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Investigation of 3D virtual reality in pre-surgical planning of malignant hepatic tumours

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RESEARCH

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ABSTRACT

Background

Personalised resection planning for hepatobiliary surgery is key to ensure successful outcomes with minimal risks or complications due to the complexity of hepatic anatomy and the relatively common presence of anatomical variants of the vascular and biliary structures. The emerging application of Virtual Reality (VR) technology in the medical domain has shown superior advantages over traditional visualisation techniques when planning complex or challenging surgeries.

Aims

This study aimed to develop a VR demonstration of hepatobiliary malignancies with surrounding hepatic anatomy, to investigate how VR assists clinicians in the pre-surgical planning of tumour resection.

Methods

3D Slicer was used to segment high-resolution computed tomography (CT) datasets, using manual and semi-automatic approaches in two selected cases of hepatobiliary malignancies: multifocal hepatocellular carcinoma and cholangiocarcinoma. The 3D segmented volume data were then demonstrated on a Meta Quest 2 VR headset using the SlicerVirtualReality extension for 3D Slicer.

Results

Two cases of hepatobiliary malignancies were successfully segmented and demonstrated in VR. Realistic 3D visualisation of hepatic tumours in relation to surrounding structures was clearly demonstrated with observers being able to visualise either individual segmented structures or the entire volume data together.

Conclusion

The VR demonstration may allow clinicians to improve their understanding of the spatial relationships between the pathology and surrounding structures, compared to the current methods of 2D/3D image visualisations. Furthermore, improvement in pre-surgical planning has potential to increase treatment outcomes by decreasing inappropriate surgical procedures and postoperative complications.

Key Words

Virtual reality, hepatic, tumours, surgery, pre-surgical planning, Visualisation, Anatomy

What this study adds

This study provided detailed analysis of different image post-processing and segmentation methods for generation of VR based on hepatic CT datasets, and our early results added valuable information to the current literature about development of appropriate segmentation approaches for hepatic structure segmentation.

1. What is known about this subject?

Many studies have shown that in the medical domain that VR technology has superior advantages over traditional visualisation techniques when planning complex or challenging surgeries.

Very few studies have shown that developing 3D segmented models of hepatic malignancies can be achieved, but that second software is required for visualisation in VR.

2. What new information is offered in this study?

Open source software can be used for segmentation of hepatic malignancies and visualisation in VR.

3. What are the implications for research, policy, or practice?

Visualisation of 3D segmented models of hepatic malignancies for the purpose of pre-surgical planning of hepatic tumour resection may improve clinicians understanding of the spatial relationships between the tumour(s) and hepatic anatomy. This has the potential to improve treatment outcomes by decreasing inappropriate surgical procedures and postoperative complications.

Background

In Australia, 2,832 people were diagnosed with primary liver cancer in 2021 alone.[1] The 5-year survival rate for this diagnosis is fairly low at 20.9% in Australia between 2013 to 2017.[1] Hepatocellular carcinoma and intrahepatic bile duct carcinoma, or cholangiocarcinoma, are the most common types of primary liver cancer[2,3]. Surgical resection plays a key role in the treatment of these cancers[4,5.] Personalisation of the surgical resection planning is of utmost importance due to complexity of hepatic anatomy and the relatively common occurrence of anatomical variants[6-9.]

Currently, 2D and 3D image visualisations based on computed tomography (CT) or magnetic resonance imaging (MRI) data are commonly used prior to surgery to develop an understanding of anatomical variations and the spatial relationships between the hepatic tumour(s) and surrounding vascular and biliary structures[10,11]. Although the developments of 3D image visualisations have improved pre-surgical planning by reducing the cognitive demand required to reconstruct the 2D images, retrieving all the information required for clinical decision making remains a mentally challenging task[12].

Advanced technologies including 3D printing, virtual reality (VR), augmented reality (AR) and hologram are increasingly used in the medical domain to overcome these challenges or limitations, thus offering optimal diagnostic approaches and strategic surgical planning by delivering personalised medicine to both surgical planning and treatment[13-19]. Further, use of these novel technologies in clinical practice will provide great opportunities as training tools to surgery trainees and registrars by increasing their confidence and skills in performing/simulating complex surgery procedures on the 3D printed physical models (patient-specific or personalized models), and increasing understanding of spatial relationship between tumours and hepatic structures through use of VR/AR and hologram tools prior to operating on patients[20]. 3D printed models have certain limitations, such as their high production cost, production time and the limited available interaction, which prevents its applications in routine clinical practice[21]. Conversely, VR allows greater interaction as structures to be turned on and off and scaled but no tactile information[22].

Previous studies have involved the use of proprietary software for segmentation and then the 3D segmented models have been imported into the Unity game engine for visualisation in VR. Alternatively, 3D Slicer is an open-source software that is capable of visualising, processing, segmenting, registering, and analysing medical imaging data[23,24]. The Slicer Virtual Reality extension for 3D Slicer works with all Open VR-compatible headsets, allowing segmentations to be produced and viewed within a single software[25,26] .

This study aimed to produce 3D segmentations from CT datasets that accurately depict the hepatic anatomy and pathology and then demonstrate the 3D models of the segmentations in virtual reality to show their potential to improve a clinician's understanding of the spatial relationships between the structures and assist with the pre-surgical planning of tumour resection.

Materials & Methods

Figure 1 is a flow chart detailing the major steps undertaken in this study and these steps were detailed in the following sections.

CT data preparation for segmentation using 3D Slicer

Anonymised CT datasets from two selected cases of different types of hepatobiliary malignancies were acquired from a tertiary hospital in Perth, WA. Case 1 is a patient with multifocal hepato cellular carcinoma (HCC) with four high-resolution CT datasets used for analysis: A non-contrast enhanced CT (NCCT) with a 0.8mm slice thickness, and 3 contrast-enhanced CTs (CECTs) with a 1.0mm slice thickness, in the arterial, portal venous and delayed phases. Case 2 is a patient diagnosed with cholangio carcinoma (CC) with two high-resolution CT datasets, both contrast-enhanced with a 0.8mm slice thickness, in the arterial and portal venous phases.

3D Slicer (Brigham and Women's Hospital, Boston, Mass), an open-source software that is capable of visualising, processing, segmenting, registering, and analysing medical imaging data was used to produce 3D segmentations of the two cases. 3D Slicer for macOS version 5.0.3, computed revision 30893, was used in this study. Prior to segmentation the CT datasets in Digital Imaging and Communications in Medicine (DICOM) format were transformed using the Landmark Registration module to minimise the impact of liver movement with respiration on the overall segmentation volume. Furthermore, the portal venous CECTs phase was cropped, with isotropic spacing applied, to assist with segmentation of the vessels.

Segmentation of the liver

Segmentation of the liver for the two cases was achieved using different techniques. The NCCT was used as the master volume for liver segmentation for the HCC case and a manual segmentation technique was used. The threshold tool in the Segment Editor module was used for masking and the threshold range was adjusted manually while visualising the liver in all three views on the observation panel (Figure 2)[27]. The liver was then manually drawn on using the sphere brush with the paint tool, and then manually edited using the eraser and smoothing tools. The cropped portal CECT venous phase was used for the CC case, as no NCCT scan was available, and the Segment CT Liver tool used for automatic segmentation. The automatic segmentation required significant manual adjustment, as shown in Figure 3, which was achieved using the paint, eraser, and smoothing tools. Although present under the Segment Editor module, the Segment CT Liver tool used requires installation of the RVesselX extension (version e6f36d3 used)[28].

Segmentation of the gallbladder, bile ducts and lesions

The gallbladder was manually segmented using the paint, erase and smoothing tools for both cases. The intrahepatic and extrahepatic bile ducts were only segmented for the CC case as only dilated biliary tree/ducts are visible on CT images. The dilated intrahepatic ducts in the left lobe of the liver were segmented using the threshold masking technique mentioned previously for liver segmentation. The extrahepatic bile ducts, the common hepatic duct and common bile duct, were manually segmented together, as lack of visualisation of the cystic duct prevented separate segmentation. The lesion for the CC case could not be visualised on CT and therefore was not segmented. Six lesions were manually segmented for the HCC case, and they were all enhanced in the arterial phase with hyperdense appearance and hypodense appearance on the portal venous phase.

Segmentation of the hepatic and portal veins

The portal vein and its branches and the inferior vena cava (IVC), right hepatic vein, middle hepatic vein and left hepatic vein and their branches were segmented for both cases using two different extensions. The cropped portal venous phases, with isotropic spacing, were used for vessel segmentation in both cases. The vesselness filtering module from the SlicerVMTK extension (version 094b64a) was used for the HCC case[29]. The logical operators tool in the Segment Editor module was used to intersect the vesselness segmentation with the liver segmentation, keeping only the segmented vessels within the liver volume, as seen in Figure 4 A. However, this segmentation still required significant manual adjustment to produce the final two vessel segmentations, as seen in Figure 4B. Manual editing required the above-mentioned thresholding tool for masking, as well as the paint, eraser and smoothing tools. Additionally, the islands tool was used to split the larger islands into separate segments which were then added together to create the two distinct vessel segmentations. 3D Slicer for Windows was used to segment the vessels for the CC case, and the RVesselX extension previously mentioned was used. In RVX Liver Segmentation module, the diagrams provided (Figure 5 A,B & C) were used to place nodes along the branching veins, which were then used to extract the vessel trees. Manual editing using the paint, erase and smoothing tools was required to refine the segmentations. Additionally, the IVC inferior to the branching hepatic veins was manually added to the segmentation as it was clearly visible throughout the whole liver volume (Figure 6 A, B & C).

Segmentation colouring

The colouring of the segmentations common to both models was consistent, and all colours were chosen from a 24-colour palette designed for two types of colour-blindness: deuteranopia and protanopia (Table 1)[30].

Segmentation viewed in SlicerVirtualReality

The VR demonstration was developed using the SlicerVirtualReality extension (SlicerVR) on version 4.11.20210226 of 3D Slicer for Windows with Meta Quest 2 VR headset. The Oculus desktop app was downloaded, and headset was set up according to the provided instructions.The controllers were used to fly in the scene and translate, rotate or scale the objects or scene itself.

Results

Segmentations (seg.nrrd file types) were created for both the multifocal HCC case and the CC case, as a result of the successful segmentation of the high-resolution CT datasets. Anatomy represented in the segmentations includes the liver, gallbladder, dilated intrahepatic and extrahepatic bile ducts (CC case only), visible lesions (HCC case only) and the portal and hepatic veins (including the IVC where visible). The seg.nrrd file types can be viewed in 3D Slicer in the observation panel, as seen in Figures 6 and 7. The opacities of the segmentations were adjusted to better visualise the intrahepatic structures and the spatial relationships of the structures. For the HCC case the IVC could not be segmented for the entire height of the liver volume, as it could not be visually differentiated from the liver parenchyma inferiorly, as seen in (Figure 6 A, B & C).

The segmentations for both cases were successfully viewed on the Meta Quest 2 VR headset using the SlicerVirtualReality extension for 3D Slicer. The segmentations were also exported as models (vtk files) to improve the performance in VR a shown in Figures 8 and 9. The controllers worked as expected with the joysticks allowing the user to fly forwards or backwards in the plane that the controller is orientated, and the grip or trigger buttons allowing you to translate, scale and rotate the rendered object with a single controller or the entire scene with both controllers (Figure 7 D, E & F). Realistic 3D relationship between hepatic tumours and surrounding structures was clearly demonstrated and the user was able to visualise these structures either individually or the entire segmented volume data.

Discussion

Segmentation of two different cases of hepatic malignancies based on CT datasets was achieved, with the first case being multifocal hepatocellular carcinoma and the second cholangiocarcinoma. Segmentations and exported 3D models for both cases were successfully demonstrated in an immersive virtual reality experience. However, the degree of accuracy of these segmentations was not evaluated as part of this study, and future research investigating this may be beneficial, for example using the tool developed by tool Taha and Hanbury[31]. Additionally, the small lesion in the cholangiocarcinoma case was not visible on CT, and additional MRI or positron emission tomography (PET)/CT data would have been beneficial to localise and segment the lesion[32].

The use of different tools for segmentation of the liver for the two cases allowed a comparison of manual and semi-automatic segmentation techniques. Although the actual time taken to complete the liver segmentations was not recorded, we found that the manual technique, even using threshold tool for masking, took significantly longer than the semi-automatic technique, taking hours compared to minutes. However, inexperience with the software may have prolonged the manual segmentation. Additionally, a semi-automatic technique for the second case was necessary due to the clear inaccuracies present when the automatic tool was used alone, see shown in Figure 3. This is consistent with the literature, semi-automatic segmentation techniques are often used, as they save time and are more reproducible compared to manual segmentation and are considered more acceptable to clinicians and more accurate than fully automatic segmentation due to user input[33]. Different extensions were also used for segmentation of the vessels, and the RVesselX extension was preferred due to its specificity, as it allows extraction of only the portal or hepatic vessels into separate segmentations, whereas the vesselness filtering module from the SlicerVMTK extension was non-specific and required more manual input to exclude irrelevant vessels and separate the portal and hepatic vessels into separate segmentations. However, at the time of segmenting the vessels for the first case, there were issues with the RVesselX extension operating on the macOs version of 3D Slicer, which made vessel extraction impossible. Therefore, for the second case, a different laptop with a Windows operating system was used for vessel segmentation so that the RVesselX extension would function as intended.[28] Additionally, our experience shows that the general user experience is better for the Windows version of 3D Slicer compared to the macOs version, for example opening certain modules was seamless for the former but not for the later (Figure 6 D, E & F).

Similarly, the main challenge with the VR component was the need for a computer that can run the VR software. The SlicerVirtualReality extension was not compatible with the macOS version of 3D Slicer used to develop the segmentations, namely due to the lack of OpenVR-compatible headsets. As such, a MSI Vector GP76HX 12UHS (i9 CPU, 32GB RAM and 3080 TI graphics card) was used to demonstrate the VR experience. Additionally, the 5.0.3 version of 3D Slicer for Windows was unable to perform the VR demonstration at this time; therefore, an older version (4.11.20210226) was used for this function. Furthermore, the actions available in the VR experience using the Meta Quest 2 with SlicerVirtualReality are currently limited. The lack of a graphical user interface (GUI) for the extension means that to perform several actions the user must either remove the headset and make changes on the 3D Slicer desktop app or a second user controlling the laptop is required. Therefore, development of a GUI for tools that allow the user to perform tasks such as changing segmentations/models' opacities, turning on and off segmentations/models and clipping planes, take screen shots and resetting the scene to remove any object transforms would improve the user experience. However, compared to other similar studies which required exporting the models from the software used for segmentation and then importing the models into the Unity game engine, 3D Slicer provides a more convenient option, as the user can segment the data and visualise the models in VR within a single software, allowing editing/adjustments to easily occur at any stage.

While this study has established that segmentations of hepatic malignancies can be generated and demonstrated in virtual reality using one main software, the clinical value of this as a tool for pre-surgical planning has yet to be assessed. We presented our results to a consultant liver surgeon and a final year medical student seeking their opinions on the usefulness of VR in preoperative planning of hepatic tumours. Both assessors agreed to the clinical value of VR in providing realistic 3D relationship between the tumour and surrounding structures with suggestion of adding hepatic artery structure to the segmented volume data. Further, creation of VR visualisation in a normal case is recommended for clinical education. Therefore, future research investigating the clinical value of this virtual reality demonstration compared to the 2D and 3D visualisations of CT data currently used in pre-surgical planning is warranted. Additionally, if this tool proves to have clinical value in terms of improving the pre-surgical planning process for hepatic tumour resection, determining whether its clinical use has an impact on surgical or patient outcomes would also be beneficial. However, a similar study that used different software compared VR to different 3D visualisations showed that VR was the best rated model for usability, and medical students and more inexperienced doctors preferred the VR model over the others, while the more experienced surgeons preferred a 3D printed model.[15] Furthermore, in addition to its potential use for pre-surgical planning, virtual reality may also be beneficial as an educational tool for medical students to learn about hepatic anatomy and pathology, or as a training tool for inexperienced surgeons to improve their confidence prior to complex hepatic surgeries[34]. Therefore, further research into its value in these contexts could also be beneficial.

Conclusion

Two cases of hepatic malignancies were successfully segmented from multiple high-resolution, non-contrast and contrast-enhanced CT datasets. Structures segmented included the liver, gallbladder, hepatic veins, portal veins, tumours (HCC case only) and the intra- and extrahepatic bile ducts (CC case only). A combination of manual and semi-automatic techniques was used for segmentation of the different structures. The RVesselX extension for 3D Slicer is specifically designed for segmentation of the liver, hepatic vessels and hepatic tumours. However, semi-automatic segmentation of the liver was required due to the inaccuracy of the automatic tool from this extension, and this observation is in line with recommendation for semi-automatic techniques in the literature. Additionally, while the RVesselX extension was the preferred method for vessel segmentation a different extension was used for the HCC case due to software issues with the macOs version of the program at the time and a different laptop with a Windows operating system was used for the CC case. Furthermore, manual segmentation was relatively time consuming but necessary for certain structures, particularly for segmentation of the tumours/pathology, due to the lack of automatic tools available for this purpose in the RVesselX extension.

Virtual 3D models of the two cases were also created as a result of the successful segmentation. The models were demonstrated in VR using the Meta Quest 2 headset and the SlicerVirtualReality extension for 3D Slicer. An older version of 3D Slicer was required for the VR demonstration because of software issues with the current version at the time of this study. Currently, the actions that can be performed in the virtual reality environment are limited and the user experience could be improved with development of a graphical user interface which would allow for additional, more complex actions. The clinical benefit of these models compared to the current 2D and 3D image visualisations used for pre-surgical planning is also yet to be assessed, and future research to evaluate this is warranted.

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CONFLICTS OF INTEREST

Authors declare that they have no competing interests.

FUNDING

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ETHICS COMMITTEE APPROVAL

Ethics approval was obtained for the use of de-identified images for image post-processing and segmentation.

Figures & Tables

Table 1. Colour names and HEX codes used for segmentations from two cases of hepatobiliary malignancies: Cholangio Carcinoma (CC) and Hepatocellular Carcinoma (HCC). Colours were chosen from a 24-colour palate designed for two types of colour blindness: deuteranopia and protanopia.

Segmentation	Colour name	HEX code	Cases included
Liver	Pale mauve	FFCCFE	Both
Gallbladder	India green	009503	Both
Portal veins	Capri	00C2F9	Both
Hepatic veins	Royal Blue	005FCC	Both
Intrahepatic bile ducts	Lime	AFFF2A	Both
Extrahepatic bile ducts	British racing green	004002	CC only
Lesions	Magenta Barbie pink Mulberry Purple heart Fuchsia Electric purple	C7007C FF5AAF 560133 65019F FF3CFE A700FC	HCC only

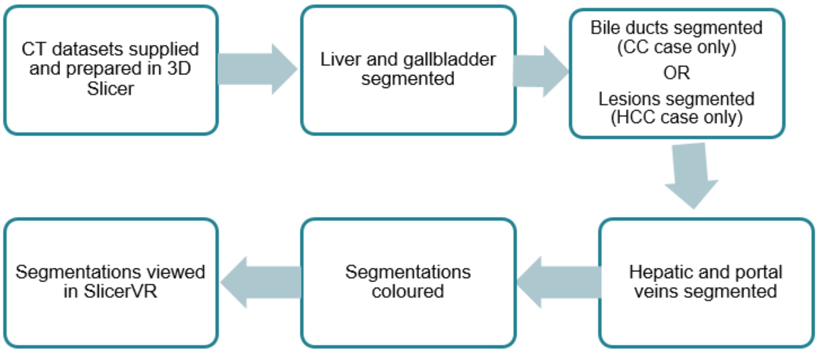
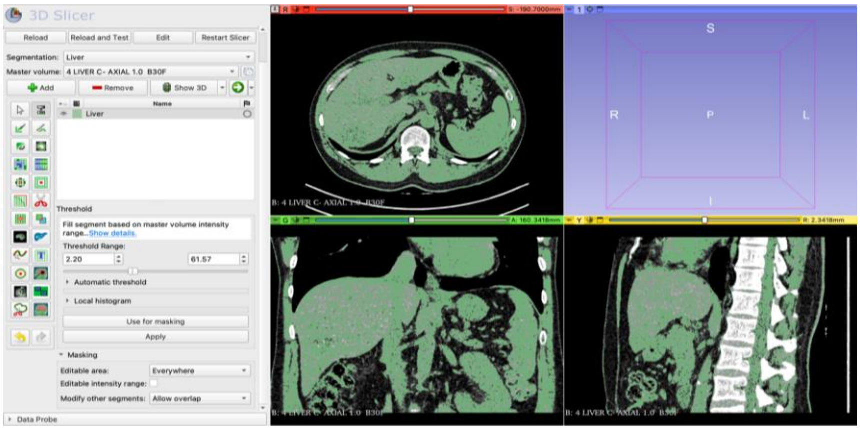


Figure 1: A process diagram of the steps undertaken in this study from image processing of original computed tomography (CT) data to generation of virtual reality (VR) views. CC: cholangiocarcinoma, HCC: hepatocellular carcinoma.



Segmentation: Liver
Master volume: 4 LIVER C- AXIAL 1.0 B30F
Liver
Threshold
Fill segment based on master volume intensity range...Show details.
Threshold Range: 2.20 61.57
Automatic threshold
Local histogram
Masking
Editable area: Everywhere
Editable intensity range: ☐
Modify other segments: Allow overlap

Figure 2: Example of the threshold tool in the Segment Editor module of 3D Slicer which was used for masking to assist segmentation of the liver for the multifocal hepatocellular carcinoma case. A non-contrast CT, viewed in the observation panel was used as the master volume for segmentation.

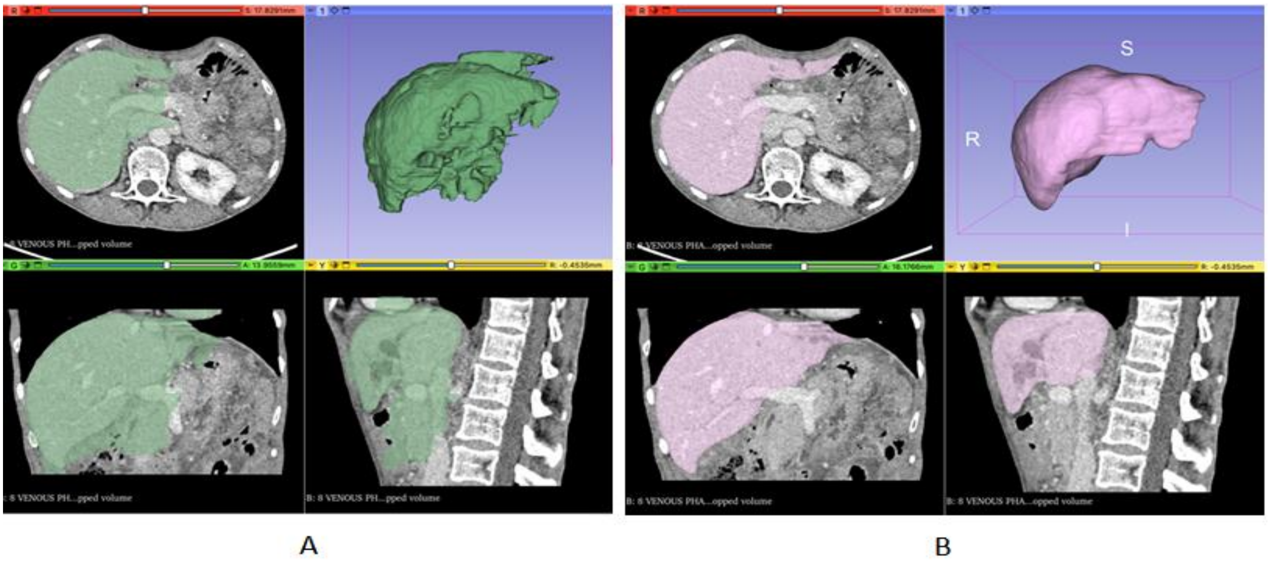


Figure 3: Semi-automatic segmentation of the liver for the cholangiocarcinoma case in 3D Slicer. A portal venous phase contrast-enhanced CT, viewed in the observation panel, was used as the master volume for segmentation. A: The automatic segmentation produced by the Segment CT Liver tool from the RVesselX extension. B: The final partial-automatic segmentation produced after manual adjustment using the paint, erase and smoothing tools in the Segment Editor module.

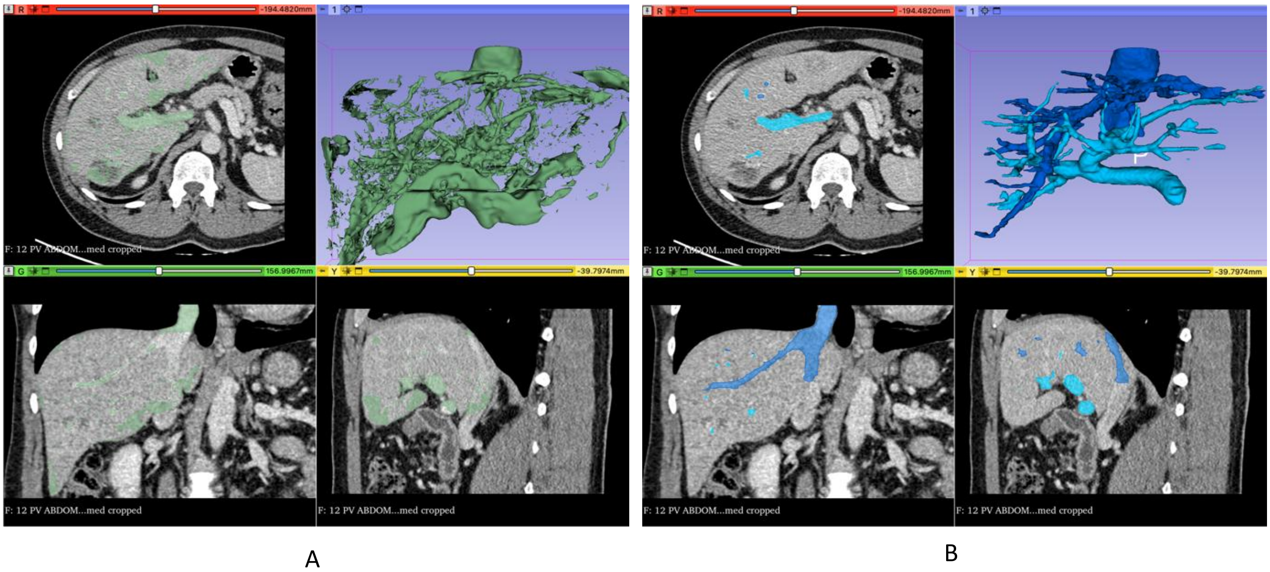
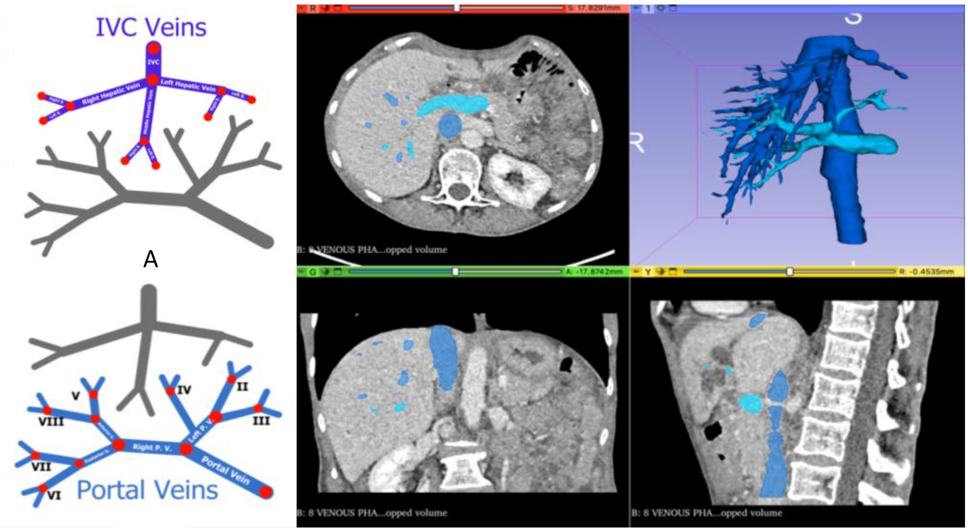


Figure 4: Segmentation of the inferior vena cava (IVC) and its branching hepatic veins and portal veins using the RVesselX

extension in 3D slicer. A: The diagram provided by the RVX Liver Segmentation module to place a nodal tree for vessel extraction of the IVC and its branching hepatic veins. B: The diagram provided by the RVX Liver Segmentation module to place the nodal tree for vessel extraction of the portal veins. C: The observation panel in 3D Slicer displaying the portal venous phase contrast-enhanced CT, with the final segmentations of the portal veins (light blue) and the IVC and hepatic veins (dark blue), in the axial (top left), coronal (bottom left), and sagittal planes (bottom right), and the anterior view of the 3D render of the segmentations.

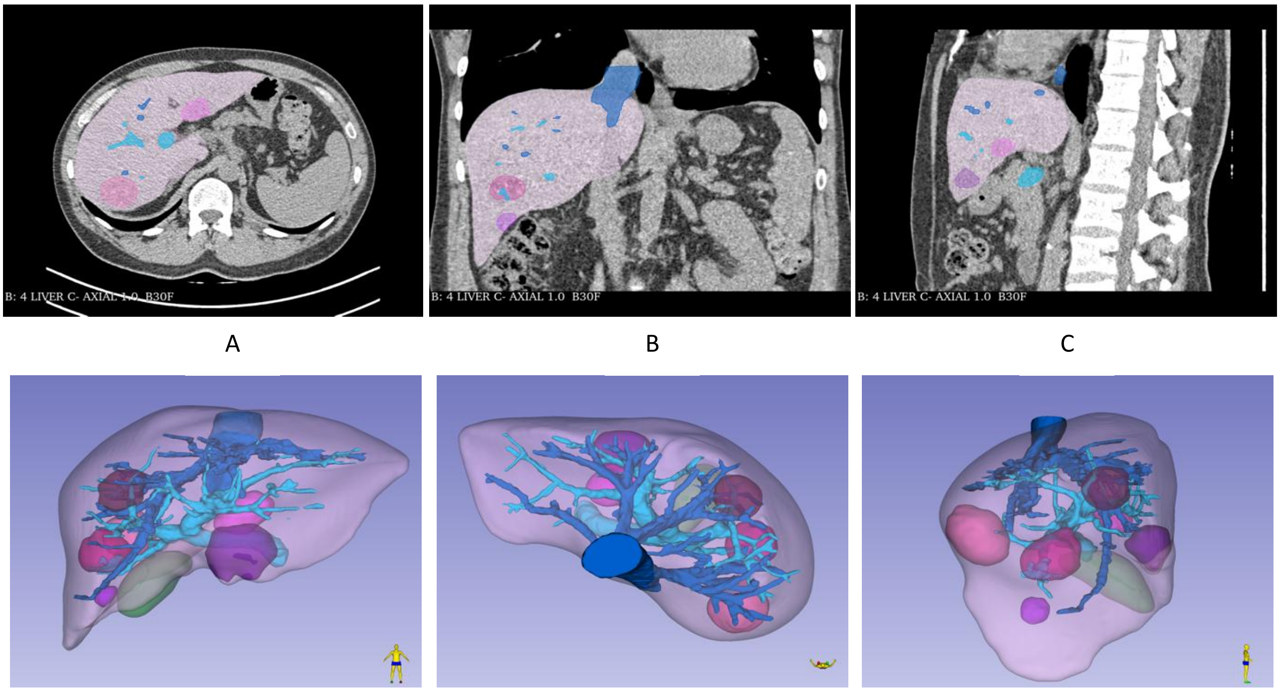


A

B

C

Figure 5: Segmentation of the inferior vena cava (IVC) and its branching hepatic veins and portal veins using the RVesselX extension in 3D slicer. A: The diagram provided by the RVX Liver Segmentation module to place a nodal tree for vessel extraction of the IVC and its branching hepatic veins. B: The diagram provided by the RVX Liver Segmentation module to place the nodal tree for vessel extraction of the portal veins. C: The observation panel in 3D Slicer displaying the portal venous phase contrast-enhanced CT, with the final segmentations of the portal veins (light blue) and the IVC and hepatic veins (dark blue), in the axial (top left), coronal (bottom left), and sagittal planes (bottom right), and the anterior view of the 3D render of the segmentations.



A

B

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E

F

Figure 6: Segmentations viewed on the non-contrast CT (A-C) and 3D rendering (D-F) for the multifocal hepatocellular carcinoma case displayed in 3D slicer's observation panel. Anatomy segmented includes the liver (light), gallbladder (green), portal veins (light blue) and inferior vena cava with hepatic veins (dark blue). Six lesions were also segmented and

coloured in shades of medium to dark pink and purple (see Table 1 for detail). A: Axial view of segmentations on CT. B: Coronal view of segmentations on CT. C: Sagittal view of segmentations on CT. D: Anterior view of 3D rendering. E: Superior view of 3D rendering. F: Right view of 3D rendering.

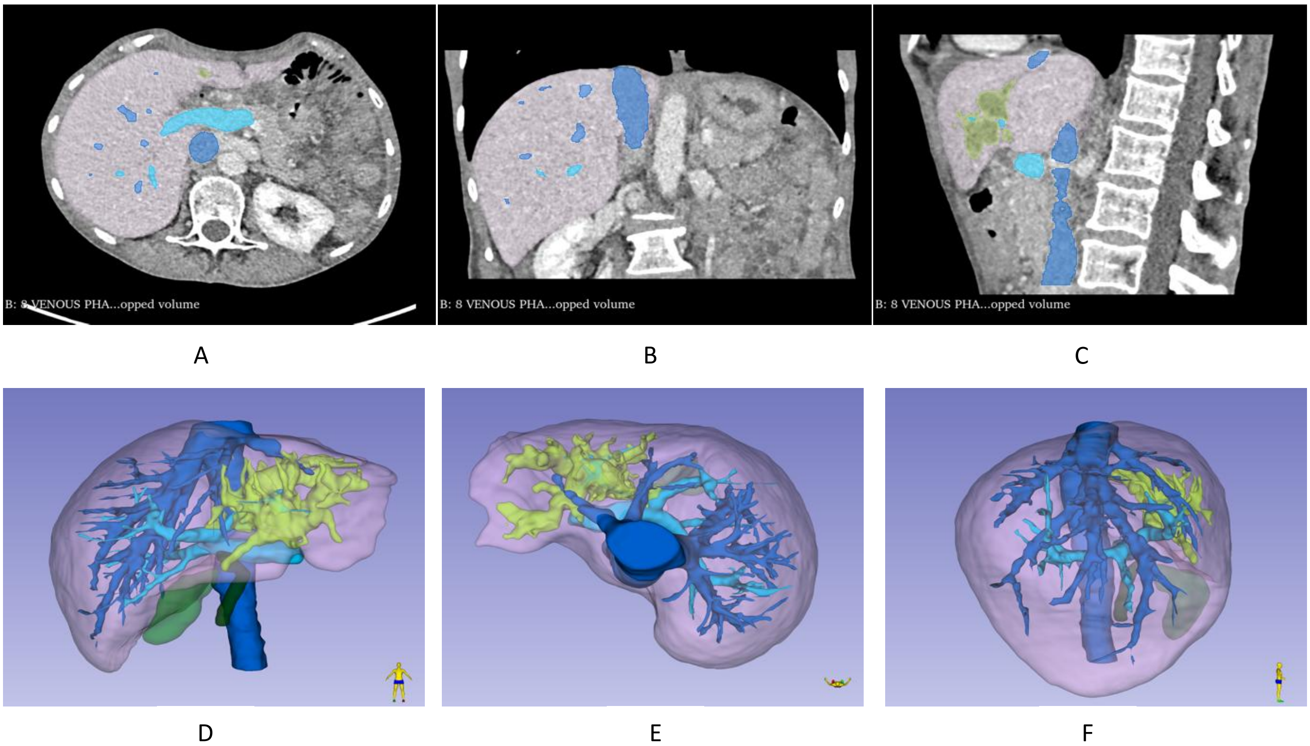

Figure 7: Segmentations viewed on the portal venous phase CT (A-C) and 3D rendering (D-F) for the cholangiocarcinoma case displayed in 3D slicer's observation panel. Anatomy segmented includes the liver (light), gallbladder (medium green), dilated intrahepatic ducts (light green) and extrahepatic ducts (dark green), and portal veins (light blue) and inferior vena cava with hepatic veins (dark blue). A: Axial view of segmentations on CT. B: Coronal view of segmentations on CT. C: Sagittal view of segmentations on CT. D: Anterior view of 3D rendering. E: Superior view of 3D rendering. F: Right view of 3D rendering.

Figure 8: Virtual reality demonstration of the 3D models for the multifocal hepatocellular carcinoma case using the SlicerVirtualReality extension for 3D Slicer and the Meta Quest 2 headset and controllers. The VR view from SteamVR was displayed on the Wedge screen at Curtin Hub for Immersive Visualisation and eResearch (HIVE) for the demonstration.

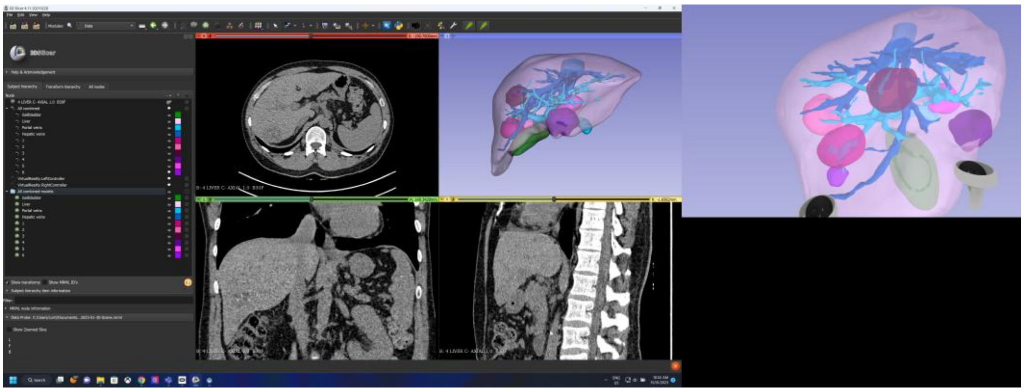

Figure 9: Virtual reality demonstration of the 3D models for the multifocal hepatocellular carcinoma case using the SlicerVirtualReality extension for 3D Slicer and the Meta Quest 2 headset and controllers. Left: the observation panel in 3D Slicer displaying the non-contrast CT in the axial (red), coronal (green) and sagittal (yellow) planes, and the 3D render of the models (purple). Right: the VR view from SteamVR during the demonstration.

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