

# Exploring and Slicing Volumetric Medical Data in Augmented Reality Using a Spatially-Aware Mobile Device

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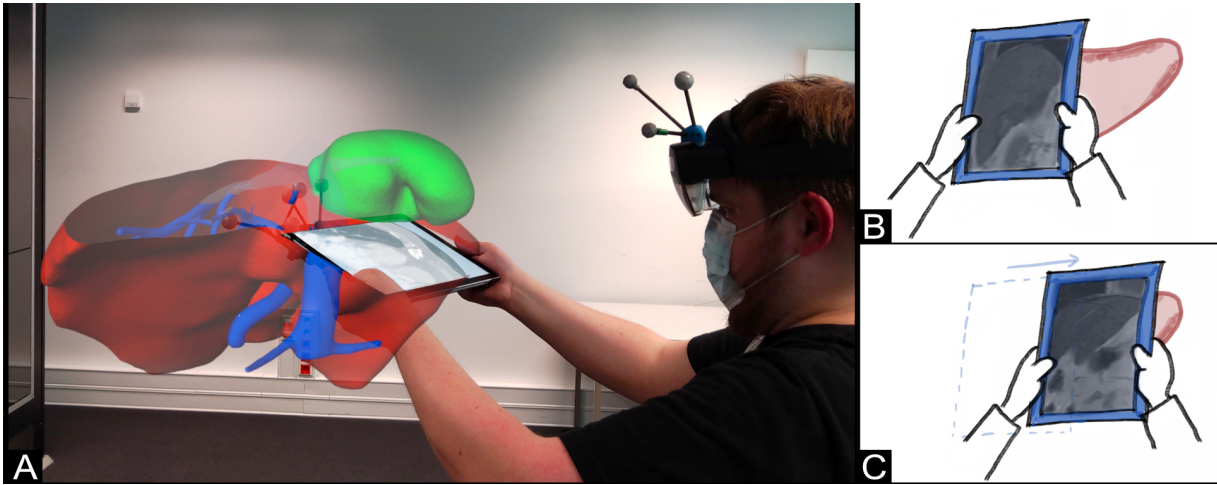


Figure 1: (A) Prototype demonstrating our setup that combines an AR HMD, showing a 3D model, with a handheld tablet which displays a 2D slice. This system enables exploring volumetric medical data by spatially moving the tablet as a cutting plane through the AR model to see the position dependant greyscale image slice of the model, shown in (B) and (C).

## ABSTRACT

We present a concept and early prototype for exploring volumetric medical data, e.g., from MRI or CT scans, in head-mounted Augmented Reality (AR) with a spatially tracked tablet. Our goal is to address the lack of immersion and intuitive input of conventional systems by providing spatial navigation to extract arbitrary slices from volumetric data directly in three-dimensional space. A 3D model of the medical data is displayed in the real environment, fixed to a particular location, using AR. The tablet is spatially moved through this virtual 3D model and shows the resulting slices as 2D images. We present several techniques that facilitate this overall concept, e.g., to place and explore the model, as well as to capture, annotate, and compare slices of the data. Furthermore, we implemented a proof-of-concept prototype that demonstrates the feasibility of our concepts. With our work we want to improve the current way of working with volumetric data slices in the medical domain and beyond.

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**Index Terms:** Human-centered computing—Mixed/Augmented Reality; Human-centered computing—Visualization

## 1 INTRODUCTION

Exploring volumetric data, such as those known from medical imaging techniques like MRI or CT, still faces many challenges. When viewing such data on conventional displays, their two-dimensional nature cannot sufficiently represent the richness of the volumetric data. Even though most physicians are trained in transferring medical images into an overall mental model of the patient's anatomy, this requires a high cognitive effort that is intensified or even becomes a barrier for less experienced individuals such as students or patients. Nevertheless, medical professionals, especially radiologists, have become so accustomed to the greyscale image slices that they cannot be simply replaced, but instead need to be integrated in the development of new exploration and visualization techniques. In particular, new systems should assist in gaining a spatial understanding of the data, e.g., in preparation for surgeries, while also supporting conventional capabilities of DICOM (Digital Imaging and Communications in Medicine) viewers.

The recent rise in immersive technologies like Augmented Reality (AR) head-mounted displays (HMDs) has provided the opportunity to explore such data as stereoscopic images and situated directly in the environment. Thus, three-dimensional representations of medical data, such as models of organs, can be explored from different directions by physically moving around them [15]. However, the

stereoscopic view on its own does not solve the issue of creating or correlating slices of the data with their 3D representation. To address this issue, we propose using a Focus+Context approach by combining the AR HMD with a spatially tracked tablet (as Focus) that enables inferring the accurate position and orientation within the 3D representation in AR (as Context; see Fig. 1A). Thus, the tablet not only serves as the physical manifestation of the virtual slice and thereby reducing the cognitive effort, it also enables creating arbitrary slices through the data by simply moving and rotating the tablet (see Fig. 1B+C). Through this tight integration of both AR HMD and tablet into a single information space, the gap between the volumetric nature of the data and the common 2D image slices can be reduced.

In our work we contribute several concepts to use this combination of devices for medical data exploration. We developed a proof-of-concept prototype for testing the feasibility of our ideas. Based on our hands-on experiences, we discuss further promising techniques, various interaction possibilities of our proposed system as well as our plan for future work. We are convinced that this device combination has a lot of potential to reduce the cognitive effort when working with medical imaging and helps in finding and analyzing diagnostic slices of volumetric medical data sets.

## 2 RELATED WORK

Our research is related to spatial interaction, AR data visualization, and volumetric medical data exploration. We start with examples from the field of Human-Computer Interaction by considering previous combinations of mobile devices with immersive HMDs. Afterwards, we focus on the use case of medical data exploration and highlight previous related approaches, with a focus on model slicing.

### 2.1 Combining mobile devices with Immersive HMD

While smartphone-based AR has become popular over the last decade, it is only recently that the approach which combines mobile devices and AR HMD is receiving increased attention. Previous research has shown various benefits (e.g., precise interaction) of this combination and several use cases have been considered such as 3D modeling design [13, 26] and information visualization [9, 12]. For instance, Hubenschmid et al. [9] presented STREAM, a system combining AR HMD and spatially-aware tablets for analyzing 3D parallel coordinates visualization. Sereno et al. [20] envisioned a hybrid environment with AR HMDs for visualizing volumetric data and tablets for data manipulation and annotation to enable collaborative data analysis. Particularly related to our idea is Montano-Murillo et al.'s Slicing-Volume [14], which uses a 2D pen-and-tablet metaphor for slicing and selecting dense datasets like point clouds in Virtual Reality (VR). However, tablets are only used as a plane of reference to specify the scope of selection and do not present additional visualizations. Previous research reveals the great potential of combining AR HMDs and mobile devices. Therefore, it is worthwhile to further explore the numerous possibilities and benefits within specific application fields.

Moreover, some research has investigated the coordination of touch interaction and spatial interaction offered by mobile devices in immersive environments. Saidi et al.'s HoloBar [18] introduced a contextual interaction technique for AR by coordinating the smartphone's spatial interaction and touch input for a hierarchical menu. Surale et al. [26] introduced an interaction technique vocabulary and Zhu and Grossman [27] proposed a design space of bidirectional interaction, based on the spatial and touch interaction of mobile devices combined with an AR HMD. Büschel et al.'s study [3] showed the benefit of spatial and tangible interaction of smartphones for navigating in immersive information visualizations. In summary, there is a growing body of research exploring and considering the benefits of combining immersive HMD and mobile devices. However, the process of analyzing volumetric medical data has rarely

been included, so the following section specifically addresses the exploration of these.

### 2.2 Image Slicing for Medical Data Exploration

Virtual cutting planes have already been used to explore volumetric data sets [8]. Song et al. proposed to remotely control a plane using a handheld device that also enables annotating the extracted slice [21]. Besides, freehand gestures were proposed to support users translating the slicing planes for analyzing medical data [1, 2, 11]. In these examples, the outputs are still limited to 2D. Approaches for immersive environments do exist as well. Schott et al. [19] presented a VR/AR environment that enables exploration of DICOM data cubes by spatially arranging virtual cutting planes via HTC Vive controllers. Additionally, the VR visualization software Spec-toVR [4] and the LiverPlanner [17] display the corresponding 2D image onto virtual cutting planes in VR. IMHOTEP presented by Pfeiffer et al. [15] display CT image slices next to a 3D model as reference while exploring it. In addition to these mainly VR applications, OpenSight<sup>®</sup> from Novarad<sup>®</sup> enables visualizing 2D slices directly onto a patient's body via an AR HMD based on the position the slice was taken from [6].

The presented examples show that already some solutions exist to connect the 3D data space of a patient's anatomy with 2D data from medical imaging by using a cutting plane approach. Those systems can, e.g., be used to support education [15, 19], surgery planning [4, 15, 17], and even surgery execution [6]. Some of the presented systems use controllers to place the planes completely flexible in space. However, controllers can only offer universal, limited haptic feedback which leads to difficulties in the hand-eye coordination of the user when slicing data. To address this issue, tangible interaction [8, 16], but even more related to our approach, spatial interaction by tangible cutting planes have been used. Spindler et al. [25] proposed PaperLens, whereby a tracked cardboard sheet acts as a handheld magic lens that shows a slice of a volumetric data set while the whole body is shown on a tabletop below. Since interaction with the data is limited, the authors suggest additional interaction possibilities, such as multi-touch, and demonstrate pen-based interaction techniques [24] as well as Tangible Windows that are coupled with the user's head [22]. In a later work, Spindler et al. [23] presented Tangible Displays, already utilizing handheld displays. Also Issartel et al. [10] proposed using a mobile device as a cutting plane representation to slice volumetric data. However, the focus has so far not been on the medical domain, which is why we specifically address the domain user's needs of such applications in our concepts. In addition to a commonly used mobile device, we also choose to use AR in contrast to the previously presented, mostly VR, applications. Thus, the connection between other people and their real surroundings can be preserved, which facilitates integrating the system into everyday clinical practice.

## 3 CONCEPTS FOR VOLUMETRIC DATA EXPLORATION

The goal of this work is to present a novel way for physicians to interact with medical scans from MRI or CT imaging to analyze them for diagnosis and to prepare for surgeries or other procedures. To achieve this, we propose an interaction concept of combining an AR HMD with a spatially tracked tablet. For the remainder of this work we refer to the use case of liver surgery planning with the assistance of MRI imaging data from [5] to describe and illustrate our concepts.

A physician wearing the HMD can examine a spatially registered model of a patient's liver in AR, after placing it in the room. They can freely explore the AR liver from all sides by walking around and looking at it. The physician carries an interactive, spatially tracked tablet as well. This tablet can be used as a slicing tool by moving it somewhere inside the liver model, which creates a cross-section with the liver. The resulting 2D image of the cross-section is shown

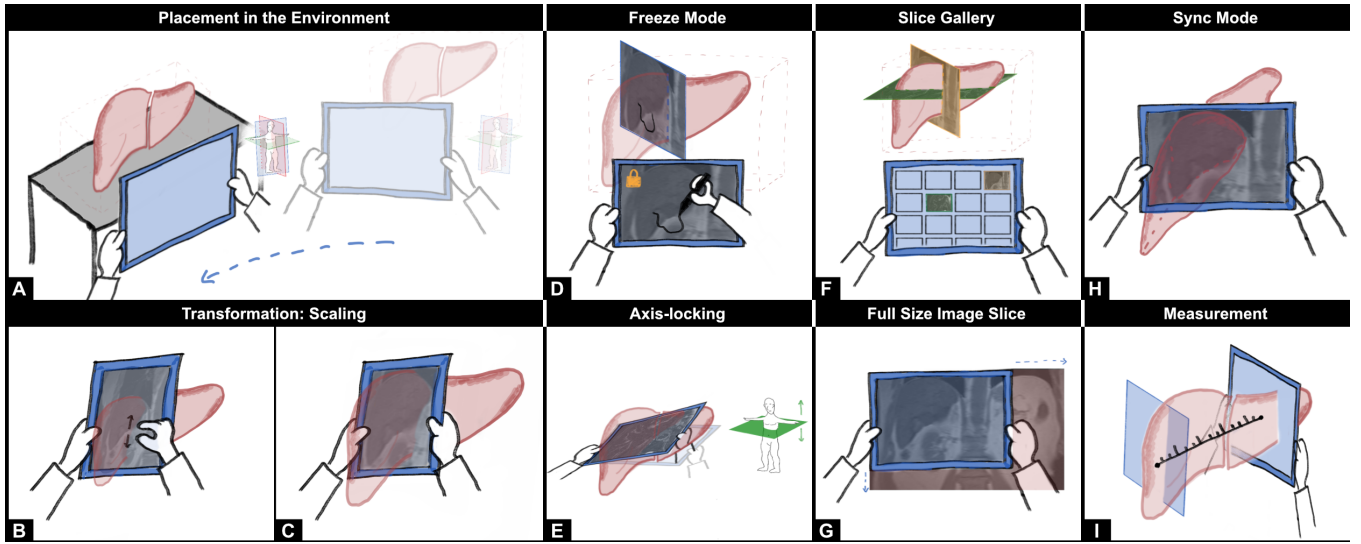


Figure 2: Illustrations of the concepts: (A) **Placing** the AR liver model at a physical landmark (e.g., table) by moving the tablet followed by the model accordingly, until the target position is reached and can be confirmed. **Scaling** the AR model and 2D slice on the tablet (B) by performing a pinch gesture on the tablet (C) to zoom in. (D) **Freezing** the 2D slice by pressing the freeze button to further explore the selected slice on the tablet while the captured position is highlighted in the AR model. In this mode, also **annotating** is possible. (E) When **axis-locking** is activated, only the movements along one axis are taken into account (here transverse plane), so even unstable movements still result in stable images. (F) The **slice gallery** enables revisiting captured slices in the grid-based overview on the tablet plus corresponding highlighted virtual representations in AR with color encoding. (G) When a single slice is viewed in detail, the full size image slice of the cross-section can be displayed in AR as **context**, e.g., to pan more precisely. (H) Additionally, it's possible to activate the **sync mode** to continue free exploration. The model automatically positions itself in a way that the tablet fits again in the cross-section of the visited slice. (I) In **measurement** mode, the distance between a selected starting point on a slice and the center of the currently shown slice on the tablet is measured and updated during movement.

on the tablet's screen. The cross-section adapts dynamically to the current position and orientation of the tablet, offering the smooth exploration of the liver model. Interesting slices can be stored for future use. Stored slices can be compared with each other, with the AR liver model providing live feedback of where a particular slice was captured. Physicians can further work with slices by, e.g., annotating them with a digital pen.

In the following sections, we describe the individual techniques mentioned above in more detail. The order in which the techniques are described is chosen to resemble a typical use case of the system.

### 3.1 Placement in the Environment

To flexibly use the system in different locations, the first thing a physician needs to do is placing the model of the liver in the environment so that it can be freely explored. To support this, the model is attached to the back of the tablet when the system is first started, hovering a small distance behind it. Whenever the tablet is moved or rotated, the model moves and rotates accordingly to stay at the exact same position in relation to the tablet (see Fig. 2A). To help the physician correlate the current orientation of the liver with the whole body of the patient, a small 3D model of the human is shown in AR next to the tablet's right border as reference. Once the physician has found a suitable location, the AR model can be anchored to its current location by performing a double tap on the tablet. Afterwards, the model is fixed in space and moving the tablet no longer moves the model.

### 3.2 Transformation

To further adjust the position, orientation, and scale of the AR liver model after initially placing it in the environment, the physician can enter a transformation mode by holding the corresponding button. In this mode, the AR model again mimics the physical movements of the tablet. Thus, to move or rotate the AR model a certain amount,

the physician moves or rotates the tablet in the same fashion. A small 3D model of a human is shown to provide the anatomical context in the same way as during the initial placement of the model. Releasing the transformation button also acts as a clutching mechanic and enables transforming the model in quick succession to avoid extensive physical movements or uncomfortable hand postures. To scale both the liver model in AR and cross-section on the tablet the physician performs a pinch gesture on the tablet (see Fig. 2B+D). Transforming the model is available at any time when exploring the model.

### 3.3 Exploration

After the AR liver model has been transformed according to the physician's wishes, they can start to explore the model in more detail. We propose three different modes to support this: Free Exploration mode, freeze mode, and axis-locking.

Since the liver model is now registered in space, the physician can **move freely around** the liver to watch it from all sides. The tablet can be used to look at the desired parts of the liver in more detail by moving it inside of the virtual liver model. This creates a cross-section between the tablet and the liver. All parts of the liver model behind the tablet remain as they were before, whereas all parts in front of model either completely fade-out or are displayed semi-transparent (see Fig. 2C). The degree of transparency is configurable using a slider on the tablet. The screen of the tablet shows a scan from MRI imaging that resembles the current cross-section through the liver.

Pressing the **freeze** button on the tablet freezes the current cross-section, so that it is not longer updated when moving the tablet. Thus, the MRI slice can be further explored more comfortably without having to hold the tablet at the exact same position of interest (in this mode, a physician can use the functionality described in section 3.5 as well). To strengthen the spatial connection of slice and its

position in the model, the frozen cross-section plane is highlighted in the AR model (see Fig. 2D). Pressing the freeze button again will unfreeze the cross-section and reactivate the spatial transformation mode of the tablet to further explore the model by viewing additional cross-sections.

Exploring the model using spatial interaction enables physicians to create arbitrary slices through the liver model. However, it can be beneficial to restrict the resulting slices to the common three MRI imaging planes (transverse, sagittal, and coronal plane) [7]. This is accomplished by pressing an **axis-lock** button on the tablet. When active the current orientation of the tablet is mapped to the closest cardinal direction. Moving the tablet forward and backward through the model still manipulates the corresponding slice through the model (see Fig. 2E). However, the orientation remains locked to the current cardinal direction until the tablet is rotated enough to match another cardinal direction. This enables viewing slices conform to the typically ones from common DICOM viewers and thus allows the physician to analyze standardized images as usual when exploring the model.

### 3.4 Capturing and Revisiting Slices

At any time while exploring the model, a physician can **capture the slice** currently shown on the tablet by pressing the corresponding capture button on the tablet's UI or by performing a double tap anywhere on the tablet's screen. This is also possible during freeze mode. Thus, physicians can quickly store important or interesting aspects of the liver model that they want to revisit later on, e.g., to discuss them with colleagues or to compare different slices among each other. All captured slices are stored in a collection on the tablet. After a slice was captured, the physician has the opportunity to name it for easier recognition later on. They can either stick with the default name, or enter a custom one using three alternatives: Type the name using a virtual keyboard that appears on the screen, write it using the digital pen, or use speech input to dictate the name.

To browse this collection, physicians can enter the **gallery mode**, which shows a grid-based overview of all stored slices on the tablet (see Fig. 2F). Slices can be highlighted by tapping on them, which creates a rectangular representation of the slice in the AR model to show exactly where a slice was captured. When more than one slice is selected, a colored outline in the gallery and in the AR representation helps to distinguish them. Physicians can double tap a slice in the gallery to view it in full screen on the tablet, also enabling pan and zoom functionality. If at least two slices are selected, double tapping shows a split screen view to compare them side-by-side. Slices displayed in full screen mode support drag-to-pan and pinch-to-zoom. The complete-cross section is shown around the tablet in AR for reference (cf. Langner et al. [12]) on demand by toggling a button (see Fig. 2G).

Pressing a **sync button** realigns the AR model with the current position and orientation of the tablet so that the tablet is now at the position within the model where the slice was captured (see Fig. 2H). Panning and zooming the slice in sync mode also moves and scales the AR model to match the slice. Furthermore, the sync mode allows to quickly reenter free exploration mode, where the liver model can be explored using spatial navigation in the same fashion as described before.

### 3.5 Working with Slices

Physicians have several options to further modify and enhance slices when viewing them in full screen mode. It can be helpful for the physician to highlight interesting areas directly in the slices and show them to colleagues, students, or patients, in order to, e.g., compare them to similar findings, mark areas and steps for surgery planning, and take notes for recording findings already made. Therefore, a physician can annotate slices using a digital pen, writing directly on the surface of the tablet (see Fig. 2D). Annotations can be config-

ured with different color and thickness options using a palette. Any annotations stored for a slice are also shown in its AR representation. Thus, by exploring the 3D model, physicians can already spot important slices made in previous sessions or by colleagues. Furthermore, to enable "Windowing", a common method of DICOM viewers to optimize visibility of certain image structures [7], the image contrast can be adjusted, thus the abnormal tissue can be better detected.

### 3.6 Measuring Distances and Volumes:

In addition to exploring the model and find interesting aspects, it is also important to perform a quantitative analysis of these findings, e.g., to determine the size of a tumor or the distance between tissue and vessels. We propose two options for this: The first one takes advantage of the touch interface of the tablet and allows to measure distances and areas on the created slices by drawing a line between two points or circling a certain area. This rather conventional technique has the advantage of being easy to understand and use, but also the disadvantage of being limited to 2D space. The second method makes use of the spatial navigation of the tablet and allows to determine the distance from a certain starting point to any other points by moving the tablet itself to make the measurement. To achieve this, a measurement mode is activated and the starting point of the measurement needs to be selected on the screen. Afterwards, the tablet can be moved through the AR model while dynamically updating the distance from the selected starting point to the point currently located in the center of the tablet (see Fig. 2I).

## 4 PROOF-OF-CONCEPT PROTOTYPE

To verify the feasibility of our concepts and to gain first hands-on experience with our techniques we have implemented them in a proof-of-concept prototype.

### 4.1 System Description

It consists of an AR HMD (Microsoft HoloLens 2) that is coupled with a tablet (Microsoft Surface Pro 6). To track the tablet, we employed an OptiTrack motion capturing system and attached infrared reflecting markers to both devices. Based on this technical foundation we implemented our core concepts in the Unity 3D engine, utilizing the Mixed Reality Toolkit (MRTK). The tablet shows a scan of a liver model, generated from a 3D texture containing the volumetric data. The data we used in our prototype was acquired from the open-source prototype IMHOTEP<sup>1</sup> by Michael Pfeiffer.

We implemented most of the techniques described in section 3 focusing on our core concept of exploring medical data with a spatially tracked tablet. Besides this core exploration functionality (see Fig. 3A+B), we also implemented freezing and annotating slices (see Fig. 3C-E), axis-locking, capturing and revisiting slices (see Fig. 3F+G), as well as adjusting the model's transparency (see Fig. 3H-J) and size.

### 4.2 Technical Challenges

Displaying a volumetric model with the limited hardware capabilities of the HMD turned out to be very challenging. The volume rendering approaches we tested only lead to unsatisfactory results regridding either resolution or refresh rate. Therefore, we decided to use a 3D mesh of the liver instead, rendering both front and back faces so it can be viewed from outside and inside. This 3D model is sliced using a custom fragment shader that clips fragments according to the current position and orientation of the tablet.

Another major challenge we faced when designing our prototype was the alignment of the tablet and the AR model, to achieve an accurate placement of the virtual clipping plane that conforms to the real-world position of the tablet. This affects how accurately the slice shown on the tablet resembles the position within the mode, as well

<sup>1</sup> <https://github.com/PfeifferMicha/imhotep>



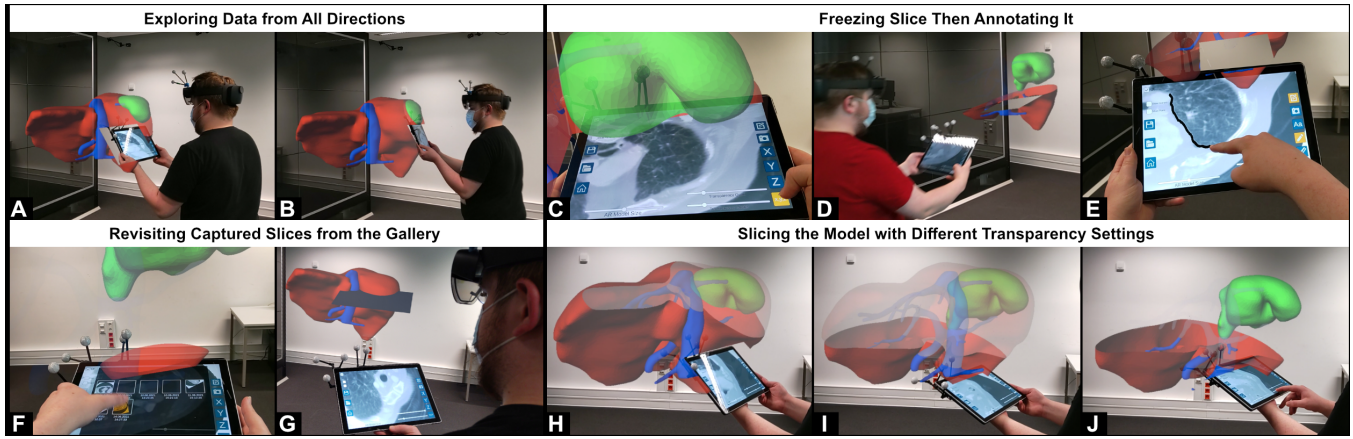


Figure 3: Demonstration of the workflow with the prototype: (A) Users can both move the tablet spatially and (B) walk around the model with the tablet, allowing for a high degree of freedom in data exploration. (C) By pressing the freeze button, the current cross-section is locked on the tablet. (D) Thus, users can move the tablet closer for a comfortable posture and (E) then further work on the selected slice, e.g., by making annotations. (F) Already captured slices can be revisited in the gallery by tapping the corresponding thumbnails on the tablet, (G) which supports users to re-examine the slices with the awareness of the spatial position where they were captured. (H-I) When exploring the AR model, the transparency of the model in front of and behind the cutting plane differs. (J) Users can either adjust the transparency level of the entire area at once or of different model parts (e.g., veins and tumors) separately depending on the task requirements or personal preferences.

as the mask in front of the tablet that hides all AR content to ensure a clear view of the screen. The first step in this regard is merging the individual coordinate systems. While the coordinate system's origin of the tracking system we used remains constant between sessions, the origin of the HoloLens 2's coordinate system differs every time the application is started. An easy way to overcome this challenge is to attach the AR model to a root object that is manually placed at the origin point of the tracking system at the start of the program. Another issue we discovered is the scaling of objects on the HoloLens 2. E.g. when an object has a virtual size of one meter the object appears slightly smaller or larger on the HoloLens 2. Through testing, we discovered that this effect is different for each individual HoloLens 2 device and is largely unaffected by calibrating the device. The only solution we found to circumvent this issue is to manually scale the content for each device in a one-time calibration step so that it conforms to the real world size of the tablet.

Despite its early stage, the first impressions of our prototype are very promising and show lots of potential for future development.

## 5 DISCUSSION AND FUTURE WORK

In our work, we presented a coherent concept that uses spatial interaction in particular to support domain users in exploring volumetric medical data. However, we present still ongoing research with concepts to be evaluated, alternatives to be weighed, and challenges to be overcome.

The integration of mobile devices into immersive environments brings numerous opportunities with regards to how to interact with the system and how to visualize the content. Our work is focused on situating an AR model in space and explore it by physically moving a tablet through the same space as occupied by the model. However, alternative interaction techniques to explore these information spaces should be considered, especially to support scenarios where physically moving is either not possible or inappropriate. This could be achieved by instead using the tablet from a certain distance to remotely control the virtual cutting plane. Physically moving the tablet manipulates the plane position inside the model, which mirrors the transformation of the tablet. Another alternative is to place the tablet on a horizontal surface, such as a table, and display the liver model in short proximity above it. The touch screen of

the tablet is then used to control all aspects of the model, such as manipulating a virtual clipping plane or selecting certain parts of the model. While this uses interaction concepts familiar to many users, it lacks the direct spatial manipulation of our main concept. Thus, this mode might be useful to familiarize people with the prototype and introduce them to the concept of spatial navigation.

In the creation of our interaction concepts, we focused on taking advantage of spatial interaction to address the coherence to the spatial data. In addition, specifically offering other interaction techniques, like mid-air gestures, gaze-based interaction, and speech interaction, to shape a multi-modal user interface could help providing alternative interaction possibilities, e.g., to enable sterile interaction, or integrating additional features, such as recording medical findings. To identify these additional requirements and evaluate the existing concepts, we are planning to conduct a user study and collect empirical results. It is crucial to involve domain experts in this study, in order to systematically compare design options and inform our design decisions for everyday clinical practice.

## 6 CONCLUSION

We presented our concepts as the combination of a spatially-aware mobile device with head-mounted Augmented Reality for exploring and slicing volumetric medical data. We propose a Focus+Context approach, where 2D slice images are displayed on the tablet while the 3D model is shown in AR. We believe users can benefit from the spatial interaction to ease extracting arbitrary slices directly from the model in AR space. This could lead to a better spatial understanding to anatomically locate the grayscale images within the volumetric data and thus reduce the cognitive load. We illustrated the feasibility and versatility of our proposed concepts using our proof-of-concept implementation. However, further and more extensive evaluation is required to validate these concepts. Nonetheless, we are convinced that our concepts are suitable for bridging the gap between the existing workflows relying on 2D scans and a better spatial understanding of inherently three-dimensional medical data. We hope that our work inspires the exploration of this new exciting combination of mobile devices with AR and transfer it to other domains that are as well working with volumetric or 3D data, like architecture, construction, design, information visualization, and data exploration.

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