FINAL SCRIPT: APPROVED FOR FILMING

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Title: Mixed Reality Technology and Three-Dimensional Printing in Teaching: Heart Anatomy as an Example

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Author Questionnaire

1. We have marked your project as author-provided footage, meaning you film the video yourself and provide JoVE with the footage to edit. JoVE will not send the videographer. Please confirm that this is correct.

√ Correct

2. Microscopy: Does your protocol require the use of a dissecting or stereomicroscope for performing a complex dissection, microinjection technique, or something similar? **NO**

3. Software: Does the part of your protocol being filmed include step-by-step descriptions of software usage? **Yes**

4. Proposed filming date: To help JoVE process and publish your video in a timely manner, please indicate the proposed date that your group will film here: **MM/DD/YYYY**

When you are ready to submit your video files, please contact our Content Manager, Utkarsh Khare.

Current Protocol Length

Number of Steps: 21
Number of Shots: 51

Introduction

NOTE to VO: Please record the interview statements.

REQUIRED:

1.1. This study focuses on integrating mixed reality into anatomy education by developing high-fidelity 3D-printed models and heart holograms, using the CarnaLife Holo application with Microsoft HoloLens in medical students' training sessions to improve their learning experience.

1.1.1. INTERVIEW: Named Talent says the statement above in an interview-style shot, looking slightly off-camera. *Suggested B-roll: 2.9.1, 2.9.2.*

What technologies are currently used to advance research in your field?

1.2. Researchers worldwide are increasingly recognizing the potential of 3D printing and immersive technologies, including mixed reality, in medical education and clinical practice. Their continuous advancement and wider adoption mark a pivotal shift in the future of medical innovation.

1.2.1. INTERVIEW: Named Talent says the statement above in an interview-style shot, looking slightly off-camera. *Suggested B-roll: 2.10.1.*

What research questions will your laboratory focus on in the future?

1.3. The objective of this study is to explore the expanding applications of mixed reality, not only in anatomy education but also in routine clinical practice across medical disciplines, including orthopedics and musculoskeletal trauma surgery, to enhance diagnostic precision and surgical planning.

1.3.1. INTERVIEW: Named Talent says the statement above in an interview-style shot, looking slightly off-camera. *Suggested B-roll: LAB MEDIA: Figure 11, 12.*

Ethics Title Card

This research follows the guidelines of the Human Research Ethics Committee of the Medical University of Silesia

The patient's imaging data were used after complete anonymization

Protocol

2. 3D Printing - Segmentation of the 3D Heart Model

Demonstrator: Wojciech Bojanowicz

2.1. To begin, open 3D Slicer version 5.6.0 *(five-point-six-point-oh)* and navigate to the **Data** module **[1]**. Click **Add Data** and select the patient-specific CT images in DICOM *(Dye-com)* format **[2]**. Assess the quality of the images by inspecting axial, sagittal, and coronal views in the **Slice Viewer [3]**. Verify sufficient contrast to distinguish between the myocardium and the heart chambers **[4].**

2.1.1. SCREEN: 67850_screenshot_1-.mov 00:03-00:11.

2.1.2. SCREEN: 67850_screenshot_1-.mov 00:12-00:23.

2.1.3. SCREEN: 67850_screenshot_2-.mov. 00:00-end.

2.1.4. SCREEN: 67850_screenshot_3-.mov. 00:00-end.

2.2. Now, navigate to the **Segment Editor** module and click **Add** to create a new segmentation **[1]**. Select **Threshold** from the segmentation tools. Set the Lower and Upper Threshold values to accurately isolate the myocardium and heart chambers **[2]**. Adjust the range using the sliders or by entering values to ensure the correct anatomical structures are properly captured **[3]**.

2.2.1. SCREEN: 67850_screenshot_4-.mov. 00:00-end.

2.2.2. SCREEN: 67850_screenshot_5-.mov. 00:00-end.

2.2.3. SCREEN: 67850_screenshot_6-.mov. 00:00-end.

2.3. After applying threshold-based segmentation, inspect the segmented model in axial, sagittal, and coronal views to ensure that the myocardium and heart chambers are correctly captured **[1]**. If any areas are missing, add missing regions using the Paint tool in the **Segment Editor** module. Carefully add segmentation to regions that were not properly captured by thresholding. Adjust the brush size as needed for better precision, especially in small or complex areas **[2]**.

2.3.1. SCREEN: 67850_screenshot_7-.mov. 00:00-end.

2.3.2. SCREEN: 67850_screenshot_8-.mov. 00:00-01:10. *Video Editor: Speed up the video as needed.*

2.4. Similarly, if unwanted tissues or artifacts are present in the segmentation, use the **Erase** tool to remove them **[1]**. For larger incorrect areas, use the **Scissors** tool to cut them away efficiently **[2-TXT]**.

2.4.1. SCREEN: 67850_screenshot_9-.mov. 00:00-00:15, 00:46-01:15.

2.4.2. SCREEN: 67850_screenshot_10-.mov. 00:50-01:15 **TXT: Check the segmentation in all 3 planes to avoid removing important structures**

2.5. Once all necessary corrections are made, review the segmentation to ensure that the myocardium is fully segmented, with no missing or extra areas, and the heart chambers are correctly defined, without unwanted connections **[1]**. Click **Apply** to finalize the segmentation **[2]**. To export the STL files for both the myocardium and heart chambers separately, navigate to **Segmentations**, followed by **Export to Files**, and then select STL format **[3]**.

2.5.1. SCREEN: 67850_screenshot_11-.mov. 00:00-end.

2.5.2. SCREEN: 67850_screenshot_12-.mov. 00:00-end.

2.5.3. SCREEN: 67850_screenshot_13-.mov. 00:00-end.

2.6. Next, to optimize the myocardium and heart chambers, open MeshMixer *(Mesh-Mixer)* and navigate to **File**, followed by **Import**. Load the STL files for both the myocardium and heart chambers. Ensure both models are correctly aligned and visible in the workspace **[1]**.

2.6.1. SCREEN: 67850_screenshot_14-.mov. 00:00-end.

2.7. Select each model and go to **Edit**, followed by **Make Solid [1]**. Adjust the Solid Accuracy slider to balance detail and mesh stability. Apply the operation and verify that the model remains intact **[2]**. Choose **Solid Type: Accuracy** *(Solid type Accuracy)* to preserve anatomical details **[3]**.

2.7.1. SCREEN: 67850_screenshot_15-17-.mov. 00:00-00:13.

2.7.2. SCREEN: 67850_screenshot_15-17-.mov. 00:13-00:15.

2.7.3. SCREEN: 67850_screenshot_15-17-.mov 00:15-00:18.

2.8. Now, use the **Select** tool to highlight small unwanted artifacts and delete them using **Edit**, followed by **Discard [1]**. If needed, reconstruct the disrupted areas by navigating to **Select**, followed by **Modify**, **Erase & Fill**, or by using brushes **[2].**

2.8.1. SCREEN: 67850_screenshot_18-.mov. 00:10-00:19.

2.8.2. SCREEN: 67850_screenshot_19-.mov. 00:00-end.

2.9. To optimize the model for 3D printing, select the area with surface irregularities, click on **Deform**, and then **Smooth**. Apply it iteratively **[1]**. Adjust the Smooth Strength slider, depending on the severity of surface irregularities **[2]**. NOTE: The VO has been edited.

2.9.1. SCREEN: 67850_screenshot_20-22-.mov. 00:00-00:28.

2.9.2. SCREEN: 67850_screenshot_20-22-.mov. 00:28-00:43.

~~2.9.3. SCREEN: To be provided by authors: **Shift** and Left Click being used to deselect areas that do not require modification.~~

2.10. Next, to merge the myocardium and heart chambers, navigate to **Edit**, **Boolean Difference**, and select both models. Ensure that the operation successfully joins the structures without creating internal holes or overlapping surfaces **[1]**. NOTE: The VO has been edited.

2.10.1. SCREEN: 67850_screenshot_23-.mov. 00:00-00:46. **TXT: Inspect the intersections and refine as needed using Erase & Fill or Smooth tools**

2.11. Once merging and refinement are complete, navigate to **File**, followed by **Export**. Save the final unified model in STL format, ensuring it is ready for slicing and 3D printing **[1]**.

2.11.1. SCREEN: 67850_screenshot_24-.mov. 00:20-end.

~~**3. Mixed Reality**~~ NOTE: The authors want to skip this section.

~~**Demonstrator: Marcel Pikula**~~

~~3.1. Open the mixed reality software and log in **[1]**. Select the appropriate folder containing CT scans. Choose the correct series of CT data. Click on the **Connect** button to visualize the data in the mixed-reality headset **[2]**.~~

~~3.1.1. SCREEN: To be provided by authors: Logging into the mixed reality software.~~

~~3.1.2. SCREEN: To be provided by authors: Navigating to the correct folder with CT scans. Selecting the CT dataset for visualization. Clicking **Connect** and displaying the visualization in the mixed-reality headset.~~

~~3.2. To segment the heart structure using the manual segmentation tool, Select the **Scissors** option and mark the areas to be removed from the CT data reconstruction by left-clicking and dragging **[1]**. End the cutting region marking by clicking the left mouse button and confirming cutting in the pop-up **[2]**.~~

~~3.2.1. SCREEN: To be provided by authors: Selecting the **Scissors** tool for manual segmentation. Marking areas for removal by left-clicking and dragging.~~

~~3.2.2. SCREEN: To be provided by authors: Pop-up appears after left clicking. Confirming cutting in the pop-up window.~~

3.3. ~~From the list of available presets, choose a predefined preset or color visualization parameters for heart structure visualization **[1]**. If needed, adjust the visualization by changing the window settings using right-click and hold while moving the cursor in the 3D View **[2]**.~~

3.3.1. ~~SCREEN: To be provided by authors: Selecting **CT CARDIAC HOLLOW** from the preset list.~~

3.3.2. ~~SCREEN: To be provided by authors: Adjusting visualization settings by modifying the window parameters.~~

3.4. ~~To load the 3D surface models of the left and right ventricles and atriums, click on the **3D Models** section in the mixed reality software and select **Load Models**. Navigate to the folder containing the surface models, select all four files, and confirm by clicking **Open** **[1]**.~~

3.4.1. ~~SCREEN: To be provided by authors: Clicking on **3D Models > Load Models**. Navigating to the folder containing the surface models, selecting all four files, and clicking **Open.** The four surface model files being loaded~~

3.5. ~~Adjust the colors of visualized models by clicking on the **Pencil** icon on the 3D models list. Click the Aspect tab on the visible pop-up **[1]**. Then, click on the white square next to the Color label. Select a suitable color with the **Color Picker** pop-up. Confirm by clicking the **OK** button. Left-click on 3D View **[2-TXT]**.~~

3.5.1. ~~SCREEN: To be provided by authors: Adjusting the colors of the models using the **Pencil** icon and **Aspect** tab.~~

3.5.2. ~~SCREEN: To be provided by authors: Clicking on the white square next to the Color label. Selecting a suitable color with the **Color Picker** pop-up. Clicking the **OK** button. Left-clicking on 3D View. **TXT: Repeat this for all models**~~

3.6. ~~To create annotations for anatomical structures, click on the **Annotate** section in the software **[1]**. After selecting the appropriate slice, zoom in using the mouse wheel and place the annotation point by left-clicking **[2-TXT]**.~~

3.6.1. ~~SCREEN: To be provided by authors: Navigating to the **Annotate** section.~~

3.6.2. ~~SCREEN: To be provided by authors: Selecting a slice in the 2D View and zooming in. Placing an annotation point with a left-click. **TXT: Repeat this until all the points are created**~~

3.7. Edit the annotation by selecting the **Pencil** icon on the annotation in the annotations list with the corresponding ID number **[1]**. Enter the annotation text, such as "Left Ventricle," in the lower part of the pop-up **[2]**. Go back to the 2D View with the placed annotation. Move the annotation label outside the 2D plane to a suitable location **[3]**. Adjust the annotation's color, thickness, and size as needed **[4]**.

3.7.1. SCREEN: To be provided by authors: Clicking the **Pencil** icon to edit the annotation.

3.7.2. SCREEN: To be provided by authors: Entering annotation text in the pop-up window.

3.7.3. SCREEN: To be provided by authors: Going back to the 2D View with the placed annotation. Moving the annotation label to an appropriate location.

3.7.4. SCREEN: To be provided by authors: Adjusting the annotation's color, thickness, and size.

3.8. Now, click the **Load File** icon next to the **Floppy Disc** icon in the upper right corner of the 3D View **[1]**. In the pop-up window, click the **Folder** icon, navigate to the directory containing the visualization state file, and select the folder **[2]**. If there is a valid file available for this particular data, a list of available visualization states will be displayed **[3]**. Left-click on a suitable visualization state to select it and confirm by clicking **Load [4]**.

3.8.1. SCREEN: To be provided by authors: Clicking the **Load File** icon in the upper right corner.

3.8.2. SCREEN: To be provided by authors: Selecting the correct folder containing the visualization state file.

3.8.3. SCREEN: To be provided by authors: List of available visualization states appearing in the pop-up.

3.8.4. SCREEN: To be provided by authors: Loading the selected visualization state.

3.9. To view the prepared visualization in holographic space, put on the mixed-reality headset **[1]**. Use the voice command **Locate here** to bring the 3D holographic CT scan reconstruction in front of the eyes **[2]**. Adjust the visualization using voice commands such as **Rotate, Zoom, and Cut Smart**, and combine them with hand gestures **[3]**.

3.9.1. Talent putting on the mixed-reality headset.

3.9.2. SCREEN: To be provided by authors: Activating the holographic visualization with the **Locate here** voice command.

~~3.9.3. SCREEN: To be provided by authors: Adjusted visualization after using **Rotate, Zoom, and Cut Smart** voice commands.~~

~~3.10. Use the **Cut Smart** voice command to apply and adjust the cutting plane perpendicular to the line of sight **[1]**. Move and rotate the head to manipulate the cutting plane's position and orientation **[2]**. Come close to the hologram to move the cutting plane deeper into the holographic re-construction **[3]**. Rotate the head 90 degrees clockwise to rotate the cutting plane accordingly **[4]**.~~

~~3.10.1. SCREEN: To be provided by authors: Applying the **Cut Smart** command and the cutting plane being adjusted to the line of sight.~~

~~3.10.2. SCREEN: To be provided by authors: The cutting plane's position and orientation being manipulated by moving and rotating the head.~~

~~3.10.3. SCREEN: To be provided by authors: Moving closer to the hologram to move the cutting plane deeper into the holographic re-construction.~~

~~3.10.4. SCREEN: To be provided by authors: Rotating the head 90 degrees to rotate the cutting plane.~~

Results

4. Results

4.1. The mixed reality visualization provided an interactive and dynamic representation of CT data, allowing real-time manipulation of heart structures **[1]**. However, over-segmentation led to surface rendering inaccuracies, distorting internal anatomical details **[2]**.

4.1.1. LAB MEDIA: Figure 11. *Video Editor: Emphasize the left panel.*

4.1.2. LAB MEDIA: Figure 11. *Video Editor: Emphasize the right panel.*

4.2. The volume rendering technique enabled visualization of different tissue densities, improving anatomical detail recognition **[1]**. This approach allowed better differentiation of complex structures where segmentation alone was insufficient **[2]**.

4.2.1. LAB MEDIA: Figure 12. *Video Editor: Emphasize the left panel.*

4.2.2. LAB MEDIA: Figure 12. *Video Editor: Emphasize the right panel.*

Pronunciation Guides:

1. myocardium
Pronunciation link: https://www.merriam-webster.com/dictionary/myocardium
IPA: /ˌmaɪ.əˈkɑːr.di.əm/
Phonetic Spelling: my-uh-kar-dee-um

2. myocardial
Pronunciation link: https://www.merriam-webster.com/medical/myocardial
IPA: /ˌmī-əˈkär-dē-əl/
Phonetic Spelling: my-uh-kar-dee-uhl

3. hologram
Pronunciation link: https://www.merriam-webster.com/dictionary/hologram
IPA: /ˈhoʊ.ləˌɡræm/
Phonetic Spelling: hoh-luh-gram

4. Boolean (as in Boolean Difference or Boolean operation)
Pronunciation link: https://www.merriam-webster.com/dictionary/Boolean
IPA: /ˈbuː.li.ən/
Phonetic Spelling: boo-lee-uhn

5. segmentation
Pronunciation link: No confirmed link found

IPA: /ˌsɛg.mənˈteɪ.ʃən/
Phonetic Spelling: seg-men-tay-shun

6. sagittal
Pronunciation link: No confirmed link found
IPA: /ˈsædʒ.ɪ.təl/
Phonetic Spelling: saj-ih-tuhl

7. coronal
Pronunciation link: No confirmed link found
IPA: /ˈkɔːr.ə.nəl/
Phonetic Spelling: kor-uh-nuhl

8. axial
Pronunciation link: No confirmed link found
IPA: /ˈæk.si.əl/
Phonetic Spelling: ak-see-uhl