# AnaVu: A Practical 3D Visualization System for Integrative Teaching of Radiological and Medical Gross Anatomy in Large Classrooms

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https://cvit.iiit.ac.in/mip/projects/anavu

***Abstract*—Undergraduate medical students are taught human anatomy typically with the aid of 2D drawings and images and are expected to understand 3D relationships from such 2D representations. This is challenging. In this paper, we present AnaVu, a lightweight visualization system for teaching 3D anatomy at a classroom scale. We propose a stereoscopic system along with an easy-to-use interface as a scalable 3D visual aid. This is an alternative to VR/XR devices that can only serve a handful of students and are heavy on computational resources. For large-scale classes ($\sim 100-150$ students), 3D visualization provides a direct way of depicting spatial relations, with stereoscopic projection further providing depth cues to distinguish fine structures. The visualization in AnaVu also integrates gross 3D and Radiological Anatomy. It is controllable by the lecturer with a mouse via a simple user-interface. The visualization supports labels for parts, animations and multimedia. Lessons can be prepared and loaded quickly in class. The proposed solution was evaluated quantitatively and qualitatively by 180 students drawn from two medical institutions, and by 24 anatomy educators. The evaluation results show the proposed solution to be viable and effective for 3D spatial learning. AnaVu's integration of Radiological anatomy enhances its applicability, providing students with a comprehensive understanding of 3D anatomical structures and correlating them with cross-sections captured in radiological images. This aspect was appreciated by both the educators and students.**

***Index Terms*—Anatomy, Visualization, Stereoscopy, Computer Graphics, Learning Evaluation**

Manuscript received 15 February 2024. This work was supported by the Science and Engineering Research Board, Department of Science and Technology, Government of India, under Project IR/SB/EF/03/2016 (IIIT Hyderabad). An earlier version of this paper was presented in part at the 2023 IEEE International Conference on Teaching, Assessment and Learning for Engineering [DOI: 12.1234/12345678.2023.12345]. *Corresponding authors: Jayanthi Sivaswamy and Pawan Harish.*

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## I. Introduction

With the reduction in class time for teaching anatomy and its heavy reliance on drawings from textbooks and 2D images, it is becoming increasingly difficult to teach Anatomy which requires students to learn names of and spatial relations between numerous 3D structures [1], [2]. Cadaveric/virtual dissection, textbook 2D images and atlases help students build up an intuition for these relations. This, however, takes time as one has to mentally generate a 3D map of structures to properly understand orientations, positions and spatial relations between numerous fine 3D structures. The underlying cognitive process, though understated, is extremely important and is the main struggle for new learners [3]. Most 2D illustrations do a poor job of defining 3D concepts and may outright not depict complex 3D relations. It is however imperative that students learn in 3D for them to successfully diagnose and treat patients in their professional role as a doctor.

Attempts have been made to directly integrate 3D visualization for anatomical teaching in class using virtual, augmented and mixed reality systems [4]. Though these systems provide a good view of the 3D anatomical landscape, they can only be accessed by a few users at a time and are not scalable to a classroom setting ($\sim 50 - 150$ students). Such systems also rely on heavy computational resources, which may not be available in a low-resource setting [5].

Visualizations based on computer graphics and artistic renditions of anatomical structures are popular but rarely represent a true picture of the various organs as opposed to in vivo images used in hospitals/clinics. This can cause a mismatch in student understanding based on classroom learning vs. practice. We propose to use in vivo images, such as MRI scans, to build 3D structures from acquired data. This allows our system to register extracted structures

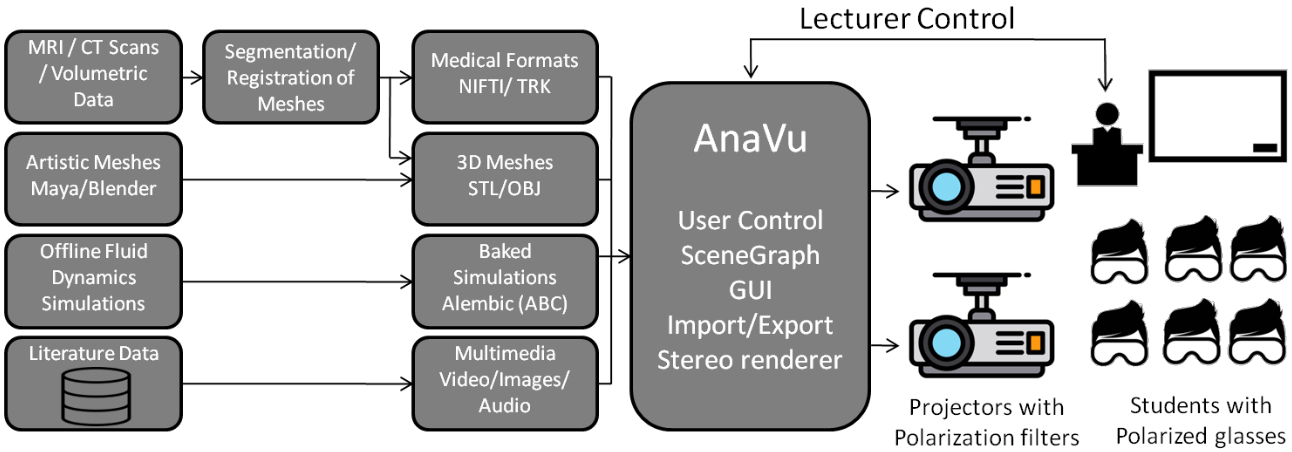



Fig. 1: The overall AnaVu framework showcases various input pipelines and applications in a classroom setting.

volumetrically and convey spatial information accurately both in terms of 3D and 2D slices. The use of in vivo images also provides an introduction to radiological anatomy - as practically used in established workflows, helping diminish the gap between what is learnt in class versus medical practice.

In this paper, we present AnaVu, an easy-to-use visualization system based on real-world data to teach anatomy at a classroom scale using stereoscopic projection. This provides a scalable middle ground between learning from 2D on the one hand and sophisticated VR/XR systems on the other. Similar to 3D projection systems used in cinema, AnaVu uses passive stereoscopic projection to provide depth cues at a large scale. This helps students identify fine structures and presents a clearer understanding of the spatial relations between them, as explored in our experimental evaluation section (Section IV).

We base AnaVu atop a custom SceneGraph implementation [6], that can support multiple medical data formats including NIfTI, Tractography and 3D meshes along with animations and multimedia files. This allows AnaVu to integrate multiple inputs into a single space to create an interactive lesson that supports static, dynamic and volumetric data. Used alongside stereoscopic projection, an easy-to-use interface and low computational resource requirements allow AnaVu to be deployed easily in most classroom settings.

We build upon the preliminary conference publication [7] of this work on the integration of medical gross anatomy, radiological anatomy, and 3D spatial understanding within the AnaVu framework. First, we incorporate detailed technical descriptions and report on new experiments conducted with a significantly larger student cohort of 137 students with two different lessons. Second, we include evaluation by anatomy educators, who serve as key stakeholders in the educational domain. Third, we employ rigorous quantitative and qualitative analyses, including a detailed examination of free-text responses, to provide a comprehensive understanding of AnaVu's functionalities and its potential impact on anatomy education.

The main contributions of AnaVu are :

- Structure extraction from *in-vivo* images for precise rendition and registration of various 3D structures in volume and 2D slices.
- A light-weight SceneGraph implementation supporting NIfTI, tractography, extracted 3D meshes, volumetric segmentation and volume files, animations and fluid simulations along with multimedia formats to show labels, videos and images using existing literature.
- A flexible GUI design - created with teacher inputs to keep various functions user-friendly for easy viewing and manipulation of on-screen data with support for 2D/3D switching and free focus on 3D data or volumetric slices for better contextual learning.

In the remainder of the article, we present the related work in Section II, followed by the design and architecture of AnaVu in Section III. Evaluation of the system in classroom settings is presented in Section IV and finally, in Section V conclusions are drawn and our outlook on future work is presented.

## II. Related Work

Integrating 3D visualization for in-class teaching has been successfully attempted [8] and with the advent of online classes, due to the COVID pandemic, its adoption has accelerated. Such systems have proven to be especially useful in rural classrooms [9], [10]. Higher education institutes can afford better equipment and are adopting the latest technologies including VR/XR devices, with anatomy teaching adopting highly specialized systems such as Anatomage [11] and Anatomical Studio [4]. Integration of stereoscopic video presentation for anatomy teaching has also been attempted with modest success [3]. A good survey of these systems as applicable to anatomical teaching can be

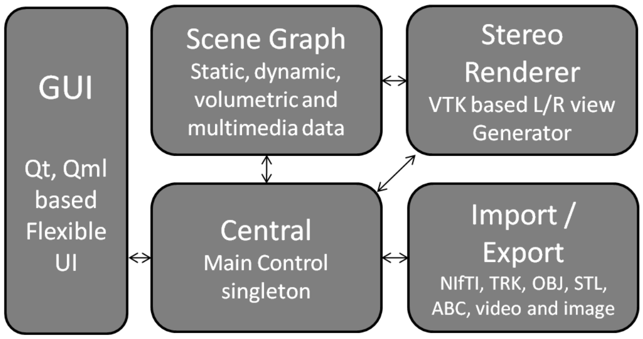



Fig. 2: AnaVu design - functional encapsulation using independent modules.

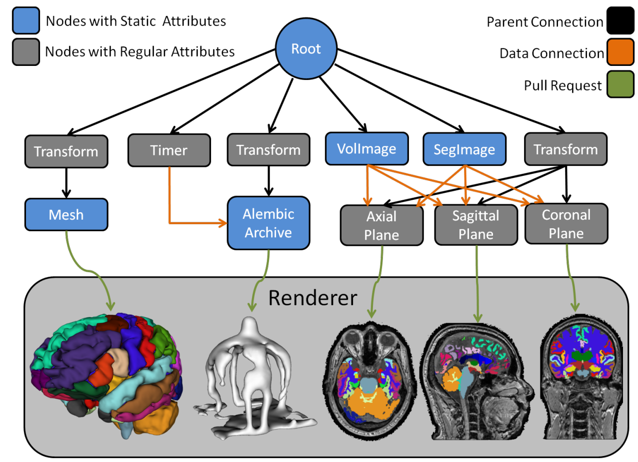



Fig. 3: AnaVu SceneGraph, showing various types of nodes and connections.

found in [12].

Most digital anatomy learning systems can be categorized in one of two ways: (i) digital representations of conventional 2D data - like images, videos and articles available online [13] or via Learning Management systems [14] and presentation systems [15] and (ii) specialized systems built especially for a particular purpose such as dissection [11] and VR/XR anatomical teaching [4]. The former are simple representations of 2D data and are no better at conveying 3D concepts than existing literature, while the latter are helpful in providing good visual feedback to students but rely on heavy computational hardware, are limited to a few students and cannot be scaled and integrated well in a classroom setting, especially in low resource settings.

Detailed graphics-based 3D anatomy teaching atlases have also been developed [16], [17]. The Complete Anatomy system [18] by Elsevier is a fully interactive system with layered fine sub-structures detailing nearly complete human anatomy. With support for videos, muscle interactions and bone mappings it can facilitate easy learning of 3D structures and their behaviours. The system, though impressive, is built upon graphical renditions of its structures. Specifically, bones, muscles, veins and other sub-structures are generated by an artist to be used as templates in the 3D system. Though a useful resource for supplementary learning, depending solely on such systems for in-class teaching can result in a mismatch between practical hospital workflows vs. in-class learning. Recently, 3D models created from *in-vivo* MRI scans have been explored to teach neuroanatomy in various ways. One approach to teaching radiological anatomy visualises 3D models on a 2D screen [19] while another teaches postgraduate students neuroanatomy using a VR headset to visualise the MRI scan in 3D rendered with the Unity 3D platform [20].

AnaVu also generates 3D structures from in vivo images in order to provide a true picture of the underlying anatomy as opposed to graphical representations. Medical 3D scans and meshes derived from them are used in contrast to generic stubs (Figure 1), along with conventional knowledge in the form of text, images and video overlays to explain concepts using real-world patient data. Low computational requirements along with stereoscopic projection further allows AnaVu to visualize these concepts in a fast and interactive manner. This is scalable to a classroom setting comprising around 150 students.

## III. Design Methodology

A visualization pipeline for classroom usage must have ease of use, scalability and low resource usage as its primary tenets. This allows for easy deployment in a low-resource setting. It is desirable to use existing infrastructure as much as possible to cater to many students to minimize the cost. Most higher education classrooms are typically equipped with a projection system and a computer to enable presentations. AnaVu is designed to use this as the base target configuration with the recommended stereoscopic projection enabled by adding a second projector with polarization filters and glasses. In order to keep the teacher in control of the teaching, we choose to implement an easy-to-use GUI that is legible at a classroom scale. The overall framework for the AnaVu system is summarized in Figure 1.

As shown, AnaVu can import data from multiple streams and consolidate it in a common space. Medical image formats such as NIfTI [21] and TRK (Tractography) [22] are natively supported. 3D Meshes can be generated from volumetric slice capture using segmentation followed by well-established pipelines such as ITK-SNAP [23], or artistic liberty can be taken using 3D software such as Maya or Blender [24]. Meshes can then be exported along with the volumetric segmentation to be viewed in AnaVu. Fluid simulations are supported in the form of pre-baked animations using the Alembic [25] format, a staple of the VFX industry. This allows AnaVu to use pre-computed fluid dynamics calculations to avoid real-time expensive operations while being consistent across all playbacks.

Internally, AnaVu is designed to be modular as shown in Figure 2. Each module is responsible for one aspect of the application and minimally interacts with other modules via

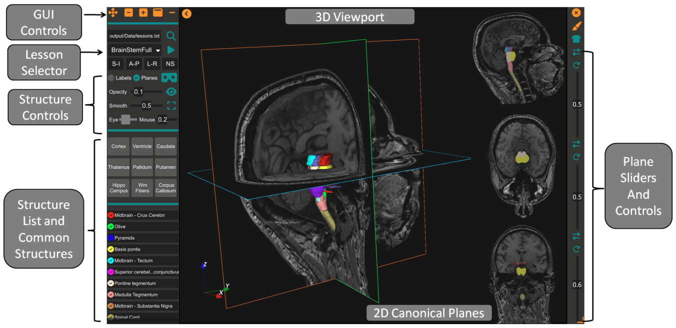



Fig. 4: AnaVu GUI showing the renderer and the panels.

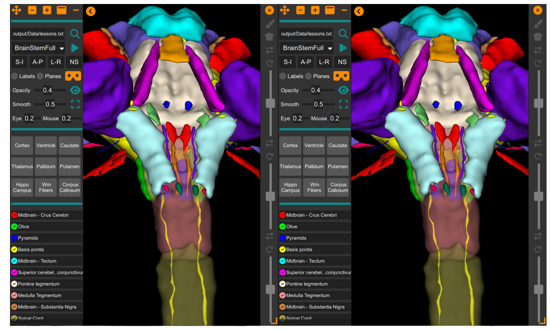


Fig. 5: Stereo projection using extended-display mode. 3D model is shown for the brainstem lesson.

the Central module. Designing AnaVu in this way allows functional encapsulation within a module and allows for further development and replacement as and when the need arises. Each module in AnaVu reflects / changes the main data structure, the SceneGraph. The user interacts with the GUI and modifies the SceneGraph, while the import and export module creates and stores the SceneGraph using files; the renderer reflects the SceneGraph using stereo/mono projection on screen, with all interactions between modules facilitated by the Central module. Since everything is stored in the SceneGraph, it is imperative that our SceneGraph implementation handle static, dynamic and volumetric data while being interactive and light on resources. These constraints define our design choice. SceneGraph data structure implementation is explained in the next section along with the 3D structure generation, GUI and rendering modules.

### A. Structure Generation Pipeline

*In-vivo* 3D MRI scans of the brain are first passed through a segmentation module which identifies structures of interest such as hippocampus, cerebrum, optic tract, and others. Segmentation of MRI scans is done automatically using open-source software tools such as FreeSurfer [26]. The whole brain, including most macroscopic structures, is segmented in this way, resulting in the segmentation of 40 structures per hemisphere, including the subcortical structures. The Brainsuite toolbox [27] is used to extract the left and right Cerebral Cortexes. Since segmentation algorithms for all structures in the brain are unavailable, manual segmentation by an expert is also used. The manual annotation from T1 MRI images is performed using the ITK-SNAP open source software [23]. Prior ethical approval through the Institute Review Board (IRB) was obtained for all the MRI scans used in this research.

The segmented structures are passed on to the next module for conversion to a surface representation, needed for rendering, using ITK-SNAP or the VTK library [28]. The conversion of segmented data to a 3D mesh is based on a voxel sub-division method, similar to the marching cubes algorithm [29]. The overall segmentation space is sub-divided into equal sized cubes (voxels) and traversed to determine if the neighbouring voxels belong to the same structure, no operation is performed if the voxels belong to the same structure. However, if the neighbouring voxels belong to different structures the faces of the cube are tested for intersections between voxel position lines. A sub-surface is drawn between the voxel position and face intersection points, generating the boundary of the segmented structure as a hollow 3D mesh surface.

The algorithm follows the following steps:

- Divide the space within the given bounds into an arbitrary number of voxels (cubes).
- Test the corners of every voxel, whether they are inside the bounds of the structure.
- For every voxel where some corners lie inside and others lie outside, a surface must pass through it, intersecting the edges of the voxel in between corners of opposite structure classification.
- Generate a surface within each voxel connecting these intersections to produce a closed mesh for the corresponding surface.

The 3D meshes are then saved as standard STL or OBJ files with further support for formats such as TRK for the tractography data. The volume data of the segmentation and the input MRI volume are also exported as NIfTI format files to register the generated meshes both with the MRI volume and its segmentation. The same colour and opacity values are applied to the segmentation and the mesh to keep consistency across data modalities, this helps in easily identifying the structures in the 2D slices when presenting the lecture using AnaVu.

### B. SceneGraph and Pull Based Evaluation

With its first introduction in the SGI-PHIGS system [30], SceneGraph and its derivatives have been time-tested, well-understood data structures underpinning modern 3D graphics applications and gaming engines [31]. At its core, a SceneGraph is a directed acyclic graph of disparate nodes connected via attributes. Each node is independent and performs its own computations based on its inputs and updates its output attributes after the computation has been completed. This allows the SceneGraph to perform independent, lazy evaluations only on the branches of the graph that are participating in an operation. It is this precise

(a) Projectors with filters (b) Stereo projection on screen (c) Students with 3D glasses

Fig. 6: Experimental evaluation in a classroom with students using stereo projection and 3D glasses.

property along with its natural organization of disparate objects that makes SceneGraph a well-suited lightweight computational structure that can also handle multiple types of data.

We design our SceneGraph based on two principles. First, it should be able to handle complex data and be light on computational resources. And second, it should provide expandability such that any datatype can be supported in the future. With this in mind we design our SGNode and SGAttribute structures using a dirty flag lazy evaluation scheme.

*1) SGNode:* The SGNode defines our SceneGraph node structure and consists of a collection of input and output attributes along with its own computation. It is inherited by other SceneGraph nodes that extend it to add their own attributes. This allows our SceneGraph to morph according to the data we want to store by adding SGAttributes depending on the type of data. For example, a SGTransform outputs the transformation matrix based on its input quaternion and translation values, whereas a SGVolImage can store the volumetric image data required to store the canonical plane information for the 3D slices of the MRI scans. Both are derived from the same SGNode, and even though they are vastly different in data both can be treated as a SceneGraph node and connected using SGAttributes, allowing disparate datatypes to be inter-connected. SGNode also allows the extendibility of the SceneGraph to any new data object should the need arise in the future.

*2) SGAttribute:* The SGAttribute is the main data storage medium in our implementation. All data in the SceneGraph is stored in attributes. Each SGNode has multiple SGAttributes (both input and output) and similar data type attributes can be connected together. Read and write operations to an SGAttribute are atomic to avoid read after write inconsistencies and/or garbage values. Each SGAttribute also has a behaviour associated with it – regular or static. Static attributes are useful when storing large unchanging data, for example meshes, volume images, videos, mesh arrays etc., that avoids performing computationally expensive operations during regular SceneGraph updates.

*3) Pull Based Lazy Evaluation:* Each attribute also propagates the 'dirty flag', which is used during the evaluation mechanism of the SceneGraph. Whenever an attribute value is written to, it sets itself 'dirty'. If any input attribute is dirty, the node is also set dirty. Dirty nodes recompute their outputs if an output attribute value is requested. Once the computation is complete, the node sets its output attributes dirty and, in turn, any attribute connected those outputs also becomes dirty, thus propagating the dirtiness along to the next node in the chain. This allows for a pull based evaluation of the SceneGraph - when a pull request is made on an output attribute, this chain of events propagates to connected nodes up the chain of the SceneGraph and only updates the nodes lying on the dirty branches, without disturbing/recomputing other nodes. Hence a pull based mechanism allows for selective computations to take place in the SceneGraph, minimizing its computational requirements.

A typical SceneGraph for AnaVu is shown in Figure 3. Most pull requests are made by the renderer as shown, as it needs to update the on-screen objects often. The GUI sets the attributes of the SGNodes, and whenever a pull request is made, the data connections propagate the dirty flag down the chain for the corresponding branches. In cases where no attributes are written, no dirty flag is set, and the SceneGraph simply uses the already computed value as the most up-to-date state for that SGAttribute.

### C. GUI and Renderer

Background colour, contrast and text legibility are very important aspects of presentations and directly apply to any good GUI design [32]. Our GUI design allows for on-the-fly control of universal scale for better legibility along with a high contrast color palette to highlight structure information. Since classroom teaching is performed by a non-expert user such as a teacher trained in medicine, our GUI is also designed to be user-friendly. Keeping these in mind we designed our GUI based on extensive feedback from anatomy teachers to facilitate their specialized needs while remaining highly interactive and customizable [33].

The GUI is designed in two parts, the renderer and the panels. We used the visualization toolkit (VTK) [28] to render our SceneGraph objects on screen while the panels were designed using the cross-platform Qt API using the QML language [34].

The Renderer is a reflection of the SceneGraph on screen with user interaction such as camera manipulation, object selection and stereo pair image generation. It renders the scene using a list of renderables and keeps a map of SceneGraph nodes corresponding to the renderable objects. The camera is manipulated by the teacher, and augmented by multiple pre-defined camera positions available to quickly select the canonical views. Object selection is achieved by simply clicking a renderable which in turn sets the selectable SGAttribute for that SGNode in the SceneGraph.

In order to perform these operations, the renderer traverses the SceneGraph and updates its renderables accordingly. As soon as the user interacts with the SceneGraph (either via GUI or the renderer), it emits a signal which is caught by the renderer that triggers the SceneGraph traversal. During this traversal, the renderer determines what renderable objects it needs to add or remove based on what has changed in the SceneGraph. During the rendering loop, the renderer updates all properties of corresponding renderable objects by calling the output SGAttributes of their respective SceneGraph nodes, which performs the pull request and triggers the SceneGraph node updates as discussed previously, Figure 3.

We use the versatile Qt signal-slot mechanism extended to QML to design our panels; the GUI is updated by changes in the SceneGraph using the same signal used by the renderer. The visual design of the GUI is shown in Figure 4. Structure and lesson controls are shown on the left with canonical plane controls displayed on the right. The GUI can quickly load a lesson from a list of pre-designed lessons using a combo box. Relevant 3D structures are displayed as a list with each structure's visibility, opacity and selectability controllable by the teacher in order to highlight inter-structure spatial relations. The teacher also has the ability to control the canonical plane slices for each dimension using the mouse wheel or sliders. The ability to switch the 3D view with the 2D canonical plane view is also available, which allows depth and segmentation information to be easily conveyed in the context of in vivo images, as shown in Figure 4. Stereo projection is supported using the extended-display mode as shown in Figure 5.

## IV. Experimental Evaluation

The evaluation of AnaVu was conducted in a classroom using two projectors with polarization filters (Figure 6a) projecting onto an anti-reflective silver screen (Figure 6b) with students wearing polarization glasses to view the stereoscopic content (Figure 6c). A Dell system with a 4-core Intel Xeon processor and 8GB of RAM was used to project the AnaVu output. First-year, undergraduate medical students from two different institutions were recruited for the evaluation. An anatomy teacher from the respective institute chose the lesson to teach with or without the tool, using stereoscopic projection. The evaluation process followed ethical guidelines, with informed consent from all participating institutions. Throughout the study, student anonymity was strictly maintained and no personal identifying information was collected.

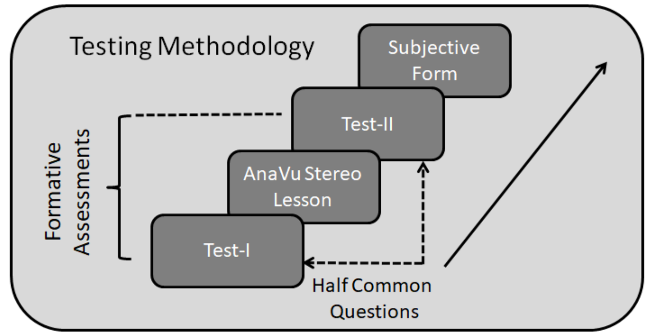



Fig. 7: Evaluation method showing stages and tests performed.

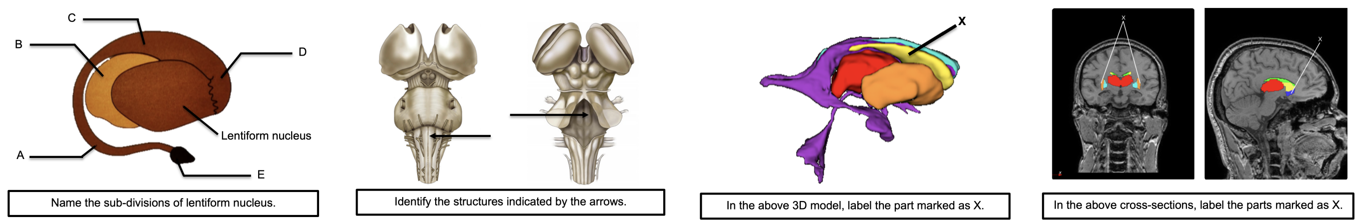
### A. *Testing Methodology*

A chosen topic was first taught by a teacher in a traditional manner (with slides, chalk and board). Test I was administered immediately before the AnaVu session to establish the baseline understanding among the students. Next, the topic was covered again by the same teacher using AnaVu's stereoscopic mode, wherein different parts and sub-structures of the anatomy being taught, their positions, orientations and relations were highlighted and showcased. A second test, namely Test II, was administered immediately after the AnaVu session. The students were also asked to fill out a subjective questionnaire to evaluate their overall experience with the AnaVu session. The overall testing methodology is summarized in Figure 7. Tests I and II contained 10 questions each, with 50% overlap (see Table I). All questions required labelling of a structure shown in an image. These images were either drawings and artistic depictions used in conventional teaching material or a 3D perspective view of the structure being taught.

### B. *Evaluation Study at Institution I*

There were 43 student participants in this site. The chosen topic was *brainstem*, which was taught one day before the AnaVu session. The distribution of questions in the Common and Unique sets of the two tests are presented in Table I. The artistic renderings are taken from material familiar to students, for example textbooks. Sample questions of different types are shown in Figure 8.

*1) Quantitative Assessment Results:* The performance in Test I provides us with a good baseline of student understanding of the brain stem topic, and gives an indication of where a student lies on the learning stage. Similarly, the performance in Test II helps evaluate the impact of what is learnt with the aid of the AnaVu system. These two tests can help assess the struggle students face during learning, where they started and the role of AnaVu in the learning experience.




(a) 2D diagrams (b) Artistic rendering (c) Views of 3D models (d) Radiological images

Fig. 8: Sample test questions of various types.

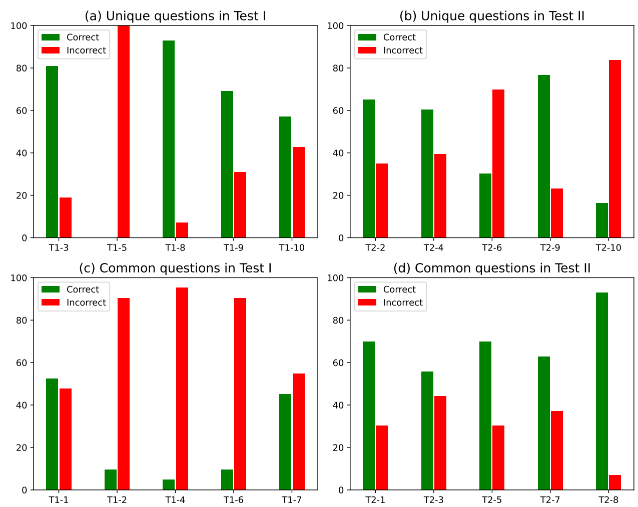



Fig. 9: Test results in Institution I. Percentage of correct and incorrect answers (in percentage) by students for unique (top row) and common set of questions (bottom row). Column 1: Results for Test I and Column 2: Results for Test II.

The questions which are common to both tests, in particular, aid a direct assessment of the role of the AnaVu system in improving understanding. The percentage of students answering questions correctly and incorrectly for both Test I and Test II is presented in Figure 9.

*a) Unique Questions:* The plots in the top row of Figure 9 show the percentage of students answering the unique questions, in Test I and II respectively. Four out of five questions were answered correctly in Test I by the majority of the students. This could partly be due to the fact that these questions were based on images familiar to the students (see Table I), suggesting they learnt enough from the traditional class the previous day. In Test II, all four questions were answered correctly by at least 15% of the group, but only 3 of 5 questions were answered correctly by the majority of the students. This could be due to the nature of the questions. All five questions in this set (in test II) were relatively unfamiliar to students as two focused on cross-sectional anatomy depicted via MRI scans with the visible part of the brain stem coloured in and the remaining three focused on 3D perspective of the brain stem. This is similar to the distribution of the questions in the Common set which can shed light on the effect of AnaVu-based intervention in learning. We discuss this next.

TABLE I: Composition of sets of questions in the two tests in Institution I.

| Question set | Question distribution | |
|---|---|---|
| | Question type | Total |
| Common | MRI cross-section (sagittal) | 1 |
| | Views of the 3D model | 4 |
| Test-I Unique | 2D diagrams | 2 |
| | Pictures of artistic rendering | 3 |
| Test-II Unique | MRI cross-section (axial) | 2 |
| | Views of the 3D model | 3 |

*b) Common Questions:* We performed a paired sample t-test to determine whether there was a significant change in the performance on the common set of questions, before and after the AnaVu intervention. Figures 9c and 9d show the performance of the students on the common questions before and after the AnaVu session, respectively. The mean value of the data shown in green represents the percentage of correct answers. These plots reveal that there is a significant increase (48%) in the mean value across the two tests. Specifically, a large tilt towards incorrect answers is observed in Test I (Figure 9c), indicating a poor understanding of radiological anatomy and 3D perspective after the traditional class, whereas, more than half the students answered all the questions correctly in Test II after the AnaVu session (see Figure 9d). The performances on the questions in the unique and common sets in the two tests, when taken together, indicate that the AnaVu session had a beneficial impact on student learning.

*c) Questions on 3D Understanding:* 3D spatial learning is essential for a good comprehension of Anatomy. Since both the common set in Test I and unique set in Test II had questions on 3D perspective of the anatomy (see Table I, we did a comparative analysis of performance on such questions across the tests to understand the effect of AnaVu on this aspect of learning. A Welch's t-test was used to compare the results. The results shown in Figure 10 indicate a notable improvement ($p = 0.0035$) in answering 3D questions after the AnaVu session. Specifically, from Figure 10a, we see that students performed poorly on such questions in Test I, whereas they improved considerably in Test II as seen in Figure 10b. This affirms that 3D visualizations, enabled by AnaVu, are effective at enhancing spatial understanding of

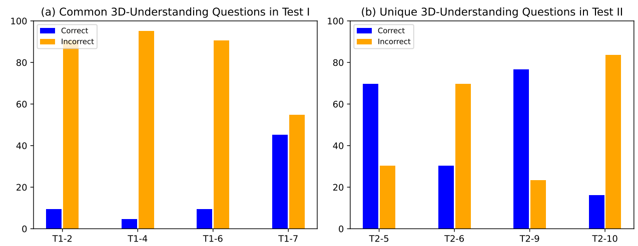



Fig. 10: Performance on questions related to 3D spatial understanding in Institution I. Plots show the percentage of correct and incorrect answers in Test I (left) and Test II (right).

TABLE II: Results of the subjective survey at Institution I.

| | *Question* | *Mean* | *Var* | *Min-Max* |
|---|---|---|---|---|
| 1 | How mentally demanding was the brain stem lesson. | 5.02 | 1.16 | $2-7$ |
| 2 | How much prior knowledge was required to learn the brain stem. | 4.56 | 2.68 | $2-7$ |
| 3 | Effectiveness of presentation in understanding the brain stem. | 5.47 | 1.82 | $3-7$ |
| 4 | Effectiveness of the presentation in understanding 3D structures. | 5.63 | 2.05 | $1-7$ |
| 5 | Effectiveness in understanding positions, orientations and relations. | 5.88 | 1.40 | $3-7$ |

anatomy amongst students.

*2) Qualitative Assessment Results:* Students also rated their learning experience on a scale of $1-7$, with 7 being very high, in a subjective questionnaire. Table II reports the score statistics (mean and variance). The questionnaire was designed using NASA TLX [35] with a focus on the topic taught. The first two questions in this survey were aimed at judging the cognitive load intrinsic in learning the topic, whereas the last 3 questions were designed to estimate the effectiveness of the technology intervention on learning. The ratings in Table II are above average for all questions barring question 2 where the score is marginally lower. This underscores the positive impact of the AnaVu session and also signals the fact that the traditional class on the topic has had a priming effect on the AnaVu session. The responses to questions 1 and 2 suggest that students found the lesson to be demanding, which corroborates the results for the unique questions shown in Figures 9a and 9b.

The average score is higher with an even larger minimum score for questions 4 and 5. This confirms the fact that the students found the stereoscopic projection helpful in understanding the 3D positions, orientations and relations of the various structures, which is consistent with the improved results of the common test questions (Test II) as reported in Figures 9c and 9d.

*3) Summary of Free Text Feedback:* As part of the subjective feedback survey, students were given a text box to comment on their experiences and the perceived effectiveness of learning neuroanatomy with 3D visualization software. The responses were analysed using prompt-based sentiment analysis with the GPT-3.5 Turbo large language model [36]. This approach was used to make sense of diverse expressions as it leverages the model's proficiency in handling various contexts, ambiguities, negations, slang, and contemporary abbreviations. Each student's response was assigned a sentiment score from 1 (very negative) to 5 (very positive) based on carefully crafted prompts. The scores are summarised in the frequency plot on the left in Figure 11. It can be observed that the sentiment is overwhelmingly positive.

Nearly 83% of the participants expressed that the experience was exceptionally beneficial, emphasizing its role in making it easier to understand intricate anatomical structures compared to conventional teaching methods. Specifically, students mentioned that this approach overcame the difficulty in learning about deeper and tiny structures of the brain stem which are hard to perceive and study even in a dissection lab with a cadaver. A representative comment that captures this is: *"It was helpful in understanding the location, size and structure of the brainstem as compared to the rest of the brain. The MRI sections with different views were especially helpful. 3D technology can be applied to learn the difficult to access parts like brainstem and deeply located tiny structures which cannot be seen clearly in the cadavers."* They also appreciated the visual and interactive elements of 3D learning, citing improvements in retention of learning owing to the use of visual memory and comprehension. Moreover, the students appreciated the technology for its ability to provide multiple perspectives and offer a clear visualization of spatial relationships within the brain stem. This feature was deemed crucial for enhancing the recognition and identification of anatomical components. A representative comment on the difference between theory class and the 3D demo is *"This is a tough topic and attending class made me get some idea about brainstem and this 3D session made it simple and better for me to understand. The parts were well displayed."* Comments that can be classified as neutral in sentiment offered constructive criticism. These were on software feature refinements related to the use of less flashy colours, adding labels to structures, improved cursor visibility and using a more effective method for highlighting a selected structure. A few students also alerted to the potential eye strain in prolonged sessions and the discomfort of wearing the 3D glasses on top of normal prescription spectacles.

In summary, the overwhelmingly positive response from students suggests that the integration of 3D technology signif-

TABLE III: Composition of sets of questions in the two tests in Institution II.

| Question set | Question distribution | |
|---|---|---|
| | Question type | Total |
| Common | MRI cross-section (sagittal) | 1 |
| | Views of the 3D model | 4 |
| Test-I Unique | MRI cross-section (coronal) | 1 |
| | Pictures of 2D diagrams | 4 |
| Test-II Unique | MRI cross-sections (coronal) | 1 |
| | Views of the 3D model | 3 |

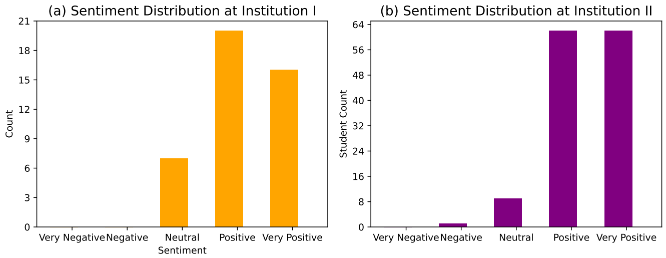



Fig. 11: Distribution of sentiments expressed by students in free-text responses in Institution I (left) and II (right).

icantly elevated the engagement and effectiveness of learning neuroanatomy, particularly the complexities of the brain stem.

### *C. Evaluation Study at Institution II*

A total of 137 students were taught the *basal ganglia* lesson using a conventional lecture at this site. They had also participated in a cadaveric dissection lab session sometime before the AnaVu session - and thus had some understanding of the material based on prior knowledge. The class was divided into equal-sized groups for the AnaVu session to handle the large number of students. The distribution of questions in the common and unique sets of the two tests is presented in Table III.

*1) Quantitative Assessment Results:* The type of analysis done for Institution I was done here as well.

*a) Unique Questions:* Figure 12 shows the percentage of students answering unique questions correctly and incorrectly for the two tests. One of five unique questions in Test II was excluded from our analysis as the direction of the pointer used to query a structure was ambiguous leading to confusion among students. A majority of the class performed better in Test II than in Test I. Specifically, correct answers were given by a majority for 3 out of 4 questions in Test II, whereas it was for 2 out of 5 questions in Test I. The poor performance in Test I is despite the fact that four of five unique questions were based on 2D diagrams encountered in textbooks students should have been familiar with, while only one was on MRI-based cross-sectional anatomy which was unfamiliar to students. This could be due to a recall latency caused by the long temporal gap ($>$ a week) between the traditional class and Test I. Turning to performance in Test II (Figure 12b), the students appear to have performed better. The questions in this set as shown in Table III were mostly on novel representations of the anatomy (MRI-based cross-sectional anatomy, 3D model of the anatomy) and hence, the good performance of students indicates a positive impact on student learning by the AnaVu session.

*b) Common Questions:* Next, we turn our attention to common questions, to directly evaluate the impact of the AnaVu session on the learning process. Results are shown in the bottom row of Figure 12. The performance on the common questions improved ($p = 0.011$) by 37% after the


Fig. 12: Test results in Institution II. Percentage of correct and incorrect answers (in percentage) by students for unique (top row) and common set of questions (bottom row). Column 1: Results for Test I and Column 2: Results for Test II.

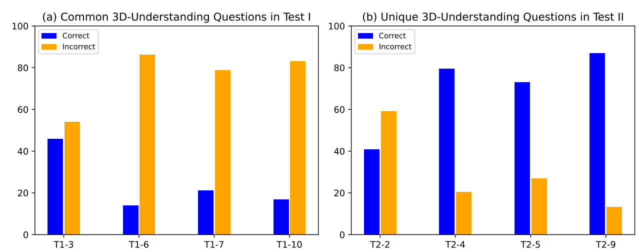



Fig. 13: Performance on questions related to 3D spatial understanding in Institution II. Plots show percentage of correct and incorrect answers in Test I (left) and Test II (right).

AnaVu session. In fact, a majority of the students answered almost all common questions in Test I incorrectly. This could be because four of these questions focused on the 3D models of basal ganglia and the remaining one was on the MRI-based cross-sectional anatomy. This suggests that the traditional lecture and cadaver lab did not help students gain enough knowledge of 3D anatomy. The performance on the same questions improved after a 20 minute AnaVu session, as seen in Figure 12d.

*c) Questions on 3D Understanding:* 3D spatial learning amongst students was also examined in Institution II. Figure 13 shows performance results on common questions in Test I and unique questions in Test II, all of which tested 3D understanding. A significant improvement ($p = 0.013$) in performance was seen after the AnaVu session. In fact, the plot on the left indicates a subpar result on all such questions in Test I. The students did much better in Test II as seen in plot on the right, with a majority of the class answering 3 of 4 questions correctly. This demonstrates the role of AnaVu in improving spatial and inter-structure understanding amongst students.

*2) Qualitative Assessment Results:* A subjective survey was once again conducted after the AnaVu session, wherein each student rated their learning experience on a scale from 1 to 7, with 7 being the highest. The questions and scores are tabulated in Table IV. The first two questions aimed to measure how much mental effort was required, and how much prior knowledge was needed for the Basal Ganglia lesson. Students gave above-average scores for these questions indicating the difficulty of this topic and the need for a traditional class on the topic prior to a visualization exercise. The high scores (above 5) for the questions on the effectiveness of the AnaVu are consistent with the findings from the quantitative assessment which showed an improvement in 3D spatial learning in students after the AnaVu session.

*3) Summary of Free Text Feedback:* Free text comments from students were analysed using the same method as in the evaluation study at Institution I. The sentiment scores are summarised in the frequency plot on the right in Figure 11. It can be observed that the sentiment among the participants is overwhelmingly positive as was the case in Institution I. Much higher proportion of students (93% compared to 83% in Institution I) expressed that the experience was highly beneficial. They emphasized the technology's effectiveness in improving their understanding of complex anatomical structures compared to traditional methods. The role of the tool in 3D learning is best captured in the comment, "*With the 3D images I understood its orientation, relations precisely.*" Many also felt the visual and interactive nature of 3D learning not only aided learning but its retention also as expressed in the following comment, "*the visual demo left an imprint in my brain, which will stay for years*". Some also suggested that given the effectiveness of this tool, its coverage should be extended beyond neuroanatomy to cover other parts of the body.

While the majority of feedback was positive, a small percentage provided constructive criticism, suggesting improvements in software features. These were the same as suggested by students in Institution I: better choice of colours for structures and improved cursor visibility and finally, concerns about eye strain during prolonged viewing or with prescription spectacles. One comment highlighted the fact that since the demo required a dark room, taking notes was not possible and that the demo works best if they had been introduced to the topic previously in a traditional lecture which can cover the theoretical aspects.

### D. Evaluation with Anatomy Educators

Our intended use for AnaVu is in teaching anatomy to a large set of students in a classroom. Hence, we also collected feedback from relevant educators. A session was conducted in which AnaVu and its role in teaching was demonstrated to educators. 24 educators from 9 medical institutions participated. Among the participants who had teaching experience, 15 were professors across various levels and 9 were post-graduates and junior residents. A survey was conducted at the end of the demo wherein participants were asked to answer a set of questions. One subset was on capturing their current practice. Almost all of them reported that they currently use traditional 2D textbook images and diagrams from internet sources. A mere 5 of the total 24 said they to use some animation or simulation for teaching. Approximately 50% of them had used some sort of videos from online sources.

TABLE IV: Results of the subjective survey at Institution II

| | *Question* | *Mean* | *Var* | *Min-Max* |
|---|---|---|---|---|
| 1 | How mentally demanding was the basal ganglia lesson. | 4.78 | 1.61 | $1-7$ |
| 2 | How much prior knowledge was required to learn the basal ganglia. | 4.47 | 1.45 | $1-7$ |
| 3 | Effectiveness of presentation in understanding the basal ganglia. | 5.74 | 1.31 | $1-7$ |
| 4 | Effectiveness of the presentation in understanding 3D structures. | 6.02 | 1.22 | $1-7$ |
| 5 | Effectiveness in understanding positions, orientations and relations. | 6.01 | 1.25 | $1-7$ |

Another subset of the survey had questions to be answered on a Likert scale of 1 to 5. Table V lists the three survey questions (Q). Here, a score of 1 is the lowest end of the scale for likelihood (Q1), interest (Q2) and utility (Q3). The score statistics in Table V indicate above average scores ( 72%) for questions regarding the likelihood of adopting AnaVu in their teaching and their institution procuring AnaVu. This is consistent with the student feedback on the tool's effectiveness. There was overwhelmingly positive (82.9%) feedback on the utility of integrating gross and radiological anatomy in teaching (Q3). This is notable and encouraging as it is a key feature of AnaVu and there is a dearth of tools for such integration during teaching.

## V. Discussion and Conclusions

In this paper, we presented AnaVu, a 3D anatomical visualization system based on real-world data (radiological scans) and passive stereo projection. AnaVu is intended to be an aid for teaching anatomy in a classroom of $\sim 150$ students. A key feature of this system is the ability to visualise 3D models either in isolation or with context which are provided by radiological images. If we consider the ventricles as an example in Figure 14, its 3D visualization in isolation only provides information on the relative positions of two lateral, the third and fourth ventricles. However, when it is viewed registered/aligned with the radiological images,

TABLE V: Results of the survey of Anatomy educators

| | *Question* | *Mean* | *Var* | *Min-Max* |
|---|---|---|---|---|
| 1 | How likely are you to use AnaVu visualization tool in your teaching. | 3.63 | 1.46 | $1-5$ |
| 2 | How interested will your institute be in procuring AnaVu software. | 3.67 | 1.19 | $1-5$ |
| 3 | Do you think the integration of gross and radiological anatomy is useful. | 4.46 | 0.43 | $3-5$ |

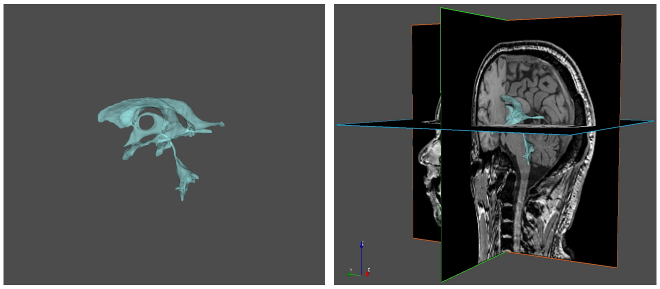


Fig. 14: Screenshots of only the 3D viewport in AnaVu for the lesson on Ventricles in AnaVu, without (left) and with (right) the radiological planes turned on.

the fact, that the lateral ventricles are in the 2 hemispheres, and that the fourth ventricle is behind the brain stem is now apparent, providing a global and relative positional information. Further, simultaneous visualization of the 3D and 2D MR cross-sections allows for teaching gross anatomy with radiological anatomy in an integrated manner even though they differ quite a lot in appearance. AnaVu thus addresses the need in anatomy education for a visualization tool that facilitates such an integration. This aspect was felt to be very useful and much appreciated by anatomy educators.

The successful evaluation of the AnaVu system with 180 undergraduate students in two institutions demonstrates the scalability of the system for teaching anatomy to a large cohort of students ($\sim 50-150$) as opposed to computationally expensive systems based on VR-XR devices. The increase in student performance on questions based on novel views of the anatomy in Test II points to an increase in their understanding of anatomical structure positions, orientations and relations attesting to AnaVu's effectiveness. This was consistent across the two evaluation sites despite the different starting conditions for the two: in Institution I the students were taught the lesson in a traditional classroom a day ahead while in Institution II they were taught weeks earlier and had also completed a cadaver lab exercise on the topic. The long gap between the traditional class and AnaVu session (in Institution II) seemed to have an adverse effect on retention in learning as students did poorly even on textbook questions in Test I. 3D visualization may mitigate this loss over time as static and dynamic visuals have been shown to enhance memory retention of anatomical information [37]. Testing the students on the topic they were taught with AnaVu after some temporal gap is needed to verify this more conclusively.

Our intended purpose in developing AnaVu is for it to serve as a supplement to conventional slide-based teaching. This guided the design of our evaluation exercise where the conventional lecture preceded the AnaVu session. The student feedback also confirmed that much prior knowledge is required to learn a topic from the visualization. Hence, it is recommended that the 3D visualization session with AnaVu be conducted for students after a traditionally taught session on the topic. This will also allow students to take notes during the conventional class as it is not feasible during the visualization session which will be in a dark room. Further, it is also recommended that the AnaVu session be conducted in rooms where there is adequate distance between the first row and the projection screen and the session is restricted to 20 minutes to avoid discomfort to students wearing spectacles and eye strain in general. Whether this session should precede or succeed the cadaver dissection lab session for effective learning, has to be determined via controlled experiments.

There are some challenges in the adoption of the 3D visualization strategy proposed in this paper. First is the need for an initial investment in stereoscopic projection equipment and accessories to darken the classroom. Second is the need for training anatomy teachers. Senior anatomy educators in general are familiar only with pictorial and cadaver-based anatomy based on which they develop mental representations of the spatial layout. This point was backed by a finding from our survey conducted on anatomy educators: in order to teach radiological anatomy along with gross anatomy, as required by the modern curriculum, teachers from the anatomy department rely on colleagues from the radiology department. Some training on radiological anatomy will therefore be required for the anatomy teachers to fully utilise AnaVu's features. The educators may be open to this requirement as it was observed that in our evaluation exercise when the two teachers prepared to use AnaVu to review a lesson for the students, the interactive controls led to some excitement in the teachers. Specifically, they exhibited and expressed enthusiasm and curiosity as the system's opacity control (which allows one to see what structure lies below/behind what) and manipulation (rotate, zoom) features allowed them to navigate the anatomy; further, they could also readily correlate cross-sectional anatomy with 3D anatomy using the 3 sliders which permits a cutting plane to be moved in 3 canonical directions independently. Allocating resources for training is essential for an effective paradigm shift in anatomy teaching. Finally, given that all visualization is done based *in vivo* images the resolution limit of the imaging modality can impose a restriction for anatomical model generation. For instance, the nuclei in the brain stem are not visible in the MR scan. This was overcome in creating the 3D model by a dedicated expert who consulted a radiologist and textbooks to do a manual annotation of the scan slices. Executing such a task, though tedious, is a one-time effort.

We hope to expand the system to cover full-body anatomy with a better presentation in terms of realistic rendering, using textures and materials, including soft body physics, full-body inverse kinematics and skeletal animations. More work needs to be done to add realistic simulations to the system to show the real-time interaction of various systems within the anatomical landscape. Further work is also needed to automatically extract and refine 3D structures from MRI scans in order to present a true picture as opposed to artistic interpretations.

## VI. Acknowledgements

We are indebted and grateful to Dr MS Valiathan for originally proposing the idea of using visualizations in teaching anatomy and guiding us in shaping up the entire idea. We are also thankful to V Mythri for developing a proof-of-concept version of the tool which paved the way for a new design. Thanks to Drs Kesavdas Chandrasekaran, Bejoy Thomas, Jayadevan and Kapilamoorthy of SCTIMST for providing MR scan data and inputs for the functionalities required of AnaVu.

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