Introduction

Adapting VR technology to study morphology is relatively straightforward. Advances in computer hardware, headsets, and software have been driven by the gaming industry, which has made the process user friendly and rapidly brought down costs. The three essential components to using VR are: (1) a high-quality graphics card; (2) VR headset; (3) software that can communicate with the headset, although there are now stand-alone headsets. The cost of the graphics cards and the headsets are rapidly falling while the performance is rapidly improving. There are both powerful open source software packages and commercial software packages available.

Members of the Farmerlab have found several major advantages of using VR for morphological studies. First, data can be shared and worked on by multiple researchers in the same virtual space at the same time, communicating with each other in real time through the headsets, no matter where they live/work. Second, we have found this tool to be valuable in preparing for surgical implantations of airflow meters into the respiratory system, or identifying points of entry for endoscopy. VR has allowed us to identify external landmarks on the surface of the animal relative to the internal topography of interest within the respiratory system, so that our surgical approaches are precise. Third, we can better visualize the results of our computational fluid dynamics models. VR gives us the ability to experience the simulations of fluid flow in a much more intuitive and natural manner. Fourth, using VR has enabled us to greatly improve the quality of the meshes we make to use CFD modelling to study fluid flow. This crucial step of the process has been one of the most difficult, but is essential to modelling the fluid dynamics faithfully. Finally, we are using VR to share the results of our research with the community and to teach morphology to undergraduates. The community work is in a trial phase, where children or other members of the community are allowed to explore the anatomy using the VR system. However, our pilot program shows this is a successful way to communicate to the public, and it is envisioned that more and more people might have an interest in exploring this anatomy at home, if they own the hardware already, or when visiting museums that have the capabilities. In the classroom, VR is very engaging and virtual dissections have the advantage that layers of tissues can be "removed" by making those densities transparent, and then replaced over and over again, the same data can be used by all students, reducing the need for the use of animals in teaching anatomy, and animals can be studied using VR that could never ethically be used. For example, computed tomography scans obtained by zoos of rare animals that need medical attention can be used by a class to have a look at the internal workings of a penguin, or a tuatara, or a Komodo dragon. In summary, VR is an immerging technology with tremendous potential to enhance the study of morphology, to improve methods used to teaching morphology; as well as to communicate the results of research to the lay community.

What's Needed to Get Started?

1. Graphics Cards-

The evolution of consumer grade virtual reality equipment has been swift, and allowed a large crossover into scientific research. Current setups can be obtained for around $1500 USD (including computer costs) and scale upward to ~$4000 for a top-of-the-line (consumer grade) system.

The primary component of a VR capable/ready system is a high-end Graphics Processing Unit (GPU). VR capable GPUs start around $250-300 USD and top out at ~$1000. The Two major manufacturers are Nvidia (with their Geforce lineup) and AMD (the Radeon lineup).

2. System Memory-

When dealing with large biological datasets a large amount of RAM is required to visualize the data without losing fidelity. 32 Gigabytes (GBs) is a recommended starting point but 64 GBs would be preferable.

3. VR Headsets-

The current state of VR headsets can be split into two separate categories based on tracking methods:

- Outside in tracking: Headset and controllers are tracked via a fixed, external set of "lighthouses". These provide position relative to the room through the use of timed infrared pulses to triangulate the position and orientation of the headset and controllers. This is combined with the use of accelerometers in the headset and controllers as a failsafe when line-of-sight is blocked.

This type of setup provides excellent positional fidelity but requires setting up a space beforehand. Lighthouses have to be strategically placed to ensure the headset and controllers can see at least two lighthouses at all times to ensure a smooth experience.

Examples: Oculus Rift, HTC Vive, Valve Index.

- Inside out tracking: The Headset and controllers are tracked through a combination of cameras in the headset and accelerometers in both the headset and controllers.

Due to the fact there is no external hardware required, inside out setups can be ideal for transitory setups. Downsides include tracking issues when controllers lose line-of-sight with the headset, for instance reaching behind the head. With the introduction of the Oculus Quest and Quest 2, these setups can also be fully wireless.

Examples: Oculus Quest (1/2), HP Reverb, Samsung Odyssey

Table A: Technical specifications of some of the most popular VR devices.

Model (first release)	Set	Resolution, Screen size	Field of View (FOV)	Refresh Rate	Cost Estimate
HTC Vive Pro (2016): Tethered or wireless	Headset (6DOF), 2x controllers, 2x base stations (IR)	2880x1700, 3.4"	110 deg	90 Hz	$800 - 1400
Oculus Rift (2016)	Headset (6DOF), 2x touch controllers, 2x IR sensors	2160×1200, 3.4"	110 deg	80Hz (S) - 90 Hz	$400 (S) - $600
Oculus GO (2018) - all-in-one headset	Headset (3DOF), 1x controllers	2560×1440, 5.5"	95 deg	60-72Hz	$500 - $600
Oculus Quest all-in-one headset (2019)	Headset (6DOF), 2x controllers	1440x1600 per eye	95 deg	72Hz	$400
Pimax 5K Plus	Headset (6DOF), 2x controllers	2560x1440 per eye	200 deg	144Hz	$700
Google Cardboard VR + SDK	VR platform for the google cardboard "headset" for phones	Screen size up to 6"			Low cost, cardboard viewer: $15

Wikipedia has a comparison of virtual reality headsets that can be found at the following URL:

https://en.wikipedia.org/wiki/Comparison_of_virtual_reality_headsets

4. Software ecosystems:

There are three primary software ecosystems for running VR applications on a computer with an attached headset:

- SteamVR: Made by software company Valve Inc, SteamVR is a subset of the Steam platform. Steam was originally used as a digital distribution method for games made by Valve. It has since evolved into a distribution platform for a wide array of software publishers. In addition to being a large repository of VR content, SteamVR is a service that allows traditional software to run in VR.
- Oculus Store: Made by Oculus (a subsidiary of Facebook) the Oculus store provides commercial content for its line of headsets. This allows for VR content distribution without the use of a separate computer.
- Windows Mixed Reality: Made by Microsoft to support Windows Mixed Reality (WMR) headsets. Similar to other platforms this provides software distribution to headsets which support WMR.

Some Commercial VR options for biology:

Elucis: Allows for multiple collaborators to inhabit the same space and work with the same biological data. Allows users to make surface mesh files and annotations within the headset. https://www.realizemed.com/elucis/

Syglass: Allows user to make volumetric meshes from biological data. Is compatible with extremely large datasets (up to ~20 TB). https://www.syglass.io/

ParaView: Widely adopted in the educational and scientific community. Free and open-source codebase. Recently added plug-ins to allow for visualization in a VR headset. Currently limited interface within the headset, but can be augmented with the traditional user interface. https://discourse.paraview.org/t/updates-to-virtual-reality-support-in-paraview/2046

Software	About	Programming language	OS	Cost
Unreal Engine:	Complete suite for real-time technology development, over visualisation and real-time rendering to high-quality game design for Pcs, consoles, mobiles, VR, AR	C++, blueprints; Supports python-scripting	Mac, linux, windows	Creator (free) and publisher version

Unity:	Creation of interactive 3D content for games for a wide range of platforms (more options in the pro version)	C#, UnityScript, Boo	Mac, linux, windows	Free and pro version
Sketchfab (online platform):	Publish, find, or buy 3D models and VR and AR content, online 3D visualisation (like youtube but for 3D files)	/	On any mobile browser, desktop browser or VR headset	/
Autodesk Maya:	3D modelling, rendering, animation and realistic effects	Maya Embedded Language (MEL)	Mac, linux, windows	License (free for academics)
Cinema 4D	3D modelling, animation and visual effects	COFFEE, python	Mac, linux, windows	License or student/educator version
Blender:	Free open-source 3D creation suite including 3D modeling, rendering, game design, motion tracing, video editing and 3D animation	Supports python-scripting	Mac, linux, windows	free

Workflow Guide for Visualizing Simulation Data (such as computational fluid dynamics or finite element analysis) in Virtual Reality

Hardware and Software Requirements

Paraview for 64-bit Microsoft/PC

The Mac version of *Paraview does not currently support virtual reality*

Loading Simulation data in to Paraview into Virtual Reality

1)   Download Paraview software (www.paraview.org)

2)   Install and run Paraview on your machine

3)   For tutorials on how to use Paraview, including setting up visualization scenes, please turn first to the official Paraview tutorials at (https://www.paraview.org/tutorials/)

4)   Acquire and set up virtual reality hardware

a.   Refer to setup guides (also in supplementary information)

5)   Save your simulation data into VTK format. In OpenFOAM, the command to do this is "foamToVTK."

6)   Activate the Virtual Reality ParaView plug-in

a.   Tools > Manage Plug-Ins

b.   Highlight the "OpenVR" plugin on the right panel and press "Load Selected"

7)   Generate whatever sort of scene you'd like to view in Paraview first on the normal 2D GUI and set opacity etc.

8)   Hit the "Send to VR" button in the bottom left of the screen (part of the XX panel)

NB, there is more information about virtual reality on Paraview on the Kitware Blog at (https://blog.kitware.com/taking-paraview-into-virtual-reality/)

Exporting a Paraview Scene into Sketchfab

1)   Save the scene that you'd like to upload as a XX file

2)   Change the file name (rename the file in windows or mac) so that it reads filename.XXX instead of filename.XXX

3)   Go to Sketchfab.com, hit upload, and choose the filename.XXX filename.