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Reframing the Paradigms of Inner Bodies

Dolores A. Steinman
Biomedical Simulation Lab
University of Toronto
Department of Mechanical & Industrial Engineering
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dolores@mie.utoronto.ca

David A. Steinman
Biomedical Simulation Lab
University of Toronto
Department of Mechanical & Industrial Engineering
-----
steinman@mie.utoronto.ca

ABSTRACT

Awareness of our environments both external and internal are in continuous flux and highly mediated by technologies we have created. The research project we shall discuss is situated at the pivotal point of reframing our perception and consciousness in the context of the current *in silico* culture. More to the point, we shall refer to inroads into the bi-modal computer-generated simulations of blood flow patterns, in the pathological situation of a brain aneurysm, leading not only to the understanding of the phenomenon but also to the optimal communication of its complexity. This new approach, removed from both *in vivo* as well as *in vitro*, brings together visual and sound artists, computer engineers, designers and cognitive scientists with the essential goal of restructuring and re-configuring our understanding of self. This being said, the need to create ways that allow remodeling and reframing our perceptions through easily interactive tools that are also increasingly autonomous is at the core of the research we shall be presenting. Through novel approaches and complex technological mediation, the accompanying conscious experiences co-evolve and develop in complexity. The aim is for this project to serve as an example and starting point for stimulating debate.

KEYWORDS

Unseen body; *In silico* experience; Blood flow patterns.

1 | INTRODUCTION

With every single beat of our hearts the world around and inside us is continuously and perpetually changing. And so is our interaction with it, through our perception and its correlated representation.

The connection between our inner worlds and the outer realm has always been present, albeit hard to assert and represent at times. The ways in which these connections have been revealed over the millennia at varying levels and through a variety of means, but particularly during the last half-century, have dramatically evolved. Exploring, perceiving and understanding our inner bodies in their wholeness and complexity, as well as their interaction with the outside worlds, has been changing while equally challenging.

As our awareness of our environments both external and internal has become mediated by continually evolving technologies mankind created, our current attempt is to tame them with the aim of better use as well as communication with each other, not to mention with our own selves. One has to acknowledge, however, that despite inhabiting the same universe, our cultural differences in approaching the issues are vastly diverging at times in their manners, as well as their ultimate intent.

The research on which we are concentrating is on the cusp of reframing the way we perceive ourselves while attempting to create an easy access portal and platform for a new consciousness of our bodies in the context of the current *in silico* culture. Blurring boundaries between disciplines, current medical investigation relies on digital developments that make for a fascinating as well as thought-provoking mix of codes, norms and resources as engineers and computer scientists became involved directly with anatomical illustrators and clinicians in generating visual representations of one of the most revered fluids of the body: the blood.

2 | HISTORICAL PERSPECTIVE

Our bodies' exterior has changed only so slightly over the last centuries, but the technology for exploring its unseen sides definitely expanded, unveiling inner worlds otherwise relegated to imagination only. One may say that we reached the point at which Borges' famed map covered the territory (Borges, 1998). Like our predecessors before us, in our group too, the phenomena within are being examined, explained and understood based a lot on mathematics and calculations but equally on imagination and extrapolation. The difference consists in the fact that currently a virtual patient can be generated based on bio-data collected and the clinician can explore this virtual body in non-invasive ways (albeit the remoteness being potentially viewed by the patient as alienating). To be clear, the advantage of the virtual patient is that it allows exploration and testing of surgical treatment options in non-invasive ways, while the gold standard remains the least mediated interaction with the actual patient. The aural representation of the bio-data collected from the actual patient – to which we will refer later in the article – is also considered as an aid and in no way a replacement to the visual one, hence our continuous effort to achieve a bi-modal way of computer-generated simulations of the physiological phenomenon.

Our predecessors were imaging inner worlds based on stories that combined observations, deep-rooted beliefs, and contemporary cutting edge scientific discoveries. The ways of communicating were also framed by either the language in which they were written, the availability of the reading material and not least the trust one could inspire in their contemporaries working in similar fields [1].

We shall not recount history here, but since we shall be referring to paradigm shifts in anatomical and clinical understanding, it is important to acknowledge the change that came not only with direct observation through dissection but also with the ability of publishing material in a *lingua franca* that allowed the spread of knowledge. Within one year, namely from Ryff's "*Die Kleyner Chirurgie"* (1542) to Vesalius' "*De Humani Corporis Fabrica"* (1543), representations of the human blood circulation transferred the central site from the liver to the heart, and with that, our comprehension of our inner selves vastly and everlastingly changed.

One may credit this move to Gutenberg's introduction to Europe of the movable type, as by 1450 his printing press was in operation and shortly thereafter two influential books that revolutionized the way in which we perceived the universe around and within us, were published. The year was 1543 and the books were Copernicus' "*De revolutionibus orbium coelestium*" – his end-of-life magnum opus revolutionizing the world of astronomy – and the aforementioned Vesalius' "*Fabrica*", which established him as a leading physician as well as modern anatomy (i.e., the way clinicians viewed their patients and, in the end the way the human body was perceived and represented for centuries). From then on, the world – both at human and cosmic scale – appeared different and the understanding of it shifted perspectives.

About half a century later, a contemporary of William Harvey (and his published discovery of the blood circulation as being pumped by the heart to the brain and through the body (1628)), Robert Fludd, made the connection between the macrocosm (as he viewed the universe) and the microcosm (in his view the human) through a series of illustrations that graphically represented the connection between the two (e.g., Figure 1).

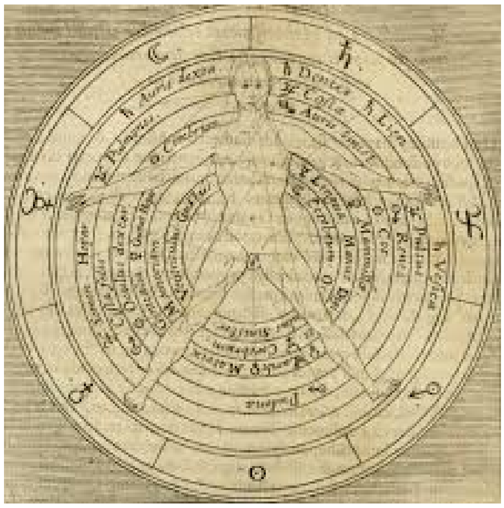

Figure 1 | Robert Fludd, Man as Microcosm and Macrocosm, illustration part of an unpublished manuscript (ca. 1619).

The reason of referencing, albeit briefly, Fludd's theory is because of his belief that blood was at the center of this connection, as it was the conduit between the spirit (in his view the sun) and the body, in addition to which he connected the astral bodies' positions to disease. As the work we will be discussing addresses ways in which blood flow connects the most remote and minute parts of the body, brings life to but may also contribute to its ending -- being the conduit of components that we share with things and beings all around -- we considered the reference relevant to the topic. For all its worth, Fludd remains known as a successful clinician but also as an astrologer, mathematician, and cosmologist (Szulakowska, 2011). To this day, knowledge regarding one's inner environments, in ways beyond the tactile, requires approaches based on sentient and emotional ways, which in return requires new means of communication (toward which we strive).

3 | FROM ANALOG TO DIGITAL

As a case study for both exploring as well as explaining, we consider the inroads made into the bi-modal simulation of blood flow patterns – in the pathological situation of a brain aneurysm – its consequences, the understanding of the physiology of the events as well as the means of communicating their complexity.

In the attempt of generating life-like virtual representation blood vessels that traverse and connect parts of the body, as well as the fluid flowing through them as it takes turns and changes patterns following a large variety of vessel geometries, the computer simulations [3] also weave observations (however mediated they may be), deep-rooted beliefs as well as new ideas, while interlacing and folding in scientific discoveries that were originally assumed to play other roles. This new approach, removed from both *in vivo* as well as *in vitro*, draws together visual and sound artists, computer engineers, designers and cognitive scientists with the substantial intention of restructuring, remodeling and ultimately re-configuring our understanding of self.

Unquestionably, like in our predecessors' practice, our current research confidently entered new territories – badly or even uncharted – and slowly (over the decades) came up with ways of creating a universe that matched not only the human anatomy but also the idea of what human bodies are and the way they function. This being said, the need to create methods and conditions that allow reframing our perceptions through easily interactive tools arose. Also of importance is the aspect of the ever-increasingly autonomous technologies. While basing formulations in conventional medical- and biosemiotics, these novel approaches and complex technological mediations render the accompanying conscious experiences co-evolving and developing in complexity [4].

Meanwhile, old things are new again: when representing blood, long-established conventions come in handy and the blue-red code (originally for venous vs arterial blood) stayed the go-to for decades. The mapping of the circulatory system didn't undergo major changes since Vesalius and the exploration of its unseen content has been a mystery that Leonardo tried extrapolating from observation of water flow, while the flow as we know it now has been studied and represented, in a variety of ways, since Harvey's time. With new technologies, new ways of imaging and imagining the body entered the scene. A quick overview would mention the mathematical models, the physics-based ones, the electrical circuit-like, to come closer to the "classical" models through glass and plastic phantoms. These steps were taken over just a few decades, as the speed of the technological changes accelerated and anatomists and bio-researchers followed the trends in technology in ways of not only trying to interpret and understand but also explain the circulatory system (Nichols & O'Rourke, 1990). The starting point, the discovery of the x-ray, was thrilling and it did revolutionize the view of and into our inner worlds, but it was by no means the end of the line for imagining inner realms, just like the microscope before them wasn't (Steinman & Steinman, 2011).

As a synopsis, as far as the anatomical representations go, over the centuries, illustrations moved from the particularities of the patient's diseased body towards a standardized, normalized version that became the go-to in understanding the particularities of each (a practice that lasted for centuries). Lately, the body representations are being re-assessed, based not solely on known maps and imagined inner worlds but also by taking advantage of contemporary technologies, our grasp of them as well as skill in using techniques at hand. This path took medical imagers and their respective attempts to understanding the physiology of the blood flow phenomenon from the idea seeded by William Harvey to the illustrations of *"Gray's Anatomy" (1858)* and the revolutionizing application of the x-ray to angiograms to the ever evolving *in silico* versions.

Of critical significance is the fact that these images are not meant to replace other means of investigations but to assist neurosurgeons in quickly and efficiently establishing decisions regarding the appropriate treatment, as detection of cerebral aneurysms became more common with the increasingly routine use of 3D medical imaging, and the consequences of them rupturing (dissecting) have potentially fatal consequences. At the same time, due to their non-invasive character and their capacity to model a phenomenon or an experiment, they are also instrumental in educating new generations of physicians and training future medical technologists.

4 | EVOLUTION OF THE LAB'S RESEARCH

To reiterate, the computer simulations generated in our and others' laboratories are representations of bio-data collected from individual patients (Taylor & Steinman, 2010). As realistic or close to the actuality of the body they may be, they have never been meant to replace the direct interaction with the patient, either for the medical student or the clinician. Moreover, computer-generated simulations represent unseen areas that escape our direct perception, thus carrying the burden of responsibility of reflecting accurately the actuality of the body. As anatomy and physiology and their respective representations, just like everyday life, are permanently affected as well as assisted, and furthered by technology, in turn, the curiosity of the medical researcher also supports, promotes and influences the respective technologies.

We consider the inroads into determining the critical areas of potential aneurysm rupture as book-ending a millennia-old pursuit: what started with trying to determine the optimal points for blood-letting as a cure, currently concludes with the pursuit of finding the location of risk of blood vessel wall dissection, thus preventing blood flowing out of its course, as a cure. We also found fascinating the fact that at both ends, this journey is partially an imaginary one: observing the body, exploring it *ex-vivo*, evoking and simulating it. As understanding of ethics and not only aesthetics progressed over time, current research traversed the invasive/non-invasive barrier, aiming towards the unintrusive albeit remote approach to exploration.

In order to achieve this goal, the simulations tend to merge ways of expression and interests from apparently unrelated disciplines and move continuously and seamlessly from macro to micro, from the seen to unseen, from image to sound and back to image, as we shall show later. The representations are technical, certainly, but they carry a huge emotional burden along with a huge responsibility. The way from the patient-data to computer-generated 4D images and sound is a multi-step one, involving encoding of patient data into numerical data and then the decoding it into either or both visual and aural representations. Due to the complex nature of the phenomenon examined, not all data can be represented, and the representations need to be not only accurate but also clear and easily accessible.

As a meaningful example from the history of the group, the same aneurysm patient-data was visually represented in a variety of ways (ranging from physics-based visualizations, engineering, fluid dynamics and not last an angiogram look-alike (Steinman & Steinman, 2010). The image that appealed most to the clinicians was the virtual angiogram, as it was an image they were most accustomed to. What stood out in this example of a clinical case, was the fact that in order to obtain a match between the real and the virtual angiogram, changes had to be made in the parameters entered, as the algorithm had to take into account not only the geometry of the vessels, but also the fact that blood flow was, in fact, disturbed by the injection of the x-ray contrast agent. Thus, what clinicians mis/took for reality was in fact an imbedded artifact, arguably rendering the simulation closer to the actuality of the body (Ford et al., 2005). Over the years, the eye of the clinician has gotten so used to this particular type of image and its significance and relationship with the other quantifiable signs and symptoms, thus becoming "reality", reminiscent in a way of Stratton's (1897) experiment in which participants were wearing goggles that inverted the image. Thus we would conclude that weaving the virtual into the real and vice-versa is not necessarily detrimental to understanding the phenomenon; on the contrary, it forms a clearer idea of the unseen. This particular case indicated that a highly mediated image may in fact be a more accurate, or truer one, that the perceived "direct" one. Does it mean that the x-ray – generated image is, in fact, the manipulated one? Did we, thus, enter new and uncharted territories of the imagination and are looking for ways of qualifying, quantifying and ultimately communicating them? Well, "[p]hilosophically speaking, semiotics is an intellectual enterprise which conceives communication as being made up of signs and signs relations" (Cannizzaro, 2014).

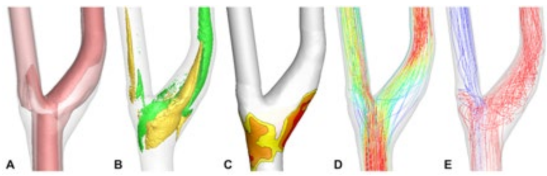

Figure 2 | Different representations of the same computational dataset: (A) Isosurfaces of speed; (B) Isosurfaces of helicity, coloured to distinguish counter-rotating flow streams; (C) Contours of wall shear stress, highlighting regions of low shear; (D) streamlines at peak systole, coloured according to speed; (E) pathlines of particles released at peak systole.

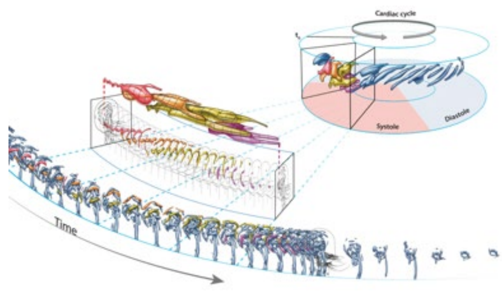

Figure 3 | Final artistic prototype of the carousel: All three rings depict the same flow pattern evolution over a cardiac cycle. For easier access of information regarding either a particular structure of the turbulent-like flow, as it changes during that period of time, or follow the multitude of these structures emphasizing the critical ones, colours having been chosen in order to discriminate the evolution of selected repeating vortex structures, highlighting their potential contribution to the risk of growth or rupture of the aneurysm. Outer ring shows hand-rendered vortex structures evolving through time; middle ring isolates selected vortices, caricatured to highlight repeating structures; inner carousel shows full cardiac cycle.

Moving away from the idea of either representing the same patient bio-data in a variety of ways, and then selecting still frames that seemed to represent critical moments within the cardiac cycle, followed by splitting that particular image into components (such as Figure 2), the group worked towards a means of representing within the same still frame the essential changes, while not discarding the less relevant information. Based on comics and information theories, cognitive science and the century-old model of the zoetrope, the emerged carousel prototype was the one in which particular vortices could be followed as they develop throughout one cycle, or the way they coexist, at a set point in time, with other surrounding vortices (Figure 3).

What made this prototype stand out is not only the clear, accurate and easily accessible way in which the information is presented but also the fact that it enables the clinician/ neurosurgeon to concentrate on the still frame of choice, to slow down, replay or stop the succession of sequences, as needed. Also of relevance is the fact that the carousel was the brilliant result of an established collaboration between a trained medical illustrator (who was actually encouraged to imagine the visualization by watching the ebbs formed by rapid river flows and not through computer-simulated representations) and an engineering student with a background in computer graphics. The fact that the selected still frames and particular vortices were chosen as being representative of the critical moments in the cardiac cycle, namely those in which the flow pattern is abruptly altered, was important, while all additional information was still available.

Equally important was the need for the information to reach the neurosurgeon in a clear and timely way. Cognitive science suggested that the bi-modal representations (i.e. concomitantly visual and aural) were superior in signaling fast changes (Grond & Hermann, 2011). Through a sequence of informal collaborations with media and sound artists, our patient-based mathematical models were translated into powerful bi-modal depiction of blood flow: the aural component accompanying the visual one making for a holistic as well as intuitive understanding and interpretation of the process studied, and not least, the body as a whole.

The use of sound as diagnostic technique is not new, on the contrary, it seems to have been the examination procedure to be recorded, dating from antiquity (Ghasemzadeh & Zafari, 2011). Also of note is the fact that it never went out of practice, as both auscultation (listening to body sounds produced in cavities or by tissues) and percussion (provoked sounds) were early associated with disorders of bodily functions. A crucial moment, in our opinion, was the invention of the stethoscope alongside the standardisation of the pulse sound notations, both important tools in diagnosing disturbances of the blood flow (Wellmann, 2017). The only brief set-back in the use of sound-based techniques in medical examinations and explorations was due to the emergence of the x-ray use; however, it did regain significance within the half century, with the emergence of ultrasound as a routine test. The critical moment in the history of the lab, as it were, was a serendipitous observation that led the way to the current project, namely that of a patient-data sonification alongside visualization. The group's research results had already suggested high-frequency flow instabilities being the rule rather than the exception in the case of aneurysm and cerebrovascular flows (instabilities difficult to visually discriminate, hence the amount and variety of efforts into visualizing them in the most appropriate way). But four decades after the momentous experiment done by Dr. Gary Ferguson, by intra-operatory placing of a microphone onto a cerebral aneurysm exposed during surgery (Ferguson, 1970) and recording the bruits, a computational modeler noticed visual similarities between these recordings and the velocity-time traces from their first-ever high-fidelity CFD of aneurysm turbulence (Valen-Sendstad et al., 2011).

Initially the sound used was in fact a soundtrack more than a sonification (Coppin et al., 2017) but it was enough of an incentive to pursue this trail. It soon led to more accurate, patient-data based sonification of blood flow that played with both the location of the virtual probe as well as the type of sound that was associated to the various data points (MacDonald et al., 2018). During the analysis of intensity and frequency in relationship with the significance of turbulence, the spectral analysis made clear certain bands that had corresponding patterns to specific geometries of the vessel/ aneurysm. Based on sound analysis, the representation came full circle back to visualization, namely simulations of blood flow that had as a parting point only the frequencies suggesting turbulence of the blood flow (Natarajan et al., 2019). For a clear representation, animations of vortices of different frequencies were represented in different colours and, moreover, in a similar move to the one already experienced in the past, the animations also presented the viewer with the option of being slowed down, for better examining and analyzing of their progress during the cardiac cycle.

Another full cycle that was achieved during and regarding the same study, namely re-creating the carousel of different parameters representation. To clarify, the vortices created during turbulence of flow may be compared to those of a storm (notion and image with which most would be familiar), and the equivalent of the eye of the storm is known in the field (as we shall see, ironically) as a "fixed point" where the fluid dynamic forces go to zero. The blood vessel/ aneurysm wall structure and its lining could be suspected of having an easier situation to handle, seeing that the forces exerted are low; however, that eye of the storm is not fixed, as it continuously moves over the cardiac cycle, thus applying strong stretching and possibly vibration forces to the cells on or within the wall. It thus became a necessity to understand where these areas are and how rapidly they move and reposition. Visualizing the locations, during a cardiac cycle, was done and a mapping of the locations followed (Figure 4A). In order to clarify it for both the benefit of the neurosurgeon but also that of the imager, another carousel was generated, this time of the variation of the fixed point over the duration of a cardiac cycle, revealing regular patterns of motion that could not easily be detected via conventional animations (Figure 4B).

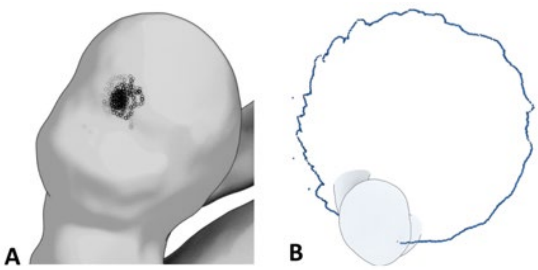

Figure 4 | (A) Accumulated motion of a single fixed point, over cardiac cycle. (B) Same fixed point traced out in a carousel.

This being accomplished, the astonishing usefulness of the carousel-type of representation became, once again, obvious. To conclude, all these trials and tribulations were meant to obtain and suggestive yet clear and accurate representation of a very complex phenomenon, otherwise undetectable.

5 | CONCLUSION

Everything we do challenges our senses, our mind, our awareness of self and our surroundings. The ever-evolving scope of our research, moving from the unseen universe exploration to the unseen body, learning from imagining new worlds (based on mathematical calculations), to imagining the unseen body (based partially on observations, partially on explorations at micro-nano levels), puts to use new tools, new techniques and technologies. What remains unchanged from the pursuits of our predecessors is our curiosity and the ability of the mind to continuously adapt to new encounters and tasks, revising ways in which we understanding our bodies and their functioning in the context of our immediate and wider environments, altering the views we held and embracing new ones, moving to new ways of framing our perception and understanding of self.

Referring permanently to our roots, the way we may address the future can succinctly be summarized by saying that one needs to look towards reality through prognostic-based science fiction (Fussell, 2013). What seemed impossible and improbable in the minds of some was achieved and surpassed.

Inferring from our field of interest, by charting and reshaping it in manners that relied on conventions long established, but generating a visual & aural lexis that allowed us to connect the past to the present, we can only speculate on what the future holds. Despite leaps and paradigm shifts, as humans we are capable of forgetting or discarding information already existent. What our research group has experienced and hopefully managed to achieve is a means for better representing the unseen and still not well-understood complex phenomenon of the blood flow.

As we walked down the path of history, we learned that one alone may be capable of envisioning worlds coming together, zooming in and out of our human scale, but we need to do it as a collective, as big paradigm shifts in science were not achieved through study and experiment only, but by gathering inspiration and opening minds to all possibilities and methodologies of knowledge production. From the establishing of the correct centre of blood circulation, to moving away from the "frog" depiction of the body (Matuk, 2006) to Leonardo's and Vesalius' aesthetics, from extrapolation based on animal anatomy to human dissections and direct observation, and throughout this trajectory using auscultation and percussion (corroborated with breath, urine, skin examination) for collecting information regarding the state of the body to the revolution that the microscope and the x-rays have brought in exploring the unseen, we carried on using human creativity, ingenious spirit and curiosity in using flow frequencies for both visualizing and sonifying, and from here on are ready to uncover new paths or rediscover forgotten ones. Our current available technology and tools used, in concert with our particular interest, refer solely to the revealing of a complex physiological phenomenon at the macrocirculatory level. Despite the major advances made in our field (and by our group, specifically), we are aware of the multitude of factors that contribute to both the complexity of the phenomenon, of the risks incurred if the wrong medical decision is taken (due to lack of understanding or knowledge provided), as well as the potential for future developments allowing investigations at the cellular and even molecular level. For now, we are presenting our research as a case study in the centuries-long process of revealing the unseen human body and thus, making a minute contribution to our understanding of our biological selves.

ACKNOWLEDGEMENTS

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ENDNOTES

[1] For example, for European physicians, Galen's anatomical representation of the human body and clinical approach persisted through centuries, until the Renaissance, when direct observation, through dissections allowed the shift to what is considered to be the base of modern anatomy, Vesalius. At the same time, one has to acknowledge the fact that low-quality versions including poorly-translated text and rudimentary drawings contributed to the propagation of incorrect information. One example of knowledge unavailable was that of Ambroise Paré, contemporary of illustrious Vesalius, who – despite his significant surgical and prosthetic innovations – was mostly unknown to his contemporaries, largely due to the fact that he used in his manuals and treatises the vernacular French and not the academically accepted Latin.

[2] Despite a long a prolific career as a writer, the manuscript of Robert Fludd's musings on the relationship between the macrocosm and the microcosm have never been published, and remained in manuscript.

[3] A computer simulation is considered the representation of the behaviour of a system/ phenomenon using appropriate algorithms to generate outcomes of the mathematical model of the system or phenomenon studied (Strogatz, 2007).

[4] As we briefly referred to this earlier in the paper, our historical references reflect a Eurocentric view. One may use as a comparison, for example, the Chinese tradition, in which the goal was not to represent in detail the particular organs or systems as much as to understand the function of the body holistically (Matuk, 2006). Also not referred to will be treatments based on traditions and herbal cures, primarily from non-institutionalized sources.

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BIOGRAPHICAL INFORMATION

Dr. Dolores Steinman trained as a Pediatrician in Bucharest, Romania. Upon relocating to Canada, she obtained her PhD in Cell Biology at Western University, in London, ON. In parallel to her bio-medical education she also attended Visual Art classes, at Western. Currently she is a Senior Research Associate in the Biomedical Simulations Laboratory, at the University of Toronto, as well as a volunteer Docent at the Art Gallery of Ontario, in Toronto. In her research, she observes the rapport and connection between medical imagery and its non-scientific counterpart as well as the ethical and social implications of these images. Her pursuit is driven by her keen interest in placing the ever-increasing technology-based medical explorations into the historical perspective and the larger context of the humanities.

Prof. David Steinman completed his PhD in Computational Haemodynamics at the Universiy of Toronto and did his postdoctoral work in Magnetic Resonance Imaging at the Robarts Reasearch Institute, Western University in London. He is recognized as a pioneer in the integration of medical imaging and computational modelling and their uses in the study of cardiovascular disease diagnosis and treatment. Throughout most of his career, he has maintained an interest in the relationship between research, the clinic, the social sciences and the arts. His current research focuses on improving risk prediction for cerebral aneurysms rupture based on blood flow turbulence. He is heading a trans-disciplinary project, involving cognitive sciences, inclusive design, anthropology and sound design, through which the group is developing novel flow visualization and sonification techniques.

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