under the same clinical settings, including displaying 3D artifacts to aid surgeon navigation, streaming the surgery from a surgeon's point of view for clinical training, more surgeon user interface methods, and integrating the CARE platform

Validation and Future Clinical Integration: The scope extends to establishing a foundation for clinical validation through the development of testing methodologies based on established research frameworks, particularly building upon the work of Liebert et al. and Aalami [1, 2], pioneering research with Google Glass in surgical environments. Although clinical trials are beyond the scope of the current thesis due to

the administrative and time commitment required, which exceeds the available resources for a Master's thesis, the thesis establishes the technical and methodological foundation necessary for future operating room studies, and hypothetical clinical trials have been planned as a future next step for the CARE project, as explained in Section 4.1 "Clinical Trials: Iterating from Clinical Insights." The scope of the current thesis explicitly does not include comprehensive clinical efficacy studies, full regulatory approval processes, or extensive comparison with competing AR surgical platforms, as these factors would only become relevant once CARE is ready to commit to larger-scale clinical trials fully.

1.4 Contributions of the Thesis

The overarching contribution of this thesis aims to encourage further research and investigation into the capabilities of the Apple Vision Pro and other current-period AR tools for surgical use. Through the foundational work that this thesis establishes, we wish for it to be a stepping-stone and catalyst for future explorations.

This thesis aims to contribute to the ongoing endeavor of integrating augmented reality into surgical practice by providing both a technical demonstration of current AR capabilities and a user-informed design methodology that bridges the gap between technological possibility and clinical practicality. First, we demonstrated the importance of conducting proper pre-design user studies and presented empirical findings of the problems that exist in the image-guided surgery space. Second, we demonstrated that a streaming platform built using off-the-shelf commercial tools is already capable of achieving latency and resolution figures that are considered acceptable for surgical use, suggesting that, if provided with additional engineering resources and access to lower-level AR headset frameworks or even custom AR hardware, resolution and latency could be further improved. Third, we present our plans for future clinical trials, commercialization, and features that were designed but not implemented into the CARE platform as a call to action for future research and exploration.

Chapter 2

User Study: Understanding the Problem Space

Identifying stakeholder groups and user needs is paramount to the design-engineering process, allowing us to understand the nature of the problem space. For the CARE user study, we aimed to interview clinicians and medical professionals working in operating rooms to inform the development of an Apple Vision Pro application designed for use in surgical settings.

Current explorations of AR in the surgical operating room emphasize various modes of monitoring and data retrieval, such as anatomical evaluations, surgical collaboration, instant access to web-based resources, and tele-mentoring [19]. Other forms of technology, such as phone apps and other planar IOT devices, continuously monitor patients at a high-resolution scale that is limited to the physical placement of the device and is only accessible before and after the surgical operation [2].

While these advances have addressed several issues that concern clinicians, the topic of UI interactivity and information display workflows in AR remains underexplored, particularly in the realm of visual design. This gap in research presents an opportunity to investigate further how AR interfaces can better support user interaction and comprehension.

2.1 Outreach Methods and Interviewee Demographics

To better understand the current landscape, we began this study by examining how augmented reality is currently being used in medical applications. This research helped familiarize our team with the area of inquiry and formed the basis for our primary research; qualitative data collection through user interviews to validate our problem space and proposed concepts. These interviews helped us understand workflow challenges and identify potential design opportunities. We asked about their daily routines, current tools, pain points, thoughts on using AR in surgery, and their vision for the future of healthcare. These interviews helped us design a well-informed minimum viable product focused on improving real-time data access, with the potential to adapt to various surgical settings as the product evolves. A complete list of standardized interview questions used by the CARE team can be found in Appendix 5. We consulted with the University of Washington Human Subjects Division, which verified that our user study is compliant with the Institutional Review Board's policies and protocols.

We based our design requirements on data from 23 participants, grouped into primary and secondary stakeholders based on their proximity to the final use case. Our main stakeholder group consisted of 9 anesthesiologists and 5 surgeons who would either be the main users of the design or actively impacted by the design's capabilities. Our secondary stakeholder group consisted of 9 outlier participants who represent other assets of the operation and prototyping expertise of the MVP. These participants included 2 patients, 1 nurse, and 6 AR designers and design researchers. The demographic information of all clinical interviewees is present in Table 2.1. The demographic information and interview responses for the 6 AR designers and design researchers are not included below, as the interviews do not contain any direct clinical insights.

Although the scale of the user study and the number of interviewees were limited by the human and administrative resources we had access to as a team, we believe that the demographic composition of our 25 interview participants reflects a strategic approach to stakeholder engagement that aligns directly with the interdisciplinary nature of modern surgical environments. As shown in Table 2.1, our primary stakeholder group comprised 9 anesthesiologists (52%) and 5 surgeons (29%), representing the core medical professionals who would directly interact with the CARE platform during image-guided procedures. This distribution acknowledges the critical role that anesthesiologists play in continuous patient monitoring throughout surgical procedures, while ensuring substantial representation from surgeons who serve as the primary decision-

Questions	Ideas	Freq	%
What is your Job?	Anesthesiologist	9	52
	Nurse	1	6
	Surgeon	5	29
	Patient	2	12
What is your highest priority during procedures?	Safety, Painlessness	11	65
	Patient satisfaction	6	35
	Verifying patient information	1	6
	Ensuring that the patient is not aware of the operation	1	6
How many people are usually in the operating room?	Case specific	1	6
	Floating nurses, instrument nurses, circulating nurses, etc	8	47
	Anesthesiologists/anesthesiology team	9	52
	Surgeons/surgical team	9	52
	NA	6	35
What kind of information is important when performing the procedure?	Patient condition, diseases, psychological status, vitals, blood pressure, etc.	10	59
	EEG detection, cardiac output detection, cerebral oxygen saturation	3	18
	Impact of surgery and of administering anesthesia, patient history	5	29
	Any patient information is crucial. Minor oversights could lead to critical mistakes	1	6
	NA	5	29
How do you typically exchange information within the team?	Group chats and morning case handovers	3	18
	Fully electronic system	3	18
	Mutual understanding between teams with reminders along the way	2	12
	Verbal, face-to-face or phone	9	52
What tools do you use throughout the process?	Endotracheal tube, laryngoscope, medication infusion pump, anesthesia machine, warming blanket, fluid warmer	8	47
	Blood verification tools	1	6
	Electrocautery, ultrasonic scalpel, ion knife, nano knife, argon gas	4	24
	Screens for minimally invasive surgeries	1	6
	NA	6	35

Table 2.1: Table depicting clinical interviewee demographic information.

makers and end-users of imaging displays. The inclusion of nursing staff (6%) and patient perspectives (12%) provides essential insights into the broader ecosystem of surgical care, recognizing that successful AR implementation must consider all stakeholders who interact within the operating room environment.

The responses regarding professional priorities reveal a remarkably consistent focus across all participant groups, with 65% emphasizing safety and painlessness as their highest priority during procedures. This unified commitment to patient safety provides a strong foundation for evaluating how AR technology can enhance rather than compromise existing safety protocols. The diversity in communication preferences, with 52% relying on verbal and face-to-face communication, highlights the importance of designing AR interfaces that complement rather than replace established workflows. Similarly, the variety in surgical tools and monitoring equipment mentioned by participants underscores the need for a flexible platform that can

integrate with existing technological infrastructures rather than requiring wholesale system replacement. This unification of stakeholder profiles enables us to identify a relatively homogeneous stakeholder group that will serve as our core users. By tailoring our design and engineering prototypes to meet the specific needs of this demographic better, we can avoid designing a one-size-fits-all solution.

2.2 Interview Findings

Table 2.2 presents interview findings on the topic of image-guided surgery procedural challenges, while Table 2.3 presents the perspectives of clinicians on the use of AR technologies for image-guided surgeries.

Questions	Ideas	Freq	%
What are the distractions and difficulties you face during procedures?	Monitor visibility, older equipment, lack of real-time monitoring	1	6
	Too many surgeries and too many patients	1	6
	Noise during electrocardiograms	1	6
	Fluctuating vitals signs during anesthesia induction	1	6
	Patient transitions can be inefficient	1	6
	Blood loss, allergies, anaphylactic shock, etc.	1	6
	Disagreements between surgeons and anesthesiologists	1	6
	None	5	29
	NA	4	24
Are there specific technical difficulties you encountered when doing your job?	Tech effective, but integration lacking; data retrieval only on screens	1	6
	Logging surgery time difficult to sync due to multiple systems	1	6
	Human error (due to multiple systems, accidents)	2	12
	Multiple monitors are inconvenient to adjust during critical procedures	1	6
	Hardware problems depending on country/institution	1	6
	Difficult intubation and abnormal anatomy	1	6
	Difficulty in arterial and venous puncture	1	6
	None	3	18
	NA	3	18

Table 2.2: Current procedural challenges and technical difficulties reported by clinical staff during image-guided surgical procedures.

The primary pain points outlined by the clinicians are listed below, matching literature findings, which also further elaborate on the extent and consequences of these pain points in the field:

Pain point 1: The physical constraint of fixed monitor setups. According to the surgeons interviewed, the fixed position of current surgical display setups causes immense strain to the back and neck throughout the operation due to active monitoring [10]. Current setups are wire-dependent and only partially address ergonomic challenges by standing 1.40 to 1.65 meters above the ground, adjacent to the surgeon’s height [13]. Studies have documented that 48-68% of surgeons experience work-related neck pain, with minimally

Questions	Ideas	Freq	%
Do you have prior AR experience?	None	12	71
	Google Glasses, DaVinci system	3	18
	Authored a paper for an AR tool before	1	6
How do you envision incorporating AR?	Training	6	35
	Virtual imaging	6	35
	Spatial awareness, aid decision making, enhance efficiency	5	29
	Communication	3	18
	Allows staff to complete procedures with fewer errors	2	12
	Simulation	1	6
	Information uploading	1	6
	Reduce contamination risk due to screens	1	6
What concerns do you have for using AR?	NA	4	24
	Stability, integrity, and verification of information accuracy	7	41
	Network speed, chip performance, system crashes, cost	3	18
	Field of view can be limited	2	12
	Long-term use is cumbersome, uncomfortable	2	12
	Increased prep time, intraoperative time increase, training	1	6
	Do not know, will only find out when used	1	6
	Battery life	1	6
	Security	1	6
	Compliance with infection prevention requirements	1	6
	None	1	6
NA	4	24	

Table 2.3: Clinician perspectives on AR experiences, implementation visions, and concerns regarding surgical applications. Note: Some participants conflated AR and AI technologies, expressing concerns about system “intelligence” rather than augmentation features.

invasive procedures associated with significantly higher rates of musculoskeletal symptoms compared to open surgery [35, 36]. However, this approach has not been entirely practical, prompting the development of bypass strategies. These include temporarily alternating positions mid-operation to view the display and requesting perioperative nurses to manually adjust the display angle and location [12]. Participating surgeons consider these methods to be inconvenient and inefficient to the operation since they add unnecessary manual effort, communication, and added time [17].

Pain point 2: Inefficient interpretation of monitored data. Displayed monitor data, such as blood loss, can be easily misinterpreted by both the anesthesiologist and surgeon due to high reliance on personal estimation instead of a calculated output provided by a technological system. Visual estimation of blood loss by clinicians demonstrates significant inaccuracy, with systematic reviews showing bias of 456.51 ml compared to validated reference methods, and 95% of practitioners providing estimations with >25% error in at least one scenario [37, 38]. Participating surgeons address the need for early detection and assisted

judgment during the operation to avoid hazardous mistakes [39].

Pain point 3: Improve ergonomic function of CT scans. From a similar vein, the ergonomic function of current in-surgery CT imaging increases risk among patients due to the surgeon's inability to monitor the patient's vital signs whilst operating the scanner. Intraoperative imaging workflows present significant challenges to maintaining situational awareness, as surgeons must often work in proximity to imaging equipment tracks, creating physical discomfort and workflow disruptions [40, 41]. Current imaging systems are typically placed in a separate room from the patient, resulting in a disparity between the patient's current state and the technology used for treatment. Having continuous access to patient data was considered a priority among primary stakeholders [42].

2.3 CARE Platform Features Informed by Interviews

The design principles guiding the development of the minimum viable product were directly informed by the pain points outlined by clinicians in Table 2.2 and Table 2.3. The principles are as follows: 1) providing surgeons with the ability to access real-time data and accommodating their viewing preferences, 2) optimizing for preserving mobility and ensuring an unobstructed surgical space, 3) streamlining the presentation of information, taking time into account in order to ensure a seamless transition between surgical scenarios, and minimizing disruptions. Fig. 2.1 presents an intended user flow of the CARE platform based on these goals.

The primary goal of this application is to have a consistent and reliable solution; as such, the minimum viable product functions primarily through hand gesture interaction. The operating room is a relatively loud environment with multiple audio signals and alarms [44, 45], where voice commands can be easily drowned out. However, hand gestures and eye capture could still be perceived in high-stakes scenarios, where these gestures are relatively safe within the conventions of the surgical environment [17]. Following established user-centered design principles [46], the CARE platform's feature set emerged directly from systematic analysis of clinical stakeholder needs rather than technology-driven development. This approach aligns with recent advances in surgical AR applications [15, 16], where clinical utility rather than technological novelty drives adoption and success.

Based on interviews and feedback, two native Apple Vision Pro features below are considered acceptable

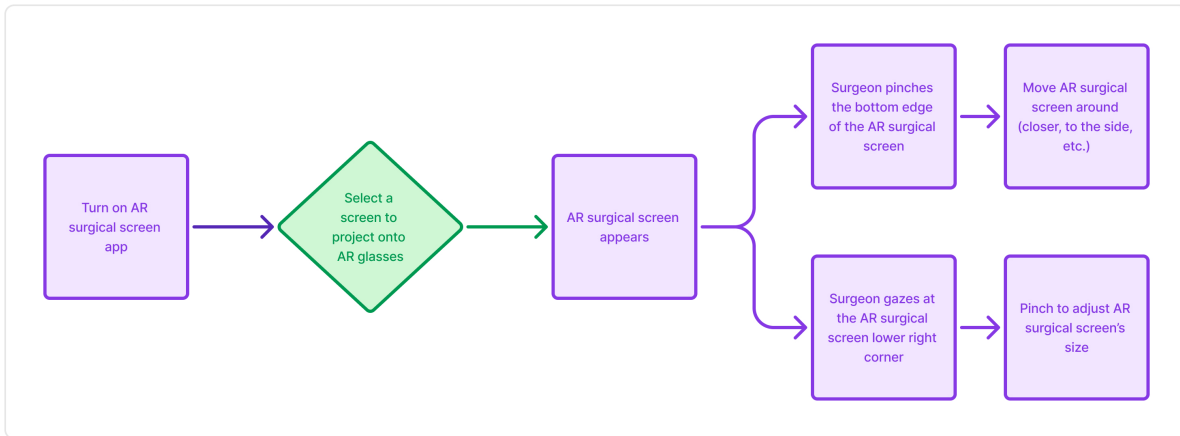


Figure 2.1: CARE platform user flow diagram [43].

to be used in future research and product development in the AR surgical space:

- **Feature 1 Drag Surgical Screen:** The surgeon selects a window for movement, and a handle appears at the bottom edge, enabling a pinch-and-drag action to reposition the window within the space.
- **Feature 2 Resize surgical screen:** When the surgeon gazes at the bottom corners of a window, a curved handle will appear. By pinching to select this handle and moving their hands outward diagonally, they can increase the scale of the view. Conversely, moving their hands inward will scale the view down.

However, surgeons may not always have a free hand to perform gestures. To address this limitation, an additional feature was introduced: monitor selection via eye capture. This interaction extends beyond the native capabilities of the Apple Vision Pro and was developed specifically to overcome the constraints of gesture-only control.

- **Feature 3 Select monitor:** Eye capture to display a monitor where a surgeon can reference a selection of monitors at the bottom of their field of vision, stare at a monitor, and the selected monitor will be displayed in front of them.

The result is a solution that offers the ability to display and access multiple augmented monitors simultaneously, allowing for varying sizes and placements, as shown in Fig. 1.2 earlier in Section 1.2 “The Potential of Augmented Reality (AR).” This solution would seamlessly sync with the surgeon’s workflow,

enhancing the overall surgical experience [15]. Our interviews with clinicians highlighted the demand for flexible and customizable visual interfaces during surgery. The hand gesture and eye-tracking interaction designs proposed for our minimum viable product (MVP) directly address this need, offering a solution that enhances agency and reduces reliance on other physicians to manage information displays [16]. Our system also mitigates potential sterilization risks by digitizing monitor interactions, which could translate to better sanitation in the operating room [47, 48]. Fig. 2.2 and Fig. 2.3 present two low-fidelity wireframe sketches produced as part of the design process, which support the conceptualization shown earlier in Fig. 1.2.

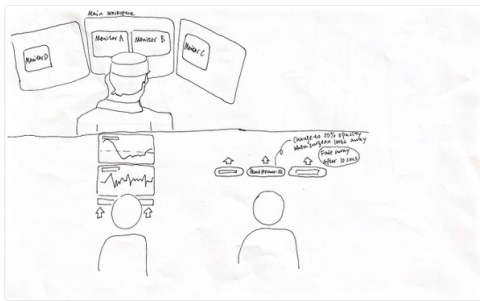


Figure 2.2: CARE platform screen navigation feature sketch [49].

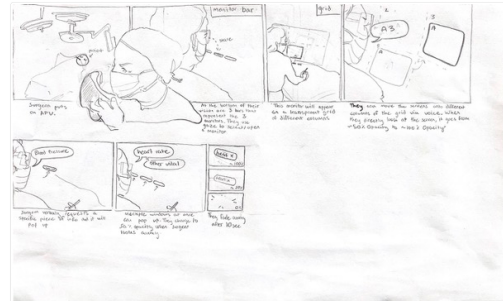


Figure 2.3: CARE platform core design sketch [50].

During the design process, several additional features and considerations, such as gaze control, voice control, and snapping grids for virtual monitors, were conceptualized and designed. However, to meet the goal of implementing a consistent and reliable solution for the first CARE prototype, these additional features are not included in the scope of this thesis. These additional features are summarized in Section 4.3 “Consideration of Future Features.”

With the three core CARE platform features established, we begin a goal-oriented technical engineering and development process.

Chapter 3

Application Development: Assessing Technical Feasibility

Following the establishment of the core CARE platform features and requirements, the CARE platform was engineered and implemented according to Fig. 1.6 presented earlier in Section 1.3. This section includes commentary and implementation of streaming, capturing video via a capture card, measuring latency, and leveraging a local network.

3.1 Platform Architecture and Technical Implementation

Our experimental setup was designed to measure latency accurately in a simulated environment while maintaining consistent baseline conditions. Before exploring specific components, it is important to understand the overall architecture. Fig. 3.1 shows that video content streams from a source through a capture card to a streaming server, which then transmits to a reference display (4K TV) and the Vision Pro headset over a controlled network environment. This setup closely follows the framework of Liebert and Aalami et al. [1, 2], who used a Local Area Network (LAN) to stream surgical vitals to Google Glasses.

It should first be noted that several components in the CARE architecture are not limited to the specific device model that we have chosen to use:

- Original Video Source: The original video source could theoretically be any arbitrary input, as long

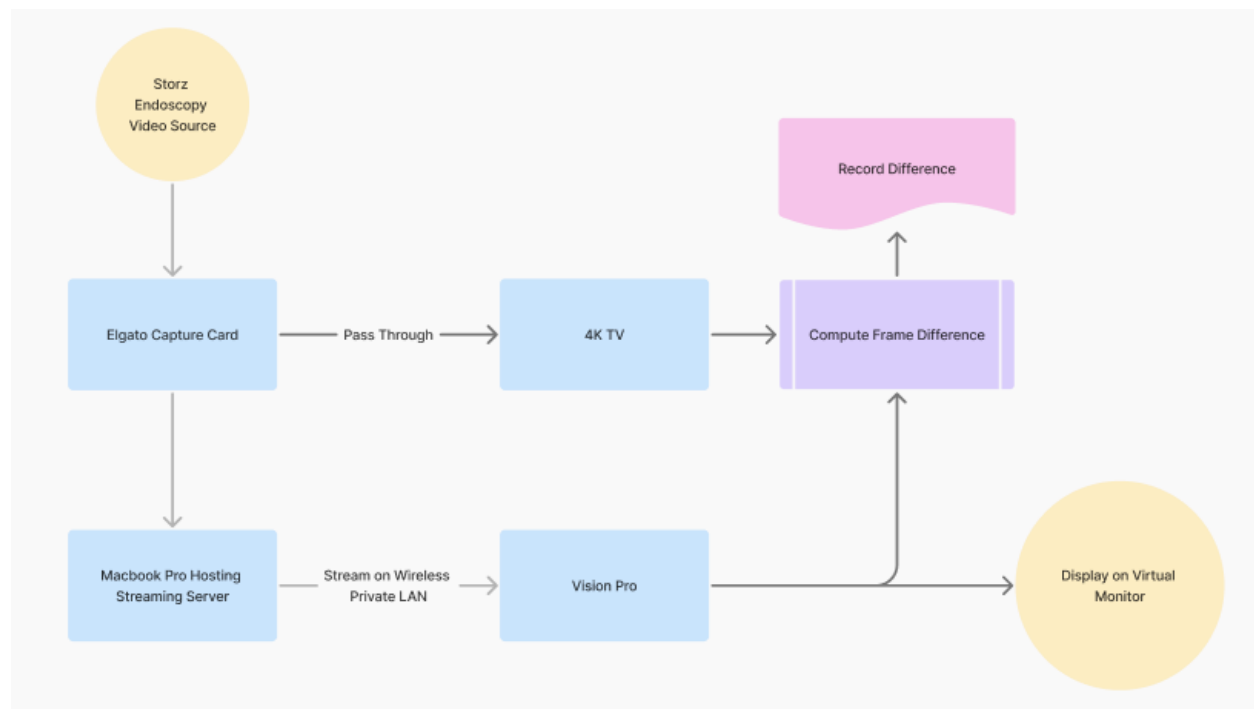


Figure 3.1: CARE platform latency testing architecture [51].

as it can be reliably converted to the input format supported by the chosen capture card.

- **Capture Card:** Any capture card can be used, as long as it is macOS compatible and has a USB capture output. If 4K capture is not needed (e.g., the original video source is constantly in 1080p), using a capture card that only supports 1080p is perfectly viable. Though we still recommend purchasing a capture card with minimal latency.
- **Mac Hosting Streaming Server Application:** any Mac computer that supports macOS 14.0 Sonoma should work (earlier macOS versions might also work, but are untested). A MacBook Pro is not strictly required. For a more stationary operating room setup, the compact Mac Mini could be a good option.
- **Original Physical Medical Monitor:** any display device that supports the passthrough output format of the chosen capture card would work, e.g., televisions, monitors, projectors. Theoretically, it is also possible to daisy-chain this passthrough output into another capture card. If this is the intention, it would be preferable to directly connect the second capture card to a vacant display output of the

original video source.

- **Router for Hosting Wireless LAN:** Any router that is capable of hosting a local area network could be used, which includes almost all commercial WiFi routers on the market today. Theoretically, both the Mac and the Vision Pro could also be connected to whatever institutional WiFi router/network is available at the medical facility and have streaming set up through that interface. However, using a dedicated router exclusively for this streaming purpose reduces traffic overhead and helps prevent unwanted inter-device interactions with unrelated devices.

An HDMI source video input from the medical device, either native or converted, would be connected as an input to a capture card. The Elgato 4K X capture card was chosen for our experiments due to its 4K 60FPS capture capabilities [52] and low-latency performance for both its HDMI passthrough output and USB-C captured output [53]. The capture card then sends the HDMI input signal via USB to a 2023 16-inch Apple MacBook Pro (M2 Max Chip, macOS 15 Sequoia [54]) connected to the same local network as the Vision Pro. A client-server relationship will be established using a macOS server application paired with a VisionOS client application to transmit video information to the Vision Pro, which will display it to the surgeon. OBS [55] and QuickTime [56] are used to present the captured HDMI signals from the capture card as windows in macOS, which can then be recognized and streamed by the server macOS application. Both the macOS server app and the visionOS client app leverage the Ensemble [57] open-source framework, primarily written in the Swift programming language [58]. Compilation and installation of these apps onto Mac and Vision Pro devices is done through the Xcode suite, Apple's Integrated Development Environment for native software development of its devices [59].

By default, full-screen casting uses a 16:10 aspect ratio that matches the aspect ratio of the 2023 MacBook Pro [54], resulting in streamed video feeds with black bars above and below the content, which limit the surgeon's field of view. Removing this involved using DeskPad [60] to act as a virtual monitor an independent aspect ratio of 16:9. Fig. 3.2 and Fig. 3.3 below, taken from the point-of-view of the Vision Pro user, shows the setup process of OBS, QuickTime Player, and DeskPad to resize the streamed content into 16:9 aspect ratio on the MacBook, with Fig. 3.4 showing both the captured video feed on the MacBook screen and the streamed Vision Pro virtual monitor with no black bars.

Note that the images presented throughout this chapter, taken from the Apple Vision Pro, are inherently

blurry around their edges due to visionOS's screenshot emulation of field-of-view blur. We noticed that the Apple Vision Pro's image and video quality were high-resolution to the wearer, but the flat screenshots were condensed and blurry at the edges.



Figure 3.2: OBS capture setup.

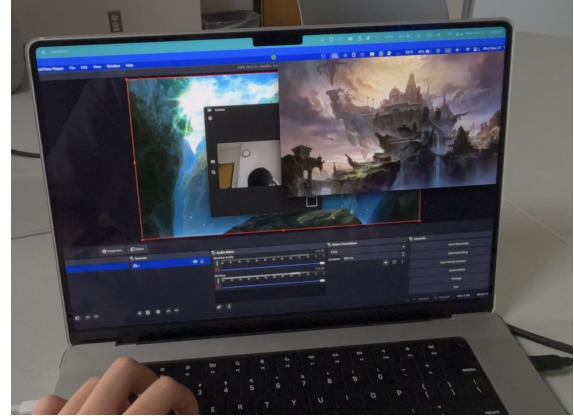


Figure 3.3: OBS and QuickTime Player capture setup.



Figure 3.4: Streaming setup without black bars.

Implementing the testing architecture presented in Fig. 3.1, Fig. 3.6 below showcases the latency measurement workflow used to measure wired casting latency through the white USB-C cable visible on the left side of the setup, and Fig. 3.5 showcases the latency measurement workflow used to measure wireless casting latency through a LAN hosted by a WiFi router, visible toward the left side of the setup, which replaces the USB-C cable. The rest of the platform remains identical between the wired and wireless setup: the

unconnected HDMI output cable (the unconnected cable on the right) is intended for the optional original physical monitor output, while the left unconnected USB-C to HDMI converter cable is intended for the original video source input from medical equipment. A USB-C to HDMI converter is used to demonstrate that video conversion can be performed at this platform component. Regardless of the video source connection format, the medical device can serve as an input, provided a suitable HDMI converter is used to connect it to the capture card.



Figure 3.5: CARE platform wired latency testing setup.



Figure 3.6: CARE platform wireless latency testing setup.

Fig. 3.1 shows how the passthrough functionality enables simultaneous wired streaming to a physical monitor, which acts as a latency comparison baseline, in addition to the wired or wireless streaming to the Vision Pro’s virtual monitor from the surgeon’s point of view. This affords a precise measurement of the latency, which was done via a frame-wise analysis of videos taken on the Vision Pro with the reference passthrough monitor visible in the shot. Since the passthrough monitor output does not need to go through the USB-capture process and the LAN streaming processing that the Vision Pro’s virtual monitors need to go through, and the passthrough process itself has minimal latency, the total latency it incurs should be negligible compared to the source video stream. Therefore, at moments of scene change, by comparing the difference in latency between when the passthrough monitor changes versus when the Vision Pro’s virtual monitor changes, we can deduce the total latency added by the USB-capture plus Vision Pro streaming process.

This practice of counting frames to determine the latency of a connection, as seen in Saunders [61] and Feldstein [62], enables us to use the number of frames to estimate latency. The number of frames between

the rendering of this frame in the passthrough and the rendering on the Vision Pro was counted, recorded, and discussed further below in this chapter.

We used a dedicated router (CenturyLink C4000) that acts as both a host and a network controller for network configuration, ensuring minimal external network interference during measurements. The same setup was first performed with Vision Pro and an Apple MacBook Pro 2023 [54] on this local network, testing 4K video and 1080p video. A final baseline was taken with a wired connection using the Vision Pro Developer Cable [63] between the MacBook and Vision Pro, to determine the lowest latency commercial tools enable this setup to provide. For the Wired connection, the Vision Pro creates a LAN between itself and the Mac. This testing process ensures that the streaming setup is left unchanged, creating a valid baseline.

In laboratory experiments, prerecorded videos streamed from an internet-connected laptop were used to simulate input to the CARE system. In a clinical setting, this input could originate from endoscopes, vital sign monitors, or other display-enabled medical devices. Our experiments specifically measured the system latency introduced solely by the CARE system, from the video source to the virtual display. Using pre-existing video content provided a consistent baseline, enabling the production of accurate and precise latency measurements.

3.2 User Interaction and Features

After setting up the hardware platform and software on macOS via OBS and Desktop, the macOS server streaming application allows any arbitrary window to be streamed to the Vision Pro. First, the user would launch both the macOS server app (Fig.3.7) and the visionOS client app (Fig.3.8), then pair the two devices together, which should automatically discover each other if they are correctly connected to the same local network. This connection process is identical for both wired and wireless streaming.

After establishing a connection, the user could then use the Vision Pro's CARE client application to select any number of active windows present on the Mac, including both the virtual captured video source from the capture card presented through OBS, QuickTime Player, and DeskPad, or any software windows present on macOS. Fig. 3.9 shows the window selection screen with three macOS software windows, while Fig. 3.10 shows the selection screen with an OBS and DeskPad-presented captured window, ready to spawn a second virtual monitor on the Vision Pro, since a first one is already present in the background.

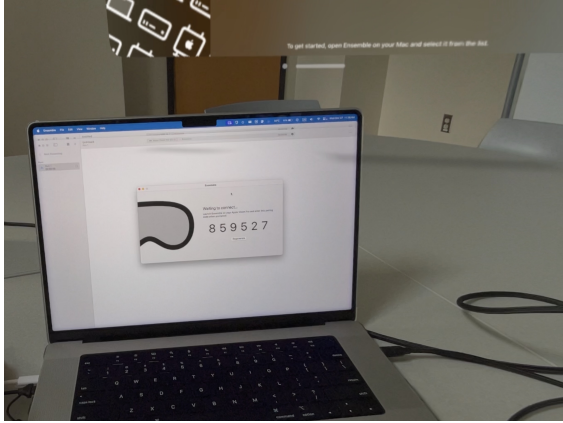


Figure 3.7: Establishing a connection on the CARE macOS server app.

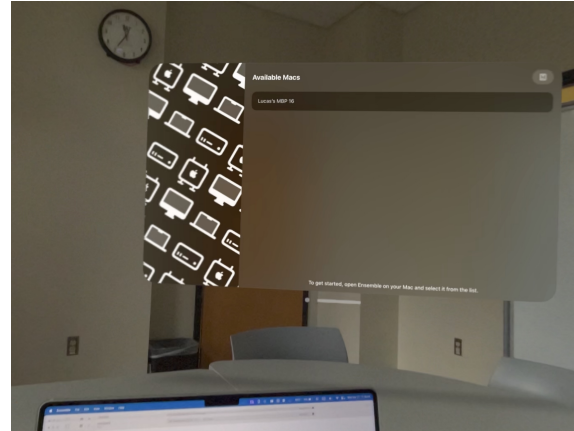


Figure 3.8: Establishing a connection on the CARE visionOS client app.

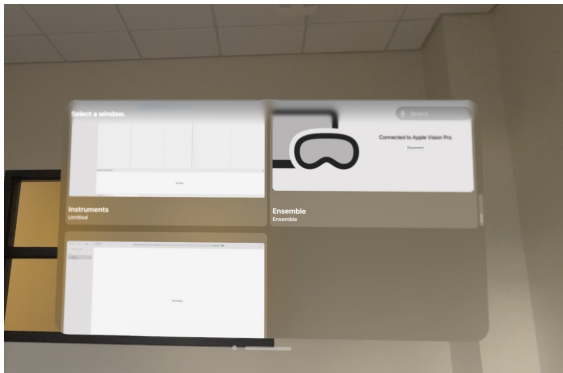


Figure 3.9: Selecting a virtual monitor on the CARE visionOS client app.



Figure 3.10: Selecting a second virtual monitor on the CARE visionOS client app.

After creating the desired amount of virtual monitors through the CARE Vision Pro client app, the user can then freely move the monitors around by reaching for and highlighting the horizontal navigation bar at the bottom-center of each monitor (Fig. 3.11) and resize the monitors by reaching for and highlighting the resize curves at the four corners of each monitor (Fig. 3.12) at any time. The window selection interface can be opened by tapping the “+” symbol beneath each virtual monitor, visible in Fig. 3.11, and virtual monitors can be closed at any time by reaching for the horizontal navigation bar, which would reveal the standard window-closing button on visionOS.

These fundamental interactions enable a wide range of virtual monitor arrangement possibilities, some examples of which are illustrated in Fig. 3.13 below. Subimage (A) shows an example of a standard in-sync video streaming during endoscopy. Subimage (B) captures the latency between the passthrough monitor,

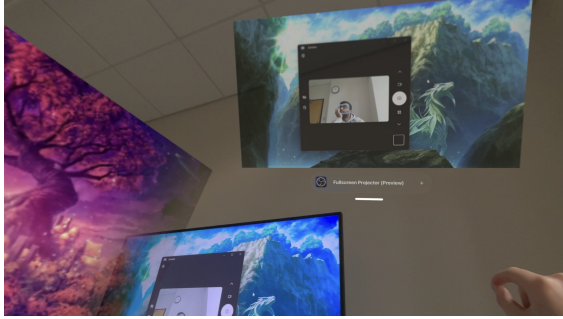


Figure 3.11: Moving a virtual monitor on the CARE visionOS client app. The passthrough physical monitor is visible beside the virtual monitors.

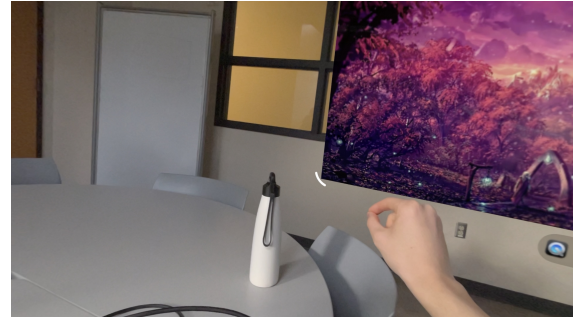


Figure 3.12: Resizing a virtual monitor on the CARE visionOS client app.

on the left, and the virtual monitor, on the right, right after a scene change, hence why the specific frame displayed on each monitor differs. Subimage (C. i) details multiple monitors streaming the same video. (i) and (iii): 2 streaming Vision Pro Virtual Monitors. (iv): Laptop monitor that sends video to both the virtual monitors and the Passthrough 4K TV. (ii): 4K TV using passthrough functionality, which acts as the wired baseline. Subimage (D) shows a baseline landscape video used to stream and collect latency measurements.

3.3 Technical Performance Testing and Results

Prior to the quantitative measurement of the streaming latency of the CARE platform, it was necessary to identify a streaming foundation framework to host the macOS server application and the visionOS client application. To do this, we conducted a preliminary performance assessment of several of the many streaming services explored (REI re:streamer [64], Ensemble [57], and Castaway [65]). The Ensemble Framework showed the most promise. Re:streamer came with latency problems, sporting a measured peak delay of 28 seconds, which is unacceptable for clinical work. Although Castaway performed better with a significantly lower latency of about 1 second, the software is proprietary. The Ensemble framework was finally selected as the primary streaming framework due to its open-source customization and testing capabilities. In addition, the latency measured was very low as well. As seen in Table 3.1, the average latency was less than 100 milliseconds for all 1080p videos, making it the ideal framework for all future latency testing.

Additionally, Ensemble implemented its frame compression using the LZ4 [66] compression algorithm. Through modifying its source code, we compared LZ4 to LZFS [67] and zlib [68]. We conducted a pre-

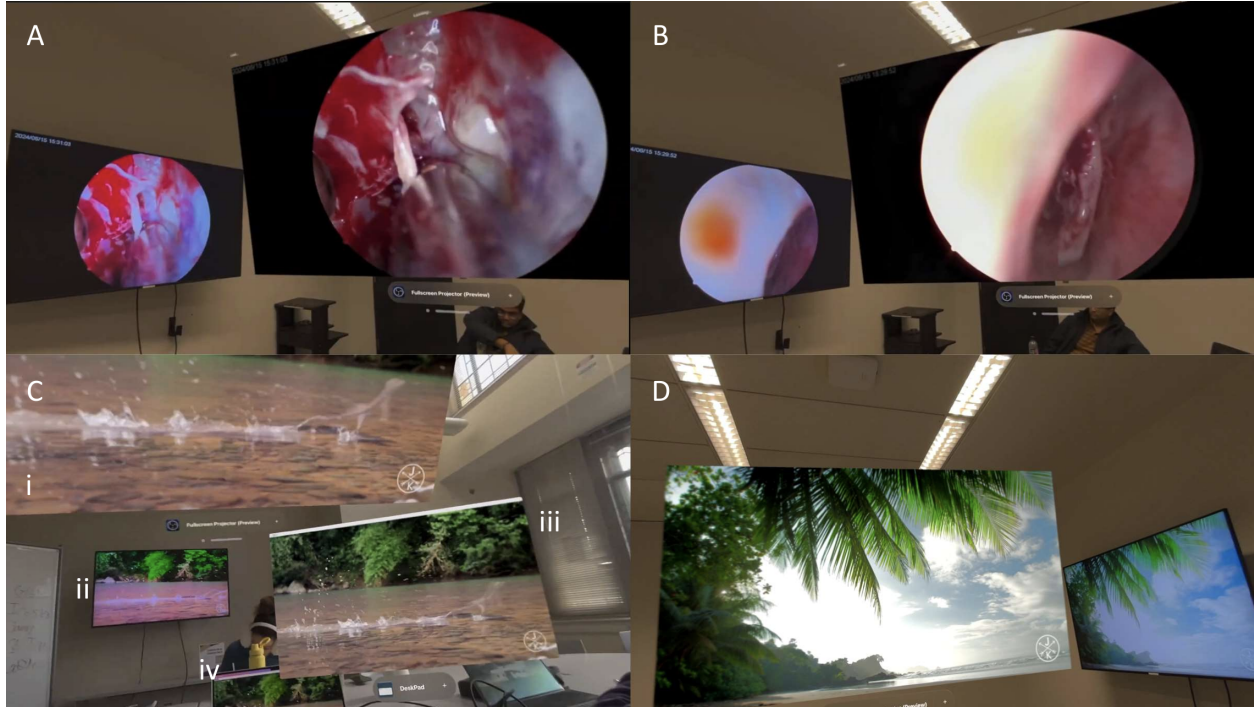


Figure 3.13: Examples of virtual monitor arrangements on the CARE Vision Pro client app.

liminary user experience analysis, drawing on papers that compare these algorithms[69], to identify more jitteriness and lag in zlib and LZ4 compared to LZFSE. Minimal latency and jitter are crucial in the clinical space with consequences extending beyond engineering optimization, as the choice of compression algorithm significantly impacts both technical performance and user experience in medical applications. Research on cognitive workload during surgical procedures has shown that visual inconsistencies and processing delays can increase mental workload and potentially compromise surgical performance [70]. Our observation that LZFSE provides smoother performance compared to LZ4 and zlib aligns with the broader requirement that medical display systems minimize cognitive burden on surgical teams.

Video Format	Wired Mode	Average Latency (ms)	Median Latency (ms)
1080p	Wireless	70.77	66.66
4K	Wireless	198.8	166.5
1080p	Wired	54.16	66.66
4K	Wired	214.79	199.98

Table 3.1: Table detailing video formats and wired modality, along with their corresponding streaming latency.

Table 3.1 compares various video formats and wiring mode latencies. It is worth noting that 4K video streaming was significantly more delayed compared to 1080p video streaming. In the wireless modes, we noted latencies of roughly 198.8ms for 4K videos versus only a 70.77ms latency for 1080p videos.

Industry standards for medical video streaming typically require latencies of less than 100 milliseconds for real-time surgical applications, with some advanced systems targeting sub-50-millisecond performance for critical procedures [71]. Healthcare streaming applications differ significantly from consumer applications due to the need for consistent and reliable performance, where delayed information can directly impact patient safety [72]. This typically necessitates the use of custom hardware and software built specifically for medical streaming purposes. Although the Elgato 4K X capture that we used was a commercial device designed primarily for content and video game capture from a host computer [52], we believe that it is still a fitting device to use for the CARE prototype, with our latency measurements showing that a general-purpose capture card could still perform at clinical standards under certain setup conditions.

Our 4K videos' latency figures show similar, but lower latency values than those found in existing literature from Ruijters (300 ms) [73], Askeland (285 ms) [74]. Note that a few of these slower sources transmit videos that have a lower refresh rate (ex., 20fps) and reduced video quality (ex., 1080p). CARE's 1080p latency figures outperform both sources further.

However, we do not outperform all existing methods. Kibsgaard [75] boasts a latency of 54-70.07ms, which even outperforms our 1080p latency figures. Even more impressive is Tokuda [76], who boasts a <10ms latency for a 32 fps video at 1080p.

These latency measurements must also be evaluated within the broader context of cognitive workload and surgical performance research. Studies have demonstrated that cognitive overload in surgical settings leads to impaired clinical decision-making and performance decline, making real-time information display critical for patient safety [77]. The sub-100-ms latencies achieved for 1080p content in our system fall well within the acceptable range for supporting surgeons' cognitive processing capabilities during complex procedures [Systematic review of measurement tools to assess surgeons' intraoperative cognitive workload].

3.4 Discussion on Technical Feasibility

The exploration of system design and the results of our latency testing sufficiently demonstrate that head-mounted displays with augmented reality (AR), such as the Apple Vision Pro, have significant potential for enhancing intraoperative workflows. Recent systematic reviews have documented a 40% increase in augmented reality surgery publications between 2020-2021, indicating growing clinical interest and validation of AR surgical applications [78]. Multiple systematic reviews have now established that AR systems can achieve performance comparable to traditional surgical navigation techniques while offering improved ergonomics and workflow integration [79].

Through our testing, we concluded that video streaming of critical surgical data to the Apple Vision Pro can be achieved with latency levels well below 100 milliseconds for 1080p footage, and acceptable latency even for 4K streaming when conditions are optimized.

Low-latency performance is crucial for clinical applications where timely decision-making has a direct impact on patient safety. Our findings suggest that the Apple Vision Pro, when paired with an efficient streaming framework such as Ensemble, can reliably display surgical information with minimal perceptual delay. These latency figures are a marked improvement over previous AR device implementations, such as the Google Glass-based systems studied by Liebrt and Aalami et al. in 2016 [1, 2], which struggled with both hardware and network limitations.

Furthermore, our interviews with clinicians highlighted the demand for flexible and customizable visual interfaces during surgery. The hand gesture and eye-tracking interaction designs proposed for our minimum viable product (MVP) directly address this need, offering a solution that enhances agency and reduces reliance on other physicians to manage information displays. Our system also mitigates potential sterilization breaches by digitizing monitoring interactions, which could lead to improved sanitation in the operating room.

Another promising takeaway is that there is minimal difference between the wired transmission modality; instead, a noticeable and non-negligible difference in latency is observed between different video qualities. The variability in the infrastructure of the hospital networks must be addressed to solve this issue. More precise measurements of latency and the causes of this latency also provide insight into the direction of future work.

The Vision Pro's high-resolution display and intuitive input systems offer considerable advantages, but concerns regarding the device's weight, comfort during prolonged wear, and battery life persist. Recent literature on head-mounted device (HMD) comfort has established quantitative relationships between device weight and user comfort, showing that heavier headsets reduce comfortable wear time by an average of 11 minutes per 33 grams of additional weight [80]. Systematic reviews of surgical HMD applications have consistently identified weight distribution, heat generation, and prolonged wear comfort as primary barriers to clinical adoption. These ergonomic factors are particularly critical in surgical environments where procedures can extend for several hours and any discomfort can impact surgical precision [81].

Finally, while our latency measurements were precise under laboratory conditions, further studies are needed to validate performance in actual clinical environments, where system performance may be affected by changes in lighting, varying room layouts, and fluctuations in existing workflows. We present our plans for future clinical testing in Section 4.1.

Chapter 4

Limitations and Future Work

It is essential to acknowledge that the process of ideation, design, development, testing, and commercialization is a complex, long-term endeavor involving numerous steps and actions beyond the scope of this thesis. Therefore, a strong plan for future actions is paramount for the longer-term success of the CARE project. This section outlines our plans for future clinical trials, including further feedback and validation of the CARE platform, the current technical limitations of the CARE prototype, potential feature additions, and an assessment of the timeline and challenges surrounding a potential path to commercialization.

4.1 Iterating from Clinical Trials

The transition from laboratory validation to clinical implementation requires systematic evaluations that account for the complex sociotechnical nature of surgical environments, which are not present in the latency measurement experiments that we have conducted so far. Established validation methodologies for AR surgical applications emphasize the importance of assessing not only technical performance but also face validity (user satisfaction), content validity (clinical relevance), and construct validity (ability to differentiate skill levels) [82]. Clinical decision support systems research has identified specific human-computer interaction elements that must be optimized for surgical applications, including information display timing, cognitive load management [83], and integration with existing workflows [84].

In addition, the latency and performance characteristics demonstrated by the CARE platform must be evaluated within the broader context of surgical safety and decision-making requirements. Research on

surgical cognitive workload has established that timely access to visual information directly impacts surgical team performance and patient outcomes [70]. The sub-100-ms latencies achieved for 1080p streaming align with established requirements for real-time medical applications, where delays beyond this threshold can interfere with the hand-eye coordination and decision-making processes critical to surgical success [71].

To uncover these important but currently unknown performance metrics of the CARE platform in a clinical setting, we plan to follow established validation methodologies for AR surgical applications, our proposed clinical study would evaluate three key validation domains: face validity (user satisfaction and acceptance), content validity (clinical relevance and workflow integration), and construct validity (ability to differentiate between skill levels and improve performance outcomes). The study would involve a randomized controlled design with 20-30 surgical staff across multiple minimally invasive procedures, comparing traditional monitor setups with the CARE platform across metrics including neck strain measurements, task completion times, situational awareness scores, and subjective workload assessments.

Our proposed clinical study design represents a direct evolution of the pioneering 2016 research by Liebert et al. and Aalami [1, 2], which established the fundamental feasibility of head-mounted displays for wireless vital sign monitoring. Understanding the relationship between their foundational work and our proposed validation study requires examining both the continuities and the significant advances that a decade of technological development has enabled [85].

The 2016 study established several critical baseline findings that inform our clinical protocol design. Liebert et al. demonstrated that surgical residents using Google Glass spent 90% less time looking away from the procedural field during bronchoscopy and 71% less time during thoracostomy procedures, with trends toward earlier recognition of critical vital sign deterioration. Their randomized controlled design with crossover methodology, where each participant served as both control and experimental subject across two scenarios, proved effective for controlling individual variation while maximizing statistical power from a limited sample size of 14 residents.

The statistical framework established by Liebert et al. provides a robust foundation for our expanded clinical validation. The demographic analysis by Liebert et al., presented in Table 1 of their study, established important baseline comparisons between experimental and control groups across age, gender, post-graduate year level, and surgical specialty. Their approach to reporting, which includes standard deviations

for continuous variables (e.g., age, 29.7 ± 3.3 years) and percentages for categorical variables (e.g., 64.3% male participants), provides a template for our expanded demographic characterization. However, our proposed study's inclusion of attending surgeons alongside residents, and our broader specialty representation beyond general surgery, requires more sophisticated stratification analyses to account for experience-level interactions with technology adoption and ergonomic benefit realization [86].

The core performance metrics established in Liebert et al., presented in Tables 2 and 3 of their study, demonstrate the power of their crossover design methodology. Their measurement of “time to recognition of hypotension” (31.8 vs 41.9 seconds) and “time spent looking at monitor” (6.4 vs 21.9 seconds) established quantifiable endpoints that our clinical validation can directly incorporate while expanding into the ergonomic domain. Their calculation of both absolute effect sizes and Cohen's *d* values provides important precedent for effect size estimation in AR surgical applications, with their reported effect sizes ranging from moderate ($d = 0.56$ for recognition time) to large ($d = 1.58$ for time spent looking away from the procedural field).

The user feedback framework presented in Liebert et al., presented in Table 4 of their study, established validated approaches for measuring technology acceptance in surgical settings through Likert scale responses. Their finding that 86% of participants agreed Google Glass was helpful in monitoring vital signs, and 93% found it easy to use, provides important baseline expectations for technology acceptance that our study can benchmark against. However, the evolution from Google Glass's limited interaction paradigm to the Apple Vision Pro's sophisticated hand and eye tracking requires expanded user experience questionnaires that assess interaction modality preferences, comfort during extended wear, and integration with complex surgical workflows.

A clinical trial at the scope and scale described above would certainly require more detailed Institutional Review Board (IRB) scrutiny, as it directly involves working with human subjects. The additional resource and time overhead of managing this process need to be carefully taken into consideration.

4.2 Consideration of Current Technical Limitations

Modern medical device streaming systems must comply with established quality management standards, particularly ISO 13485 for medical device quality management systems, which provides the regulatory

framework for devices that transfer, store, and display medical device data [87]. The FDA’s Medical Device Data Systems guidelines further specify that systems like CARE, which are intended to “transfer, store, convert formats, and display medical device data,” must meet specific performance and safety criteria [88].

A more in-depth analysis of the precision of the CARE interface would also be beneficial in establishing more advanced features in the future, such as the overlaying of three-dimensional shapes and other assets on the surgeon’s field of view to serve as visual surgery guides [89]. Recent advances in surgical AR applications have demonstrated the potential for real-time anatomical registration and surgical planning overlay. However, these applications require sub-millimeter accuracy and robust tracking capabilities that exceed our current implementation [90].

More precise analysis of the CARE macOS server app and visionOS client app could also be conducted using Instruments.app, which could be set up in profiling mode to record a runtime profile of the apps as they launch and operate [91]. Fig. 4.1 shows an instruments run throughout the launching, connecting, and streaming of the visionOS CARE streaming client app, and Fig. 4.2 shows the same trace being examined mid-session by the user from the Vision Pro’s perspective. The Instruments.app analysis, as shown in Fig. 4.1 and Fig. 4.2, represents an initial step toward comprehensive performance profiling of both the macOS server application and the visionOS client application. These profiling sessions reveal memory usage patterns, CPU utilization spikes, and network transmission bottlenecks that occur during typical streaming operations. Future development should prioritize optimization of the video encoding pipeline, implementation of adaptive bitrate streaming based on network conditions, and development of predictive buffering algorithms that anticipate surgical workflow patterns. The real-time nature of surgical procedures demands not just low average latency, but consistent, predictable performance that surgeons can rely upon during critical moments. Instruments.app also allows us to collect empirical quantitative statistics on the performance of the CARE platform, exposing a much larger surface area for future experimentation and literature [92].

Additionally, working with existing frameworks, such as Ensemble [57], introduces computational overhead that may limit the ultimate performance potential of our system. A comparative analysis against Apple’s native frameworks, such as AirPlay and built-in desktop casting capabilities, would provide valuable insights into optimization opportunities. Future development should explore direct integration with Apple’s developer frameworks, potentially requiring applying for specialized developer certificates that provide ac-

cess to lower-level system APIs. This approach has the potential to reduce latency while improving power efficiency and system stability significantly. When paired with Instruments.app performance profiling methods, this approach could also surface additional experimental findings, such as low-latency software and algorithm implementations [93, 94].

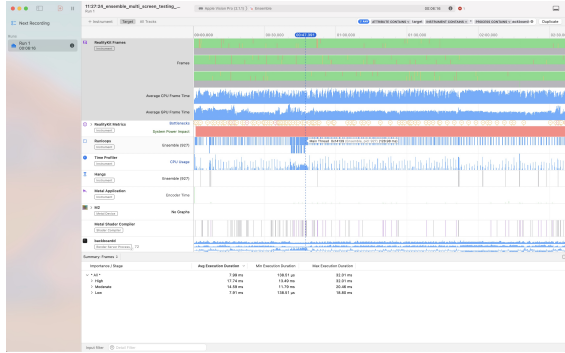


Figure 4.1: Screenshot of Instruments.app trace of CARE visionOS client app.

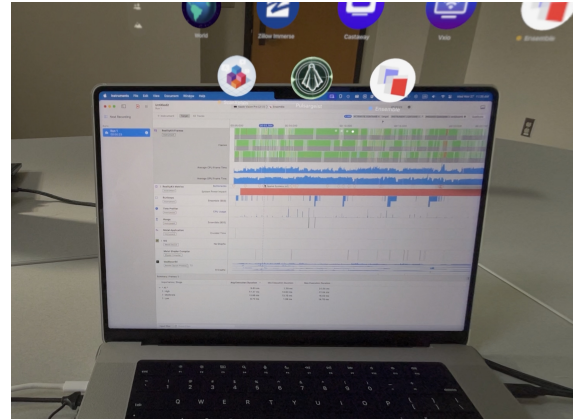


Figure 4.2: Examining an Instruments.app trace mid-session while wearing the Vision Pro.

4.3 Consideration of Future Features

Fig. 4.3 shows a collection of hypothetical feature concepts that were designed during our user study phase but deemed beyond the scope of this thesis implementation. These features emerged from specific clinical needs identified during our stakeholder interviews, but required technical capabilities that exceeded our development timeline and resources. The features include advanced gaze-controlled navigation systems, voice-activated monitor switching for hands-free operation, and intelligent monitor placement algorithms that automatically optimize display positioning based on the surgical procedure type and surgeon preferences.

Figure 4.4 demonstrates a prototype vitals monitoring application built using native visionOS development tools, featuring hand-tracking debugging models and real-time visualization of physiological data. This dedicated application addresses the specific need identified by anesthesiologists in our user study for continuous, easily accessible patient monitoring data. The benefits of a purpose-built vitals application include optimized data visualization explicitly designed for AR viewing, reduced cognitive load through in-



Figure 4.3: CARE platform extra feature design sketches [95].

telligent alert prioritization [83], and seamless integration with existing hospital monitoring systems. Hand-tracking capabilities enable precise interaction with complex data visualizations without compromising sterile surgical environments.

The current implementation focuses primarily on hand gesture and eye-tracking interactions. However, future development should explore voice control integration, particularly for scenarios where surgeons' hands are occupied with surgical instruments. Research in surgical environments has shown that voice com-

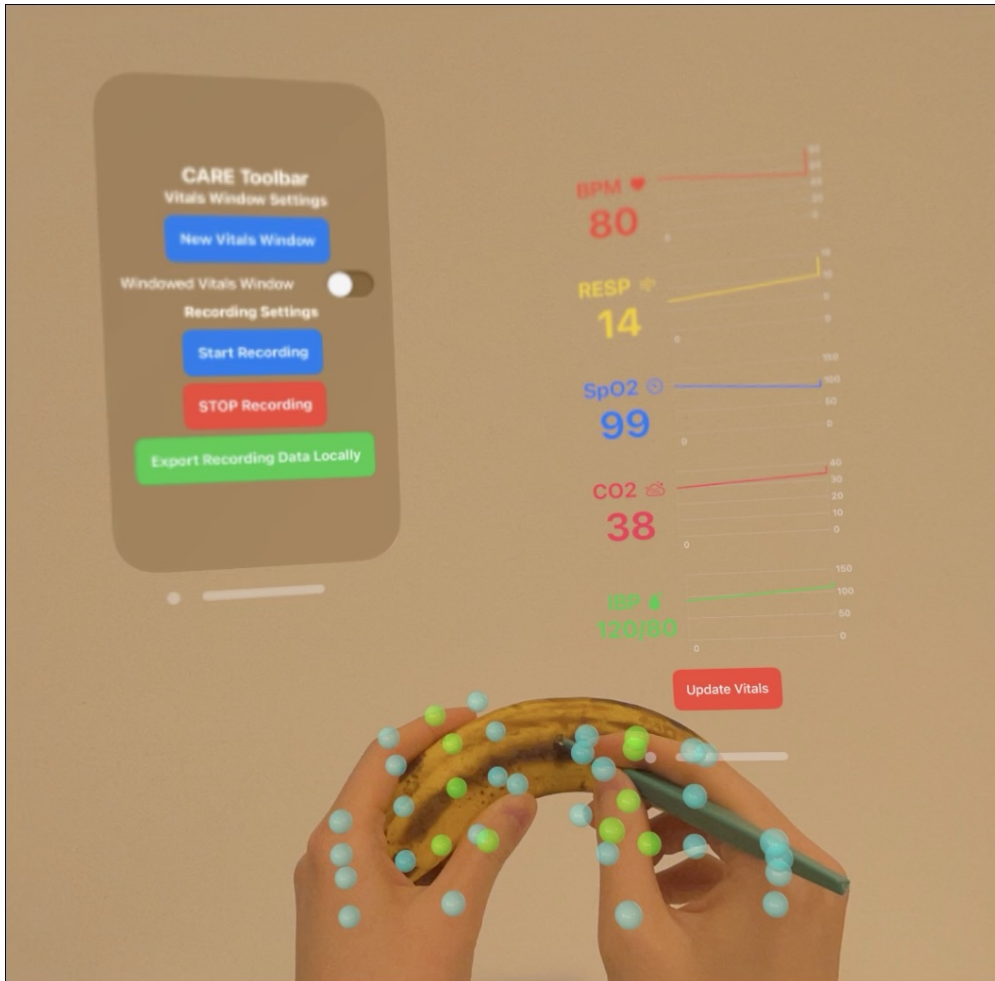


Figure 4.4: CARE dedicated vitals app concept demo.

mands can be effective when properly filtered and calibrated for the acoustic challenges of operating rooms [45]. Additionally, investigation into foot-pedal integration or other body-tracking input methods could provide surgeons with additional interaction modalities that complement rather than conflict with existing surgical workflows [96]. Some of these hypothetical user interactions are conceptualized in Figure 4.4.

During our user study and design iteration process, significant stakeholder input was collected regarding the potential for CARE to serve as a platform for broader clinical decision support applications. These conceptual features include integration with electronic health record systems through standards such as the HL7 FHIR [97, 98], real-time surgical guidance based on preoperative imaging, and collaborative tools that enable remote consultation during complex procedures. The modular architecture established in this thesis provides the foundational framework necessary to support these advanced applications while maintaining

the core functionality of virtual monitor placement. These integrations open up new application possibilities for CARE, such as use in more imaging procedures, clinician training, and remote collaboration [99].

4.4 Commercialization Pathways and Challenges

Our participation in the University of Washington CoMotion NSF I-Corps Northwest regional program provided valuable early-stage exposure to the product commercialization process, revealing the complex pathway from research prototype to commercially viable medical device. It is essential to have an early understanding of the challenges and anticipated time and resources these pathway points would require as CARE approaches commercialization.

The complex medical device approval process of the FDA requires extensive clinical trials, safety documentation, and efficacy demonstrations that extend far beyond our current prototype validation. Medical devices that display patient data must undergo rigorous testing for accuracy, reliability, and cybersecurity resilience. The FDA's guidance on Medical Device Data Systems [88] requires comprehensive risk assessment and quality management systems that align with ISO 13485 standards [87]. This regulatory burden represents a significant time and financial investment, typically requiring 3-7 years [100] and hundreds of thousands to over \$94 million of dollars in development costs before market approval [101]. Although the CARE platform aims to build on top of the Vision Pro platform, rather than engineering a completely new integrated hardware platform from scratch, which should reduce the amount of regulatory scrutiny, the remaining requirements still stand as significant hurdles in CARE's path to commercialization. Additionally, international requirements would further complicate this process should CARE seek to enter the international market [102, 103].

The medical AR market is experiencing rapid growth [78], with established players like Microsoft [23], eXeX [104], and emerging competitors developing specialized surgical applications. CARE's competitive advantage lies in its specific focus on ergonomic monitor placement for image-guided procedures, addressing the documented problem of surgical musculoskeletal disorders that affect 50-85% of practicing surgeons [10, 35]. In this highly competitive landscape, larger corporations and device manufacturers will likely outpace CARE in terms of raw technical performance, particularly in accessing lower-level engineering frameworks and developing custom hardware for ultra-low-latency applications. Successful commercialization

requires demonstrating not just technical superiority but also clear return on investment for healthcare institutions facing budget constraints and competing technology priorities [6, 81]. CARE must maintain its niche of prioritizing ergonomics and user comfort as its forté.

The rapid advancement of artificial intelligence technologies [105, 106] presents both opportunities and challenges for CARE's commercialization strategy. Future versions of the platform could incorporate AI-powered surgical guidance, predictive analytics for surgical outcomes, and intelligent automation of monitor positioning based on procedure type and surgeon preferences, which would be integrated into potential cloud infrastructures, as suggested earlier in Section 4.3. However, AI integration introduces additional regulatory complexity [107] and requires expertise in validating machine learning models for medical applications [108]. The development timeline and resource requirements for AI-enhanced features must be carefully balanced against market demands and competitive pressures.

Chapter 5

Conclusion

In the evolving landscape of modern surgical practice, the widespread adoption of minimally invasive procedures has fundamentally transformed how surgeons interact with visual information during operations. While traditional physical monitors have become indispensable for image-guided surgeries such as laparoscopy, endoscopy, and fluoroscopy, their fixed positioning creates significant ergonomic challenges that contribute to musculoskeletal disorders affecting 50-85% of practicing surgeons [10, 35]. This thesis investigated how augmented reality technology, specifically the Apple Vision Pro platform, could address these challenges through the development of virtual monitor systems that enhance both surgical ergonomics and clinical workflow efficiency.

First, through comprehensive stakeholder engagement involving 25 clinical professionals, including 9 anesthesiologists and 3 surgeons, we established an empirical foundation for understanding the real-world challenges faced in image-guided surgical environments. This user-centered design approach revealed that 65% of clinical participants prioritized patient safety and comfort as their primary concerns, while consistently identifying monitor visibility and positioning as significant workflow impediments. The user-centered design methodology that guided this research emphasizes the critical importance of grounding technological development in genuine clinical needs rather than pursuing innovation for its own sake. As the AR industry advances with more capable hardware platforms and sophisticated software frameworks, the principles we established for stakeholder engagement and iterative design validation will remain essential for ensuring that future developments truly serve the needs of healthcare providers and their patients.

Second, we successfully developed and validated the Clinician Augmented Reality Environment (CARE) platform, demonstrating that contemporary AR hardware can achieve the performance thresholds necessary for surgical applications. Our implementation achieved latencies of under 71 milliseconds for 1080p video streaming and approximately 200 milliseconds for 4K content. These performance metrics meet the established requirements for real-time medical applications, where delays exceeding 100 milliseconds can compromise critical hand-eye coordination and decision-making processes. While our 1080p streaming meets clinical standards, we also present possible future methods for improving 4K streaming latency.

Third, we established a comprehensive technical framework that integrates off-the-shelf components, including capture cards, local area network streaming protocols, and native Apple Vision Pro applications. This approach demonstrated that effective surgical AR systems can be constructed using commercially available tools, suggesting that widespread adoption may be more feasible than previously anticipated. The modular architecture we developed enables integration with diverse medical imaging equipment via standard video interfaces. It also paves the way for integration into more holistic healthcare platforms, such as cloud systems and electronic health records, which could be future features. The foundation established by this research provides multiple pathways for future investigation and development.

The clinical significance of this research extends beyond the immediate technical achievements to address fundamental challenges in surgical ergonomics and workflow efficiency. From a technical perspective, our work demonstrates that the convergence of high-resolution displays, advanced tracking systems, and low-latency networking has reached a maturity level that makes practical surgical AR applications viable. The validation of our streaming architecture using established performance measurement methodologies provides a foundation for future optimization efforts. Technical development should focus on addressing the identified performance bottlenecks through optimization of video encoding pipelines, implementation of adaptive streaming protocols that respond to network conditions, and exploration of direct integration with Apple's native frameworks for improved efficiency.

While our research demonstrates the technical feasibility of AR-based virtual monitors for surgical applications, several important limitations must be acknowledged. The current validation was conducted entirely in laboratory settings using simulated video feeds. Although our latency measurements and user

interface evaluations provide strong indicators of clinical potential, the complex sociotechnical nature of actual operating room environments introduces variables that cannot be fully replicated in controlled technical testing conditions. Hardware limitations also present ongoing challenges that must be addressed before widespread clinical deployment can be achieved. The Apple Vision Pro's weight, battery life constraints, and thermal characteristics during extended use remain concerns for surgical procedures that can span several hours. Our planned clinical validation studies, building upon the established methodologies of Liebert et al. and Aalami [1, 2], will evaluate the CARE platform's performance in actual operating room environments through randomized controlled trials measuring ergonomic outcomes, task completion efficiency, and surgeon satisfaction metrics.

The regulatory landscape presents another significant consideration for translating research prototypes into clinical practice. Medical device approval processes require extensive validation studies that exceed the scope of academic research projects, and the timeline for regulatory approval can span multiple years. The competitive pressures from established medical device manufacturers and technology companies with greater resources for regulatory compliance and clinical validation represent additional challenges for research-based innovations seeking market entry.

With the CARE project, we aim to offer another step of advancement in the decade-long ongoing endeavor to adapt AR technologies into the operating room. The broader research community can build upon our findings to explore additional applications of spatial computing in surgical environments. While this thesis focused specifically on virtual monitor placement for image-guided procedures, the technical framework and validation methodologies we developed can be extended to support 3D anatomical visualization, real-time surgical guidance systems, and collaborative training platforms. The modular architecture of the CARE system provides a foundation for investigating these expanded capabilities while maintaining compatibility with existing surgical infrastructure.

The competitive landscape in medical AR continues to evolve rapidly, with major technology companies and specialized medical device manufacturers investing significantly in surgical applications. Our research demonstrates that academic institutions can make meaningful contributions to this field by focusing on specific clinical problems, conducting rigorous user studies, and establishing validation methodologies that bridge the gap between technical capability and clinical utility. The work presented in this thesis represents

a significant step toward realizing the potential of augmented reality to enhance surgical practice through improved ergonomics and workflow efficiency. By successfully demonstrating that contemporary AR hardware can achieve the performance characteristics necessary for surgical applications, while simultaneously establishing a user-informed design methodology that prioritizes clinical needs, we have created a foundation for future research and development efforts.

The challenges that remain, including clinical validation, regulatory approval, and competition from well-resourced commercial entities, are substantial but necessary towards the overarching goal of adopting AR technologies in the operating room. Our vision extends beyond the immediate application of virtual monitors to encompass a future where augmented reality seamlessly integrates with surgical practice, enhancing both practitioner capabilities and patient outcomes. Through continued research, clinical validation, and thoughtful technological development guided by genuine clinical needs, this vision can become a reality that transforms surgical practice for the benefit of healthcare providers and the patients they serve.

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Appendix A: User Interview Questions

Interview Questions (Outline) – CARE Team; Spring 2024 CoMotion/NSF I-Corps Regional

General Questions

1. What do you plan to achieve when performing any procedure?
2. What is your highest priority when performing any procedure?
3. How many people are usually in the operating room and what are their roles?
 - (a) What does collaboration look like within the team?
4. What kind of information is important when performing the procedure?
 - (a) Can you rank the level of importance of the information required
 - (b) Other than taking information, what information do you output during the procedure, and how do you typically exchange information within the team?
5. Are there any current distractions and difficulties within the general procedural process?
 - (a) Are there specific tech difficulties you encounter in the procedural process?

Conscious Sedation

1. (Involve mind-mapping) Could you please go over the conscious sedation procedure with us? Please draw manually on paper

- (a) What are some key steps?
 - (b) Who do you work with and when throughout the process and for how long?
 - (c) Create a timeline for what tools are used when throughout the process and for how long?
 - (d) How often do you look at the monitor and when throughout the procedure?
2. What are the current issues with administering anesthetics, or more specifically, performing conscious sedation?

AR in Healthcare

1. Please describe your experience with AR (Augmented Reality) in or outside of the medical field.

Experience with AR & No Experience with AR

1. Were there any limitations to gaining experience with AR in healthcare?
2. What do you know about AR in healthcare?
3. How would you envision incorporating AR in a procedure or surgical training? What do you think AR would help you achieve and if you think it is a must-have/nice-to-have/not your interest or top priority?
4. What are concerns that you may have using AR for this specific procedure?

Appendix B: Dr. Oliver Aalami's AR in Surgery Presentation

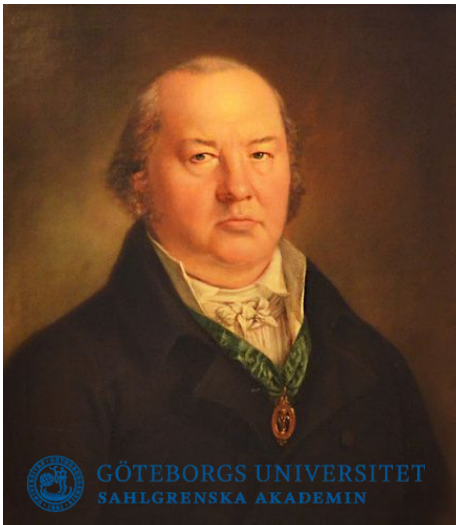
Appendix B contains the complete presentation slides from Dr. Oliver Aalami's talk "AR in Surgery" delivered at the Engineering Health - The Legacy of William Chalmers Initiative Seminar at Chalmers University of Technology, November 2017. The presentation provides valuable historical context for the development of augmented reality applications in surgical environments. These presentation slides are included as Appendix B due to limited public accessibility online.

Copyright Attribution: The presentation slides that follow are reproduced from Dr. Oliver Aalami's original work. These materials are included under academic fair use provisions for scholarly research and educational purposes. All rights to the original presentation remain with Dr. Oliver Aalami.

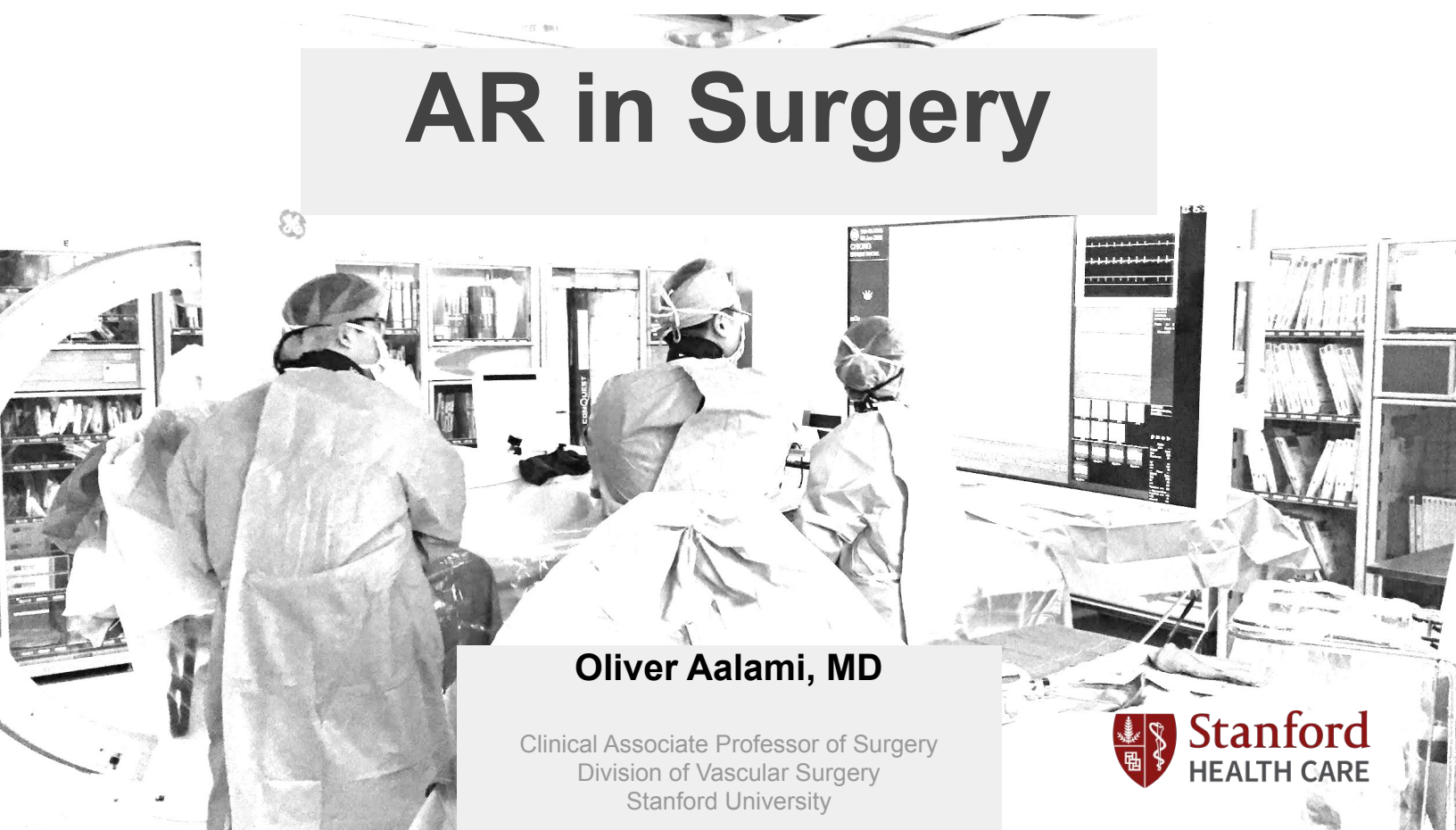
The Legacy of William Chalmers

Life Science Engineering AoA initiative seminar
2017, November 8-9, Runan

It's in our genes



AR in Surgery



Oliver Aalami, MD

Clinical Associate Professor of Surgery
Division of Vascular Surgery
Stanford University



Stanford
HEALTH CARE



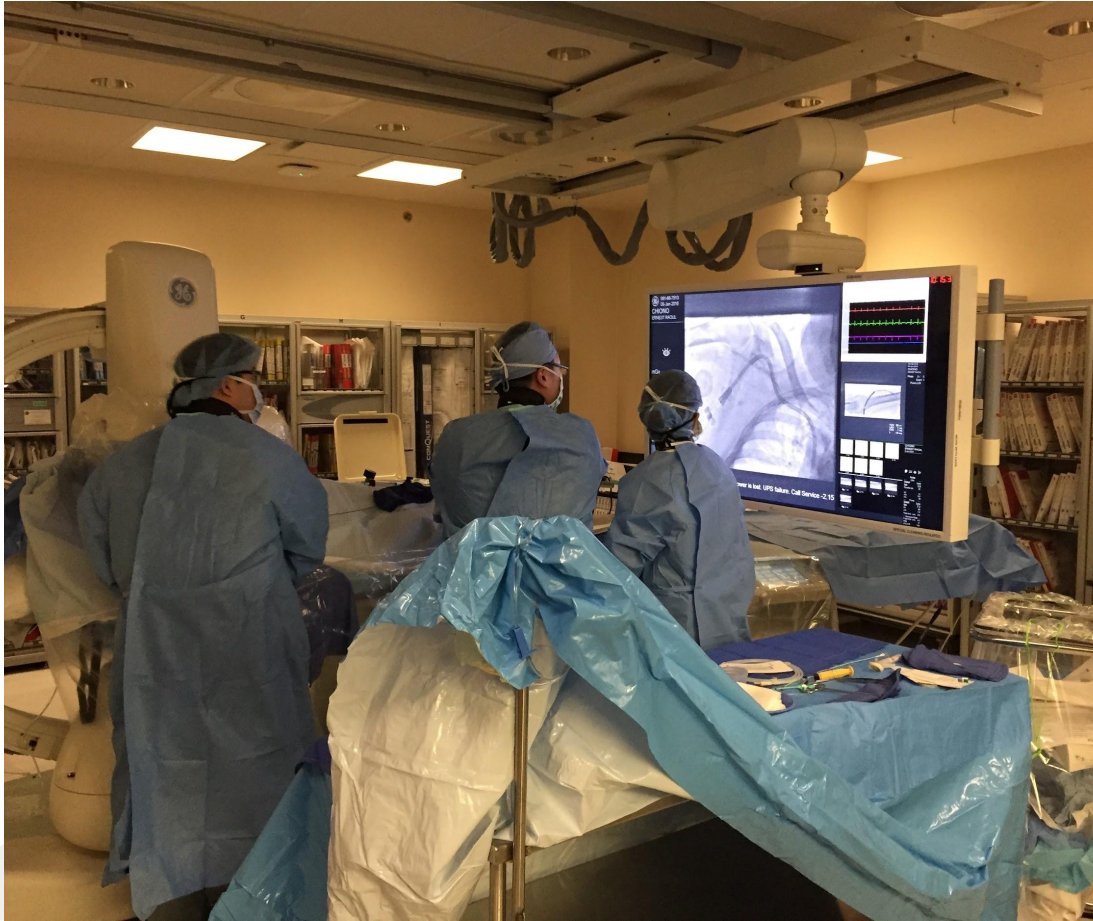
Operating Room

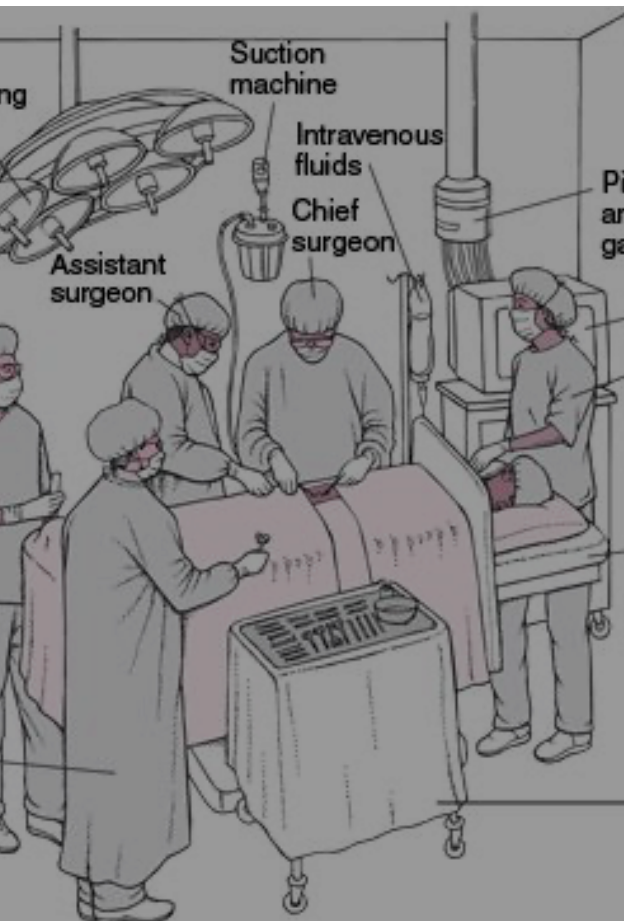
Surgery is Complex

Team Sport

Live Monitoring

Image Guidance





Team

Operating Room

- 1) Surgeon
- 2) Assistant
- 3) Scrub Nurse
- 4) Circulating Nurse
- 5) Anesthesiologist

Recovery Room / ICU / Ward

- 5) Mid level provider (PA/NP)
- 6) Nurses
- 7) Residents
- 8) Fellows
- 9) Students

Office

- 10) Nurses
- 11) Schedulers

Live Monitoring

Conscious sedation

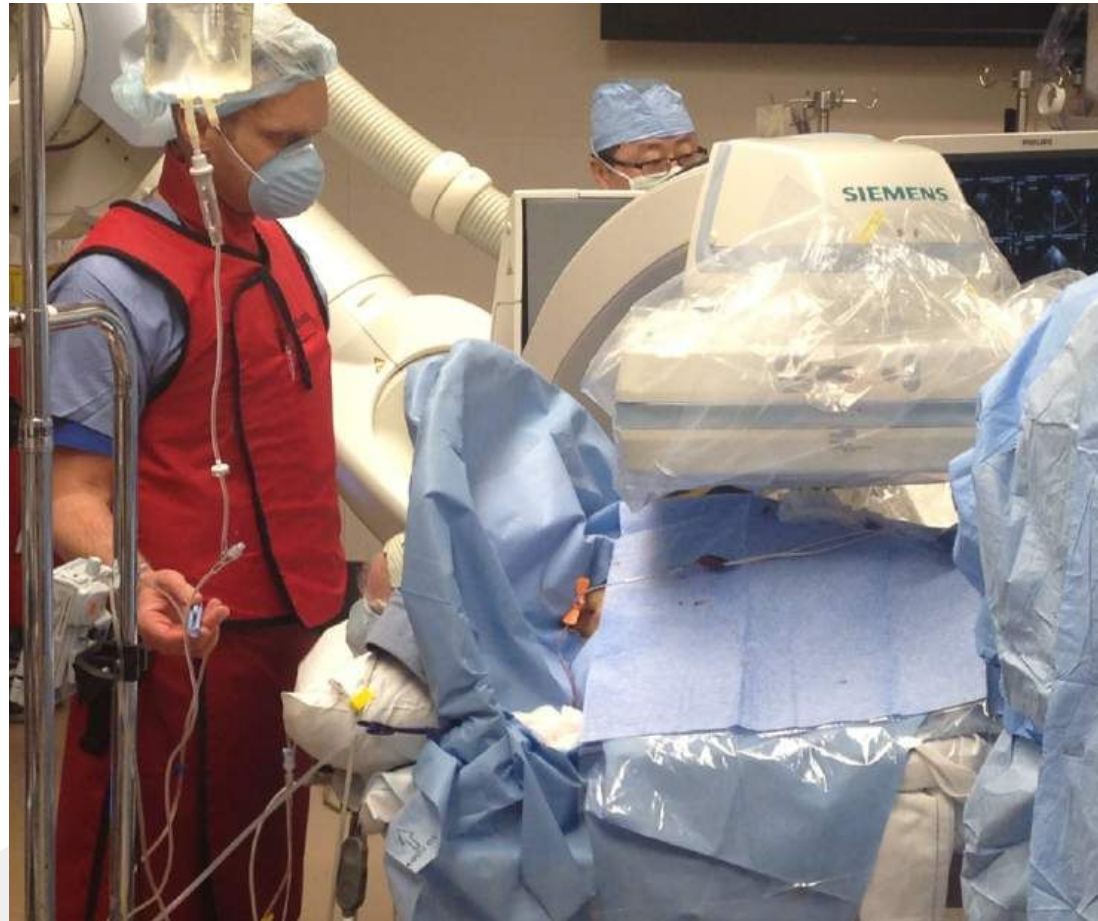


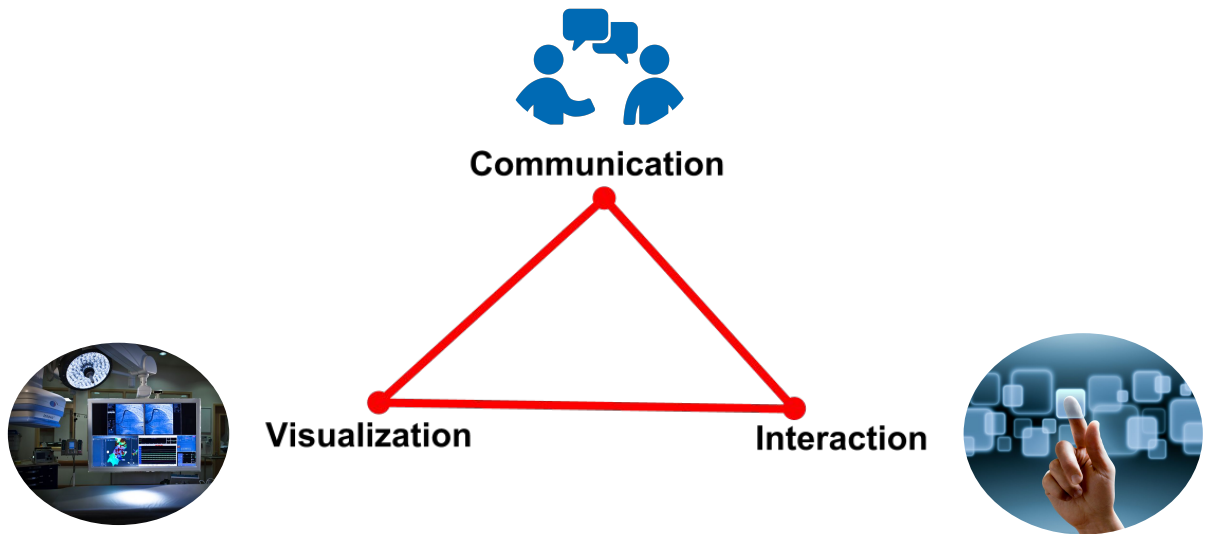
Image Guided Procedures on the rise...



Ortho | Neurosurgery | Vascular Surgery | Interventional Cardiology | Ear Nose Throat | General Surg



Disparate Data + Large Teams



Smart Glasses Can Bring it All Together...



My Journey...



2012







2013

Issues to consider for Operating Room

1. Hands Free / Sterile field
2. Surgeons used to asking for things
3. Need to focus on procedure
4. Magnification
5. Lighting

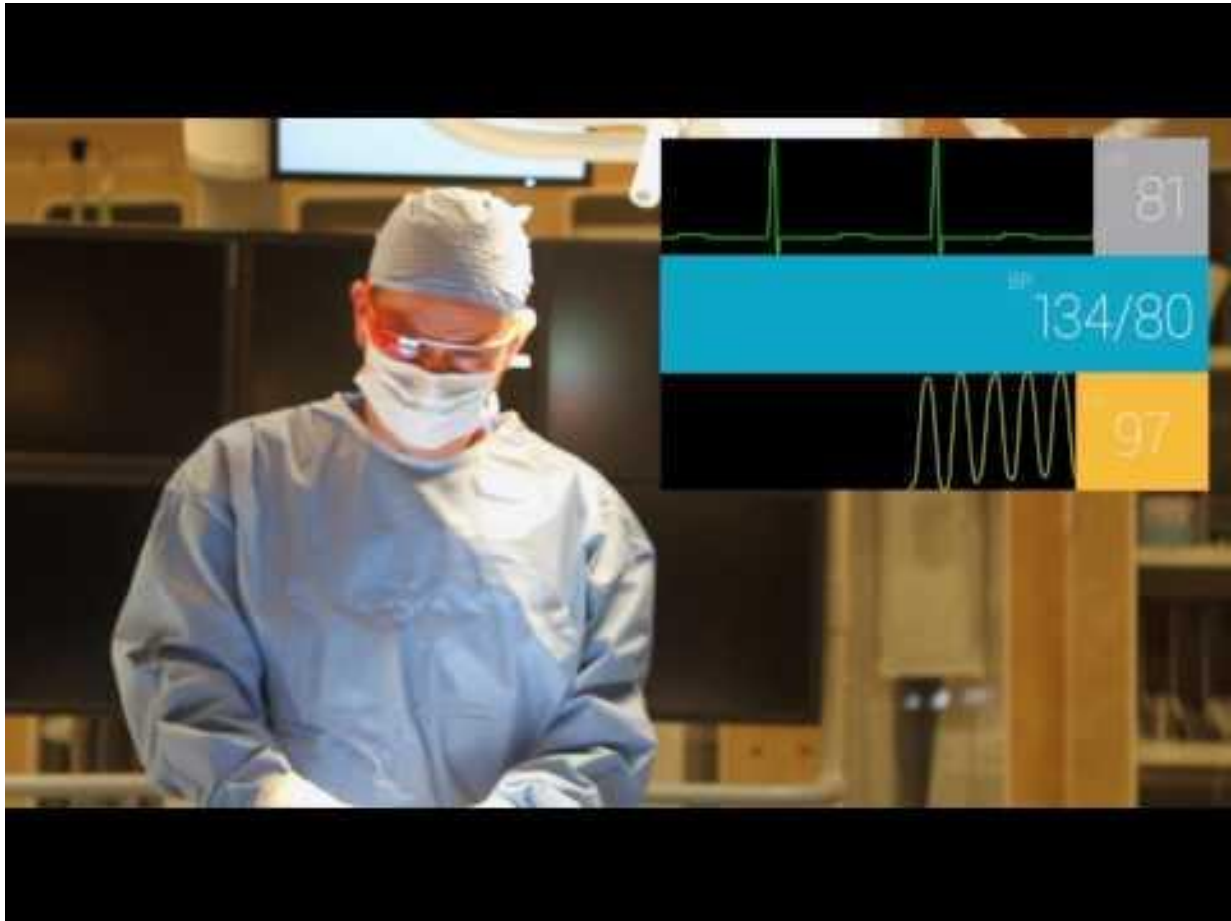




Conscious Sedation



Vitals On Glass



Novel Use of Google Glass for Procedural Wireless Vital Sign Monitoring

Cara A. Liebert, MD¹, Mohamed A. Zayed, MD, PhD^{2,3},
Oliver Aalami, MD^{1,4}, Jennifer Tran, BS¹, and James N. Lau, MD, FACS¹

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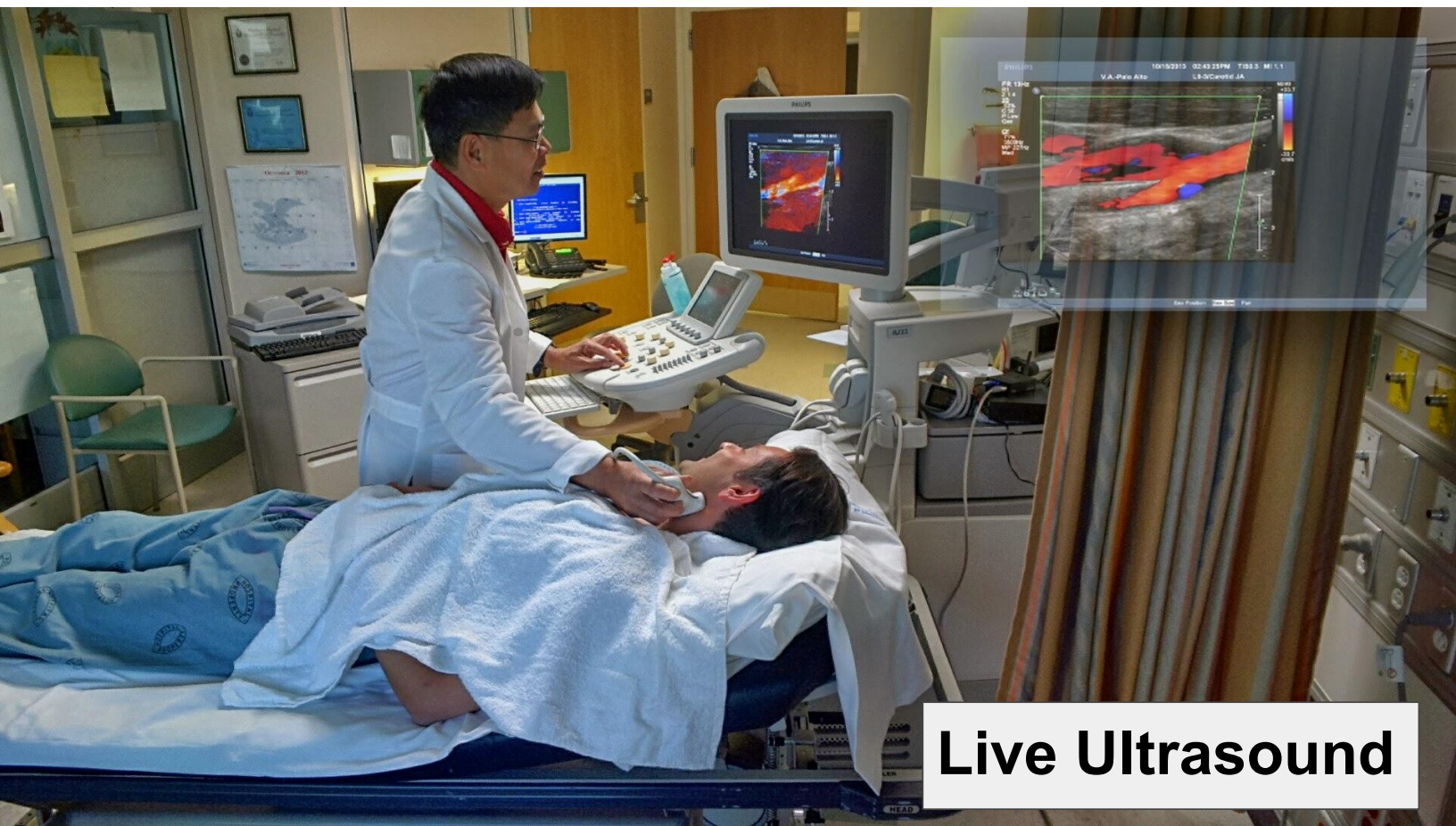


Figure 1. Wireless streaming of vital signs to Google Glass in a simulation setting.

- 1) Significantly fewer glances at monitor
- 2) Significantly less time spent looking at monitor



Live Fluoroscopy



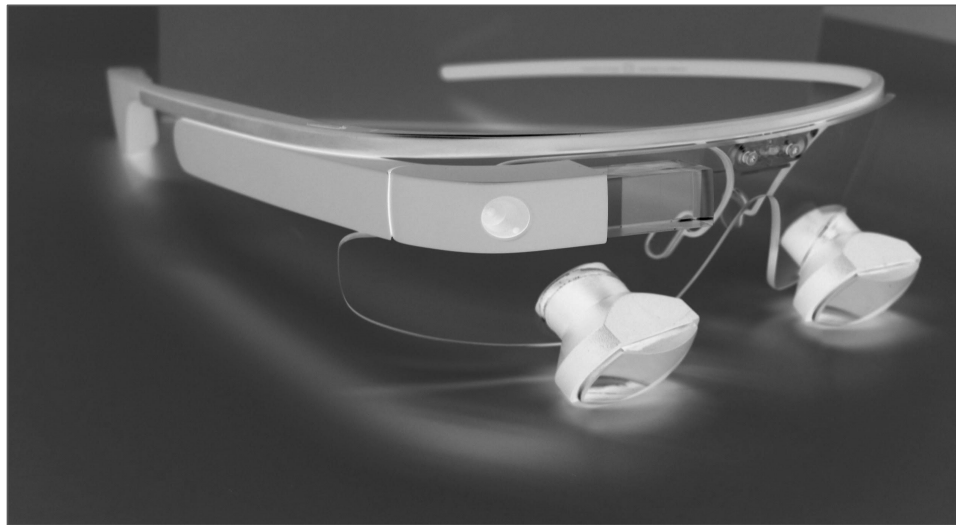
Live Ultrasound



Live Endoscopy

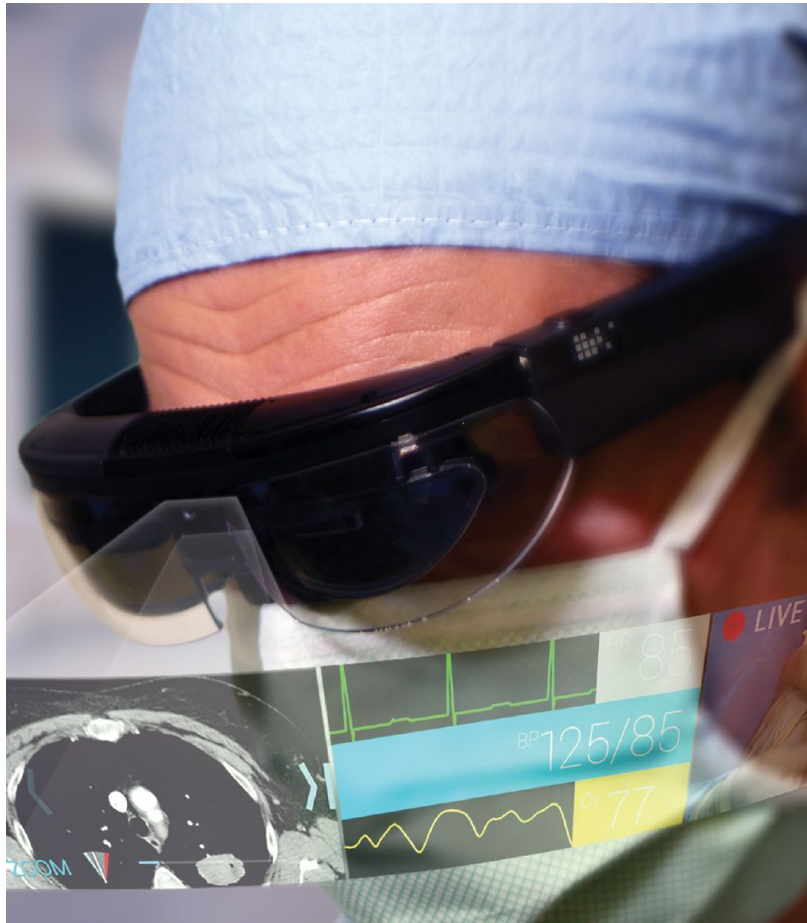
GG v1.0 Exciting....But Many Issues....

- Overheating
- Poor video streaming quality
- Poor battery life



ODG 

R-6
Smart Glasses

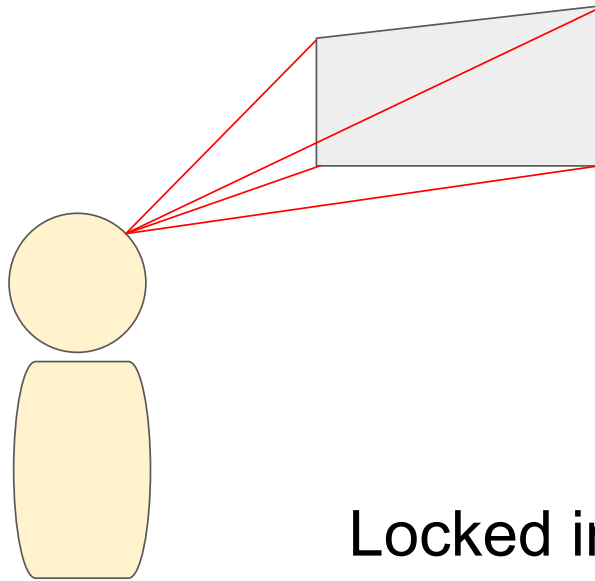






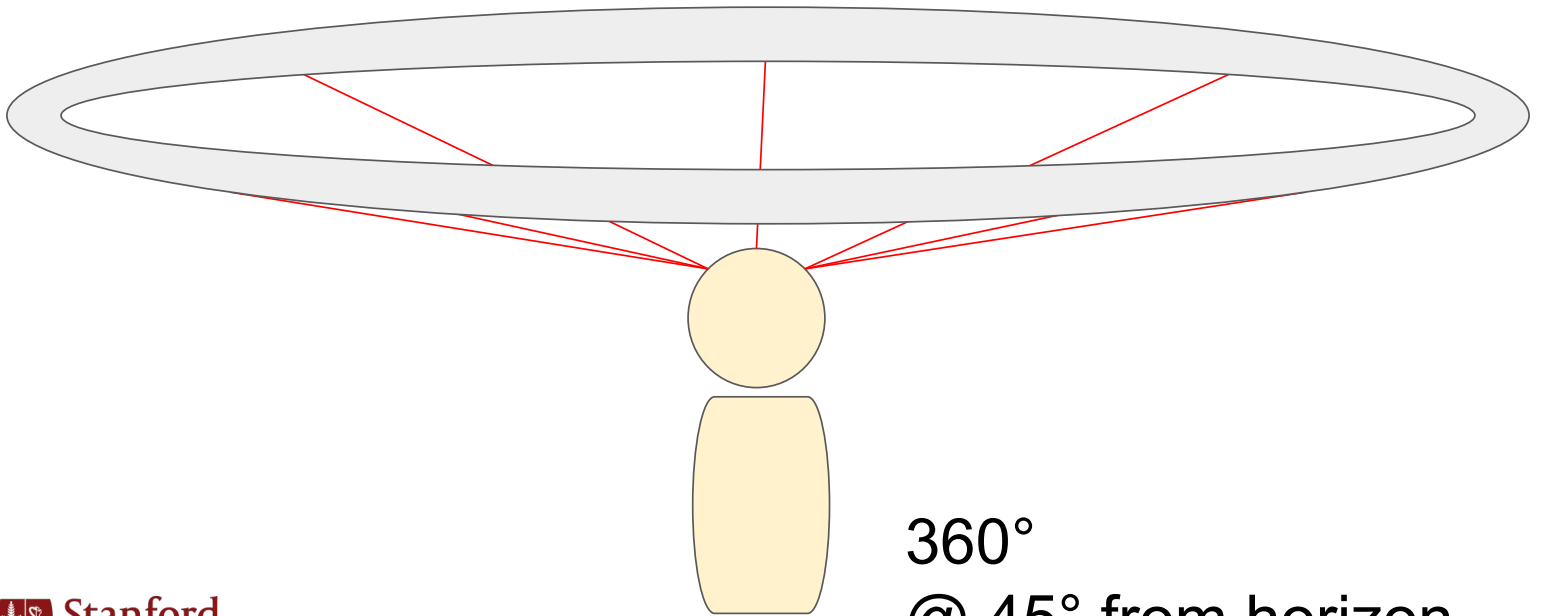
ODG R-6

Virtual Monitor: First iteration



Locked in space

Virtual Monitor: Second Iteration



Lessons Learned

Critical that new innovation does not disrupt current workflow

Try not to do everything!

Keep it simple!

What does the future hold?

Communication- Pure Audio

Data Visualization / Image Guidance- Augmented Reality

Anticipation/Teamwork- Screen Sharing

Education- Screen Sharing

Vue- going back to basics



Bone conduction audio

Bluetooth connection

Activity tracking



Microsoft HoloLens

Maps world

True Augmented Reality

Not tethered



Meta-2



Maps the world

Ture Augmented Reality

Tethered



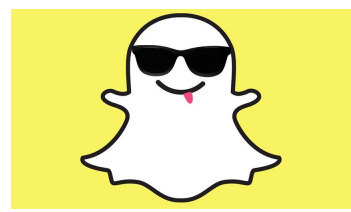
What would make surgeons wear smart glasses for every case?

- Connection to smartphone
 - Text messages / calls
- Flawless video connectivity
 - Live video for image guided procedures
- Team collaboration
- Excellent battery power
- Lighting option
- Magnification option



Has to be dumb stupid and work every time!

 Spectacles



Thank You!



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Experimenting With AR in Surgery



Oliver Aalami, MD

Clinical Associate Professor of Surgery
Division of Vascular Surgery
Stanford University

Co-Founder: Vital Enterprises



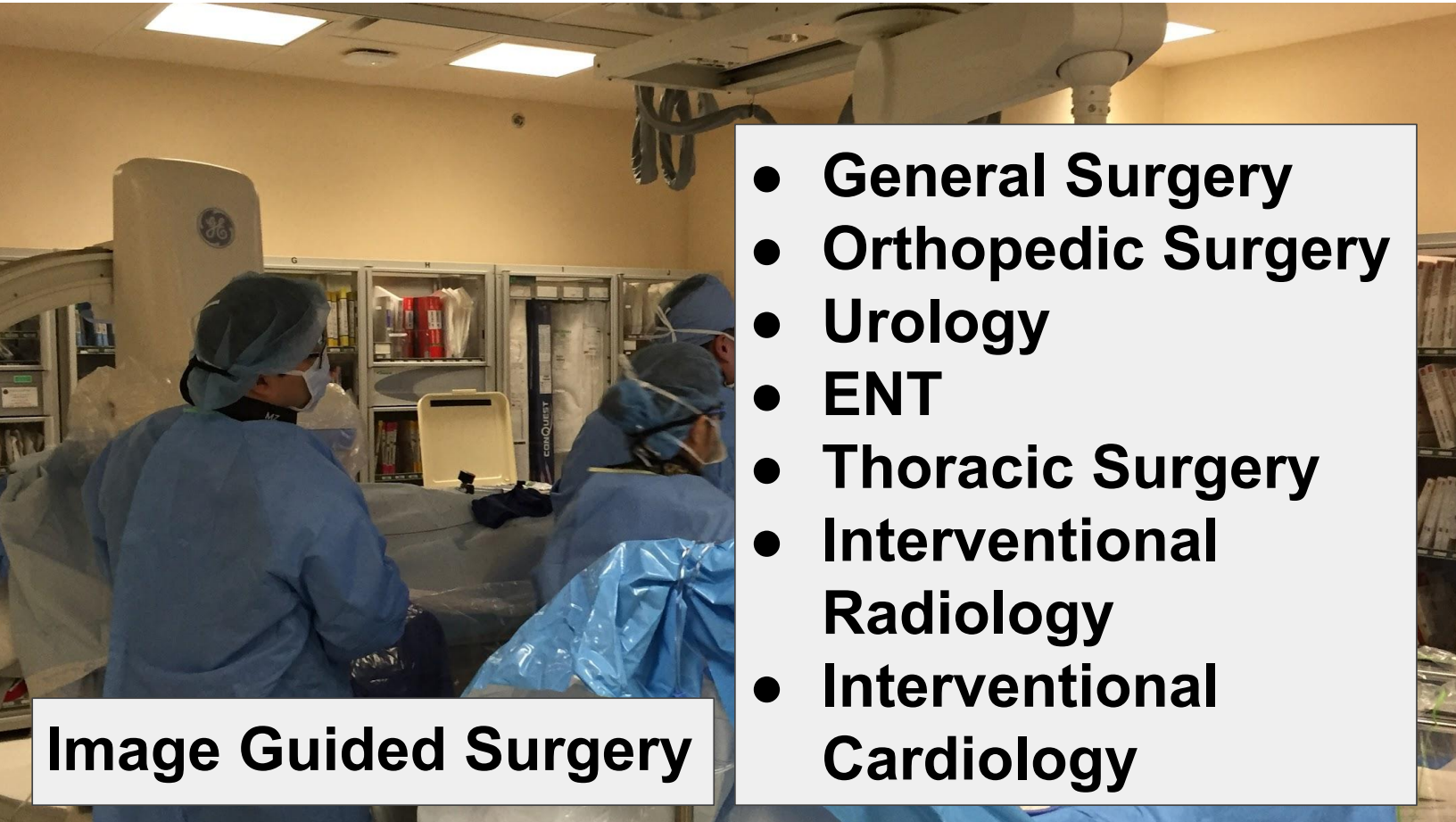
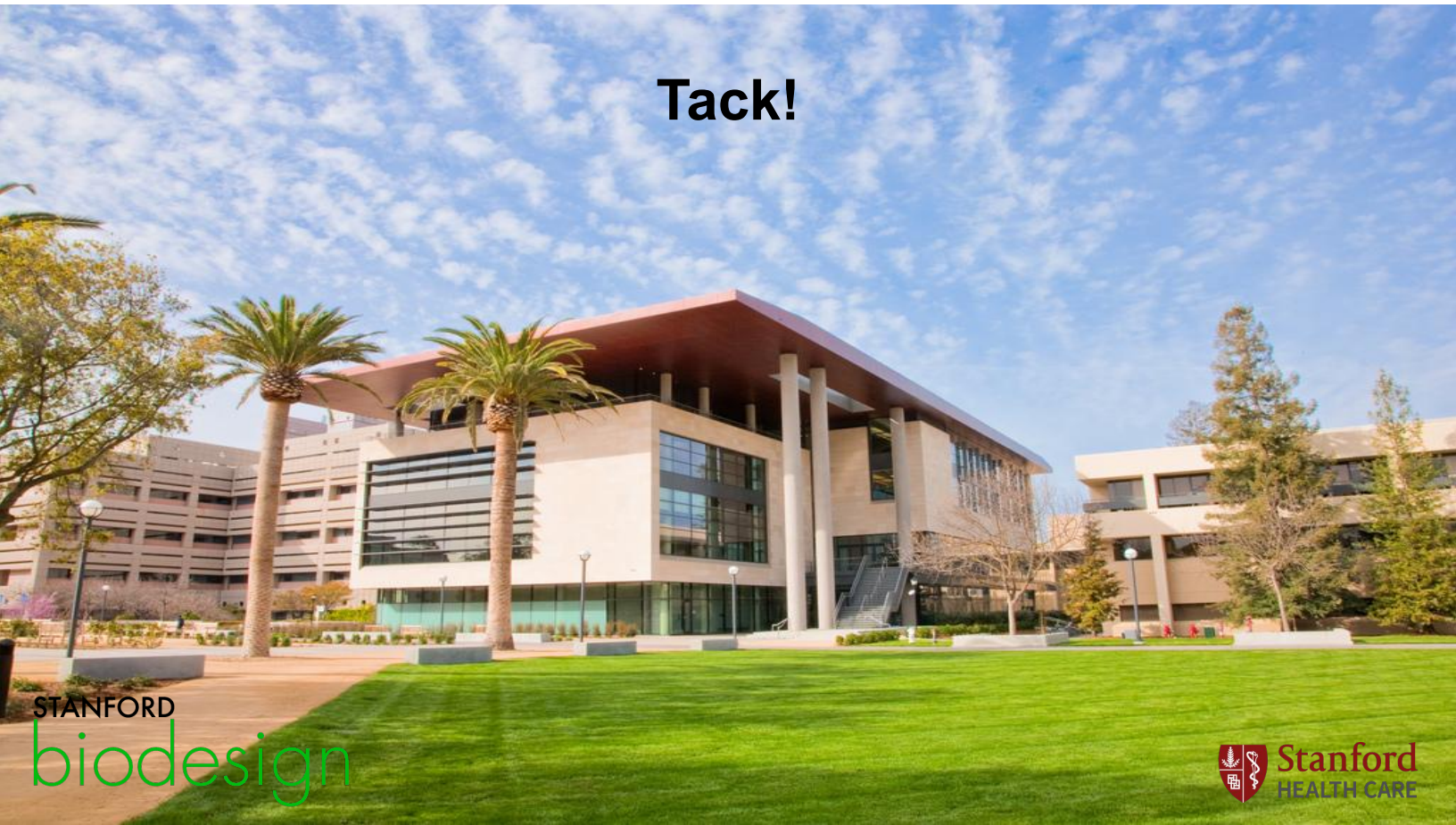


Image Guided Surgery

- **General Surgery**
- **Orthopedic Surgery**
- **Urology**
- **ENT**
- **Thoracic Surgery**
- **Interventional Radiology**
- **Interventional Cardiology**

Tack!



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