Freehand SPECT, an intraoperative nuclear imaging modality, is the first system involving AR visualization that is used routinely in real-life surgeries.

Nuclear medicine has become one of the most important tools in medical diagnostics. Doctors inject into the patient radiolabeled tracers that target specific body parts; dedicated detectors then use the radiation emitted from these tracers to create images. These detectors can vary from small handheld radiation counters to nuclear imaging systems containing several detectors on huge gantries.

Most 3D nuclear imaging systems such as SPECT are not suited for intraoperative use due to their size as well as operating room time constraints, so they are used only for diagnosis and planning. Physicians regularly use handheld counters during surgery, but these devices often fail in complex clinical cases because they only provide acoustic information.

Freehand SPECT offers a compromise: adding tracking to the radiation counter makes it possible to reconstruct 3D SPECT-like images during surgery with minimal disruption to the surgical workflow. First introduced in 2007, Freehand SPECT has evolved in the past five years from a prototype to a commercial product, the declipseSPECT cart system. Several clinics around the world now routinely use this device, which has received a European conformity marking and has been certified and approved by the US Food and Drug Administration.

Researchers are developing augmented reality visualization systems to provide accessible and user-friendly interfaces for medical intervention and patient information systems.

In the 1990s, researchers began proposing and partially validating augmented reality (AR) concepts and prototypes specifically aimed at the medical field. System calibration, synchronization, real-time rigid body tracking, registration, and real-time rendering of virtual data have received the most research attention to date, thus, different solutions satisfy technical requirements for different applications.

However, the development of AR systems for use in the medical field still faces three major challenges: the correct perception of virtual data in the real world; integrating AR into complex medical workflows; and implementing the required change in culture, which today involves modifying traditional education and training procedures before experts can focus on developing applications for diagnosis and treatment.

Here, we focus on three systems recently developed at the Technical University of Munich: Freehand SPECT (single-photon emission computed tomography); CamC (camera-augmented mobile C-arm); and Mirracle, an AR magic mirror.

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First Deployments of Augmented Reality in Operating Rooms

Researchers are developing augmented reality visualization systems to provide accessible and user-friendly interfaces for medical intervention and patient information systems.
Creating 3D reconstructions from a handheld detector requires using tracking technology. To be patient-specific, rather than mounting the detector inside a rotating gantry, as in SPECT imaging, the surgeon moves the detector intraoperatively in a freehand fashion. Based on the radiation counter’s positions and orientations, Freehand SPECT can use iterative image reconstruction techniques to generate 3D tomographic images.

Figure 1 depicts the declineSPECT cart system in use; it incorporates Freehand SPECT technology and uses a Polaris Vicra optical tracking system for spatial positioning, which requires two tracking attachments (“targets”) with retroreflective markers. One target is attached to the handheld radiation detector system, and another is placed on the patient to serve as a reference coordinate system for all the calculations as well as to compensate for slight patient movements such as breathing. A touchscreen monitor provides visualization and supports user interaction.

The difference between this imaging system and other interventional devices is its integration of an optical video camera inside the tracking system arm, which is visible in the upper left portion of Figure 1a. The video camera and tracking system are mounted in such a way that a one-time calibration after initial construction is sufficient to guarantee precise and continuous augmentation.

In most clinical cases, the system can reconstruct the volume in less than one minute after scanning the desired body region from at least two directions for about one to two minutes. This is well-suited for intraoperative use because it is much faster and needs fewer computational resources than conventional SPECT imaging, which requires much more time for image acquisition as well as computation of the final 3D volume.

The main advantage of image acquisition and reconstruction is optimized usage during the surgical procedure itself. However, this is only possible if the proposed reconstruction is visualized for the patient’s specific anatomy, facilitating intraoperative planning and guiding the surgeons to their surgical target. A patient study confirmed that integrated AR and virtual reality (VR) visualization is effective for this purpose.

Clinical applications

In a preoperative validation study of sentinel lymph node mapping in breast cancer, we mapped at least one SLN in 87.5 percent of 85 patients, with a sensitivity of 83.33 percent compared to the SPECT/CT, the highest sensitivity device available for diagnostic imaging.6 After this initial success, we took the Freehand SPECT system into the operating room in our university hospital to conduct feasibility studies of SLN biopsies for breast cancer and melanoma patients.6 Currently, Freehand SPECT is being used in several centers in the US, Europe, and the Middle East for SLN biopsies in breast, head and neck, vulva, penis, cervix, and prostate cancer, as well as the treatment of melanoma.

A new nonrandomized clinical study for SLN biopsy using Freehand SPECT recently was approved and is planned to include 150 breast cancer patients in our hospital over a two-year period to validate the clinical benefit of the system for this patient population.
Use of the Freehand SPECT system is not limited to SLN biopsies. Generally, it can be applied in most cases in which radioactive tracers are injected during surgery and detected using a dedicated radiation counter. Using Freehand SPECT extends the conventional radiation counter's functionality, making it easier for users to distinguish among different hotspots.

Additional clinical uses for Freehand SPECT include excisions of neuroendocrine tumors, thyroid cancer metastases, and paragangliomas; bone transplantations; and parathyroidectomies.

AR visualization

From the beginning, AR was an integral aspect of research on Freehand SPECT. Although the major goal was to create 3D tomographic reconstructions using signals from the radiation counter, even the first system prototype included AR visualization. Prior to the commercial product's availability, AR was the only choice for visualization.

With AR techniques, the reconstructed radiation distribution is overlaid atop the patient. As Figure 2 shows, surgeons using the system can clearly distinguish between the injection site, SLNs, and background radiation based on their anatomical locations. However, this visualization limits the use of 3D imaging because it does not give exact depth information.

This can be avoided by adding an alternate VR view, also called the 3D-view mode. As its name implies, this mode is a purely virtual visualization of the 3D reconstruction from the radiation detector's view; users can see the 3D volume from different angles and distances simply by moving the radiation counter, and it also allows depth measurements. The availability of alternate viewing modes improves the system's flexibility because the surgeon can choose the appropriate mode based on the current workflow stage.

Physicians also use the AR viewing mode for acquisition guidance. Due to its freehand nature, Freehand SPECT acquisitions depend on the scanning pattern, which has an impact on the resulting reconstructions. Getting 3D information requires scanning from at least two orthogonal directions, which is difficult to assure in the operating room, so proper guidance during scanning is essential.

In the system's current version, this is realized by providing online guidance during scanning in the AR view, showing scenes with an overlay of the volume of interest and a color-indexed visualization of how much information each unit in the volume has already received through the collected measurements.

Usability studies

Having a novel imaging device in regular use at our university hospital gave us an incredible opportunity to collaborate closely with physicians on usability evaluations.

Our operating room-specific domain model reduces complexity into three main views—surgical workflow, human role, and target device—and the interactions among them. The evaluation of any AR solution in a real application must take into account the complex models of interaction among these three views.

We conducted a study to demonstrate how the declipse-SPECT system can help usability engineers understand and model the surgical environment and its requirements as well as to analyze and evaluate usability problems in an operating room context. Our workflow-based analysis focused on sentinel lymph node biopsies; specifically, we analyzed the differences between AR and VR modes in the declipse-SPECT system with different surgical teams.

We reported on 52 surgeries that included 100 Freehand SPECT acquisitions in two different phases. Although the teams used both AR and VR during most surgeries, they chose AR more often. We also found that the use of AR and VR depends on both the requirements within
the current surgical workflow stage and user tendencies. Therefore, having two complementary viewing modes improves the system’s overall usefulness.

An interesting aspect of AR visualization within Freehand SPECT is its easy acceptance by the surgical crew. The physicians perceived AR visualization of injection sites and SLNs and the AR guidance in the acquisition process quite positively.

**CAMERA AUGMENTED MOBILE C-ARM (CAMC)**

In orthopaedic and trauma surgery, successful treatment requires that surgeons understand the spatial relationships between anatomy, implants, and surgical tools. This often requires considerable mental effort, time, and radiation exposure.

CamC offers a surgical AR technology that provides video-augmented x-ray images without the need for additional tracking technology or on-site calibration or registration. A workflow-based study of the use of CamC to insert interlocking intramedullary nails in cow cadavers showed a significant reduction in radiation exposure compared to the traditional use of x-ray imaging.

**Concept and construction**

A mobile C-arm is an x-ray device commonly used in orthopaedic and trauma surgeries. The CamC system extends a standard mobile x-ray C-arm with a video camera and a mirror so that the camera’s optical center and the x-ray source virtually coincide, and the video camera has the same view of the patient as the x-ray imaging system. As Figure 3 shows, this helps the CamC system provide an intuitive, real-time, intraoperative overlay visualization of x-ray images with live video acquisition from the coregistered camera.

To facilitate the correct overlay for the entire x-ray projection geometry, the CamC system must be calibrated, a procedure that happens once during the initial attachment of the video camera and mirror construction. A simple alpha blending method helps visualize the coregistered x-ray and video images. The surgical staff can operate the CamC system like any standard mobile C-arm, enabling smooth integration into the clinical routine.

Surgeons in the trauma section at the Leiden University Medical Center in Munich, Germany, have performed more than 40 orthopaedic and trauma procedures using CamC’s AR imaging. Although some of these surgeons had never used CamC, they could easily work with it after a quick introduction.

**Clinical applications**

As Figure 3 shows, augmenting x-ray images with coregistered live video helps surgeons quickly and intuitively see the spatial relations between patients and medical images. Once the system acquires the x-ray image, the surgical procedure can continue: surgeons can place a surgical tool or locate an internal target from this combined video imaging of the patient’s anatomy.

Clinical trials on 40 patients helped us identify the following surgical tasks that directly benefit from CamC’s medical AR imaging.

**X-ray positioning.** When taking an x-ray image of a particular anatomical structure, the C-arm must be moved to the correct position. With CamC, the medical staff can intuitively and efficiently position the C-arm, achieving an optimal view and avoiding the usual acquisition of multiple x-ray images.

**Optimal incision.** After acquiring an x-ray image showing bone structures or an implant, the coregistered live video helps plan the correct incision, minimizing surgical trauma by placing it with the optimal length exactly above...
the fracture or implant. Figure 4a shows the incision for an elbow fracture under the guidance of the x-ray and live video image overlay.

**Instrument axis alignment.** The insertion of linear surgical instruments along a specific axis requires first positioning the C-arm in the so-called down-the-beam position—the insertion axis is along the direction of the radiation beam and projected as a single entry point onto the acquired x-ray image. The instrument’s precise alignment with the correct axis is usually achieved by first aligning its tip with the entry point and then orienting it along the axis, a common surgical task that typically requires obtaining many x-ray images.

As the video camera and radiation beam share the same projection geometry in CamC, the process of instrument axis alignment and insertion can be guided using the live video coregistered with a single x-ray.

**K-wire guidance.** Doctors often use K-wires to temporarily fix bone fragments or immobilize a joint. For wrist fractures, they must take great care not to injure the radial nerve’s sensory branch when inserting K-wires, which requires checking the K-wire’s insertion point and direction relative to the bone structures via C-arm x-ray images. By using CamC, the surgeon can intuitively anticipate a linear K-wire’s direction relative to bone structures from the overlay image showing the bone and the K-wire in a correctly augmented image. Figure 4b shows the placement of a linear K-wire via CamC in a patient with fractures of the distal radius.

**Avoidance of direct radiation exposure.** As Figure 4c shows, with the CamC system, surgeons can see in the augmented image whether their hands are directly inside the x-ray imaging area. Moving their hands out of the imaging area during the x-ray or fluoroscopic image acquisition can reduce direct radiation exposure, especially in situations where the surgeon must hold the patient’s extremity in a special position to acquire a particular image.

**Current limitations**

One challenge for CamC is operating room lighting, which can over- or underexpose areas in the video image. The superimposition of x-ray and video images with alpha blending could make it difficult for the surgeon to quickly recognize and differentiate structures in the overlaid image. To address this, we are introducing advanced visualization and image-enhancement methods to improve video-augmented x-ray visualization.

Another challenge occurs when the anatomical part moves away from the position in which the x-ray image was acquired, a scenario in which the static x-ray image and the live video image can be misaligned and lead to misinterpretation of the augmented image. One solution is a sterilized visual marker rigidly attached to the patient. If the person moves, the system can inform the surgeon.

Figure 4d offers an example: the initial marker positions set during x-ray acquisition are drawn as green quadrilaterals, and their positions in the current video image are highlighted in red. The length of the gradient color bar on the right side of the augmented image indicates the pixel difference between the marker's initial and current positions.

Surgeons are responsible for acquiring a new x-ray image when misalignment occurs, but in our case studies, many of them decided not to—instead, they either reversed the movement to the original position or did not require an exact overlay at that particular point of the procedure.
Because visual markers are often attached to the skin surface, minor movement tends to occur relative to the underlying bone. The visual marker tracking method could therefore slightly misinterpret image alignment, which must be addressed in future work. To completely resolve the misalignment problem, a feasible and commonly used method in clinical practice is to physically stabilize the patient using specially designed extension tables.

**Overall outlook**

When a new medical AR system is introduced into the operating room, surgeons must explore the system fully to take advantage of its full potential. At this stage, close collaboration between surgeons and engineers is extremely crucial, because the system, its functionalities, and user interface play an important role in further development and clinical impact.

Full collaboration could eventually let surgeons modify single workflow steps, optimizing the way they perform surgeries or even inventing novel, less invasive procedures that take full advantage of the AR imaging and visualization technology that CamC provides.

**MIRRACLE**

Medical education and training are promising areas for bringing AR into everyday use and changing the culture within the medical domain. To provide proper treatment, medical practitioners need a mental model of patients and pathologies, and medical knowledge is an essential aspect of their general education. AR offers a powerful tool for providing new and intuitive perspectives on medical knowledge that can help students build and improve their mental models.

The requirements for medical training and education are very different from those for using AR in patient treatment, which requires highest precision, accuracy, and reliability. AR systems used for education must be intuitive, motivating, and inexpensive.

MIRRACLE, an AR magic mirror for medical education, borrows its main ideas from well-established concepts used in entertainment. The AR magic mirror concept creates the illusion that the user is standing in front of a mirror, which adds virtual objects to the mirrored image. The concept is familiar to anyone who has used a virtual fitting room to try on shoes or shirts, but instead of augmenting objects such as clothing, MIRRACLE creates the illusion of seeing inside the body, as in Figure 5.

To correctly augment anatomy onto users, their pose must be known. For this, we used Microsoft’s Kinect, a commercial off-the-shelf product that tracks a user’s pose with a depth camera.

Although the hardware setup is similar to other magic mirror implementations, some issues are much more complex in the medical domain. Object augmentation inside the human body is more challenging than augmentation of objects projected onto a user. Simply augmenting a virtual organ onto the patient will lead to incorrect depth perception as the organ occludes the patient. When an object occludes another object, this is a strong depth cue for being in front of the other object, which is problematic especially for a monocular display in which other depth cues such as stereo disparity are missing.

To address these challenges, MIRRACLE uses a medical volume renderer that offers video-based focus-and-context visualization adapted for AR visualization. As in Figure 5, internal objects appear only through a focus window, and the skin is preserved as context. This technique avoids wrong occlusions and restores parallax as a depth cue.

Another area in which a magic mirror for medical education must go beyond simpler systems is data presentation. MIRRACLE uses the Visible Korean Human (VKH) dataset, which consists of CT and magnetic resonance images, photographic slices providing full-color images,
and the labeling of more than 900 structures; based on this data, we implemented different visualizations. Using CT, we can superimpose an in situ visualization of bones on the user. Alternatively, we can simulate an x-ray image so that the user has the impression that he is standing in front of an x-ray device. If a CT scan is available, we can create a patient-specific visualization, which is beneficial, for example, for patient-doctor communication.

The user can select slices from the CT or the photographic volume via gestures. The slice always corresponds to the hand’s position, so users can relate the images to their body. In Figure 5, users selects a sagittal plane, which divides the body into left and right sides. The currently selected slice is visualized as a green rectangle that is augmented onto the user.

Interaction with additional information such as text, photos, videos, and 3D models of organs requires a more powerful user interface. For this, we developed a novel AR visualization for gesture-based interaction in which a video image of the user’s hand is visually colocated with the virtual information. A depth camera creates the illusion that the hand can touch information displayed on frosted glass.

So far, we have presented Mirracle to the public in various settings, such as during open house events at hospitals, universities, and schools. It has proven to be robust and attracts attention, especially from children. It has also generated interest from physicians in various fields, including those who teach physiotherapy, anatomy, radiology, sports medicine, and children’s medicine, and for general education in science centers.

In addition to our local university hospitals, we have set up the system at the Academic Medical Center Amsterdam and are currently developing a game to use for learning anatomy and radiology. In this way, AR would become a natural part of medical education and training and also would be exposed to the general population. This would hopefully pave the path for information systems in which medical practitioners would use AR technology to inform and educate their patients. If such systems are adapted for medical education and training, the next generation of medical doctors would be better prepared to accept and interact with cutting-edge AR solutions within their operating rooms.

AR user interfaces will continue to be integrated into an increasing number of medical solutions, especially in computer-assisted interventions.

FUTURE DIRECTIONS

Augmented reality is finding its way into our everyday lives, from entertainment to advertising to communication and gaming applications. The medical field is the natural next frontier. Freehand SPECT and CamC have been introduced into multiple operating rooms and are now used by hundreds of clinicians in a wide variety of facilities. Mirracle has been set up for use in a hospital, and we are planning to use it for medical education.

We believe that AR user interfaces will continue to be integrated into an increasing number of medical solutions, especially in computer-assisted interventions. Although researchers have developed many such interventions in the past few decades, few have found their way into routine use, partly because of the lack of appropriate user interfaces that integrate such systems intuitively and without generating additional complexity for the surgical staff.

AR has a huge potential to enable seamless integration of novel technologies into the clinical workflow and to facilitate visualizing novel multimodal imaging within the human body. However, many challenges remain before full integration of such advanced solutions is possible.

One technological challenge is to develop optimal medical AR display devices for each given surgery or even each surgical phase. Although we have developed two systems that augment the surgeon’s view into the human body, from the AR point of view, the ultimate vision of being able to directly look into the patient using head-mounted displays (HMDs) has not yet been fully realized.

Some misconceptions exist in regard to AR solutions for surgical procedures.

First, ceiling-mounted solutions could avoid the problems associated with weight and cable connections to HMDs. Therefore, even though they could be advantageous because of their mobility and availability in multiple operating rooms, there is no need to wait for lightweight, wireless HMD solutions.

The second issue is access to patient data through hospital information systems. Even if this does not seem to be a major technological issue, it is still a major barrier because of the complexity of data availability and communication in clinical settings. Because the AR systems described here take advantage of their integration into interventional imaging devices, they could access complementary medical images located elsewhere in the system. Despite recent work on improved perception and interaction within medical AR environments, further advancement in these fields is necessary to advance the acceptance of surgical AR solutions.

A remaining barrier for acceptance and full integration of AR technology within medical procedures is the required change of culture. Fortunately, the integration and success of AR both in everyday life applications such as
We strongly believe that a successful AR solution is one that the user does not perceive as such. AR technology must be seen as another simple user interface, offering data representation and a display solution that provide required information at a given time in the most optimal way. Familiarization with technology would let users consider AR as a natural viewing possibility that enables them to go beyond human capabilities in terms of sensing and observation.

**References**


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