The Art and Science of Visualizing Simulated Blood-Flow Dynamics

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Looking at images across disciplines can help us to think about the cross-fertilization that occurs among the different kinds of visual media.

—Marita Sturken and Lisa Cartwright [1]

Beginning with Vesalius in the 16th century and continuing through the 19th century, anatomists and physiologists relied on the skill of artists to represent the unseen body. With the advent of photography an important step was taken in terms of scientific visual recording. Toward the end of the 19th century came the rudimentary forerunner of the moving pictures used by Marey and Muybridge exclusively for scientific recordings [2]. Later, computer animation became an important tool used to visualize chemical structures (such as the DNA helix) and bonds, because it not only recorded but also modeled changes in conditions and the local environment. Currently, digital representations simulating real-life radiographs or angiograms are becoming commonplace. This is a result of the medical profession’s increasing interest in developing less invasive visualization techniques, as well as a growing familiarity with such images among the general public.

Over the centuries, efforts to reveal the unseen body have taken the physician from direct visualization (dissection/vivisection), to the recording of both macroscopic and microscopic images through cinematography, to the use of contrast/radioactive agents and, finally, to the notion of “computational imaging,” whereby computers are used to enhance or even simulate real-life conditions [3]. It is interesting to note that initially advanced scientific visualization techniques was the clinician’s need to document any observed pathological change, along with the laboratory researcher’s need to register and catalog observations. Today the goal is to translate data obtained in the laboratory or through clinical techniques into information easily interpreted by the clinician. Thus the computer-generated images created by scientists working in this field function as a metalanguage comprehensible to researchers and clinicians alike (that is, to specialists who have, over the years, developed a separate vernacular).

Fig. 1. (a) A typical textbook presentation of blood-flow patterns in an aneurysm [27], in which blood is shown to enter the aneurysm at the distal neck (labeled “d”) and to exit through the proximal neck (labeled “p”). (Figure 6.11 from G. Hademenos and T. Massoud, The Physics of Cerebrovascular Diseases [Heidelberg, Germany: Springer, 1998] p. 198. With kind permission of Springer Science and Business Media.) (b) A still frame from a visualization of a canine vein pouch aneurysm simulation, which demonstrates blood-flow dynamics broadly similar to that in (a). © David Steinman) (c) A different perspective from the same visualization, now demonstrating very different 3D blood-flow dynamics. Note: Dark streaks emphasize the fast-moving blood “particles”; lighter streaks highlight increasingly slower flow. (© David Steinman)
ated, we generate visual representations of the CFD data intended to be both accurate and aesthetically pleasing. In the process, we pay special attention to the means by which this process can be manipulated or is manipulating the viewer by altering his or her perception. So, imaging scientists face the task of taking an intricate, multifaceted reality and presenting images of it that ultimately may or may not alter the perception of that reality.

**PROGRESSION OF REPRESENTATION**

No serious aeronautical engineer today would consider advancing a new aircraft design without extensive computational testing and optimization. The potential of CFD to play a similar role in cardiovascular intervention is very high.


The study of hemodynamics (blood flow) is important because of its existing relationship to vascular diseases such as aneurysms (the ballooning of blood vessels) and atherosclerotic plaques (buildup of fatty material in vessel walls), abnormalities that tend to develop at sites where hemodynamics are most complex. A veritable menagerie of hemodynamic factors (e.g. wall shear stress, wall shear stress gradients and blood particle residence times) has been implicated in the development and progression of these vascular diseases. Hemodynamic forces likely play a role in the rupture of a plaque or aneurysm, an event that usually precipitates a heart attack or stroke. It may be important for the clinician to consider hemodynamic information when deciding upon treatment, for it has been seen in clinical practice that judicious control of hemodynamic factors and positive “sculpting” of the hemodynamic environment can affect the outcome of minimally invasive procedures employing balloons, stents or coils, as well as surgeries such as aneurysm clipping, bypass grafting or plaque excision. Although the putative links between vascular disease and hemodynamic forces are almost universally accepted, they remain poorly understood. This may be attributed to a simple but unfortunate fact: The hemodynamic factors of interest are extremely difficult to measure in patients using clinical medical imaging techniques. Instead, much of what we understand has been elucidated over the past four decades by means of increasingly refined models.

In art, visual representations of the human body have changed over the millennia. From the initial drawings and carvings on stone (e.g. the Altamira drawings and the Red Desert and Viking petroglyphs, essentially described today as “stick-people”), through the more “evolved” representations encountered on the walls of Mayan and Egyptian tombs, Pompeii villas, for example, to the “perfection” of Leonardo’s depictions, humans have faced a number of challenges owing to changes in their ability to process the information acquired, as well as in the skills required for representing this information. It is very important to understand that, despite the fact that the human body has not changed radically, both its perception and its portrayal are continuously changing [5]. Similarly, in the field of blood-flow simulation, mathematical models and their visual representations have evolved, paralleling the availability of increasingly sophisticated tools, skills and knowledge.

Until about the 1950s, our understanding of blood-flow dynamics was limited to relatively simplistic mathematical models, which assumed that blood vessels were infinitely long, straight tubes and that the blood moved steadily rather than pulsating in response to heart contractions. Refinement of these mathematical models to include the effects of blood pulsatility led, in the 1960s, to the realization that the flow of blood in arterial circuits follows the same general rules that govern the flow of current through electrical circuits. This led to the use of real or simulated electrical circuits to predict, for example, how alterations to the vascular trees (by disease) might affect clinically measurable quantities such as blood pressure waveforms.

Following the suggestion in the late 1960s that the complex forces exerted by flowing blood near arterial branches and bends might explain why atherosclerotic plaques are usually found near these sites, engineers began to translate their considerable skills in visualizing aerodynamic and industrial flows to the challenge of visualizing arterial blood flow. Often, however, the branching or curved tube models were necessarily idealized, sporting circular cross-sections and convenient planes of symmetry that facilitated the construction of the physical models. With the introduction of relatively in-
expensive desktop workstations in the 1980s, engineers and physicists began turning toward CFD [6]. Paralleling the evolution of physical models, early CFD simulations simulations still typically exploited simple geometries and planes of symmetry, the former being easy to generate using computer-aided design tools and the latter allowing only half of the model to be simulated, with the other half merely represented as its mirror image.

Advances in the 1990s in high-resolution three-dimensional medical imaging techniques such as magnetic resonance imaging (MRI), computed tomography (CT) and ultrasound (US) made it possible non-invasively to study vascular structures with unprecedented accuracy and detail. Still, concomitant accuracy and detail in the measurement of blood-flow dynamics in vivo remained—and remains—elusive. Coupled with advances in medical imaging processing, this decade has seen an explosion in image-based CFD simulations whereby vessel geometries derived from in vivo medical images are used to construct patient-specific CFD models for the purposes of more clearly understanding the role of blood-flow dynamics in the development of vascular disease, as well as for planning and optimizing vascular interventions.

The enormous amount of blood-velocity data generated by even a single image-based CFD simulation (often on the order of gigabytes), the absence of convenient planes of symmetry and the need to present these simulations in a clinical setting raise important conceptual and practical issues in their display [7]. The resolution of these issues at the interface of art and science is presented and discussed below, using examples from our research into elucidating the role of hemodynamic forces in treatment and prevention of cerebrovascular disease.

**THE ART OF IMAGE-BASED CFD SIMULATION**

Cubism undertook a completely two-dimensional transcription of the three-dimensional phenomena.

—Clement Greenberg [8]

The process of creating clear and visually pleasing representations is not a trivial one, since our images need to portray events that evolve in both time and space. Artists have the option of expressing these events in a manner that, for our scientific purposes, lacks pedagogic clarity. If we take the case of Duchamp’s series of *Nude(s) Descending a Staircase* (1913), the difficulties of imaging a body in motion in an accurate yet aesthetically acceptable way are made clear. Unfortunately, despite Duchamp’s reference to Marey’s scientific images, we cannot use such depiction of time and motion. In addressing the differences and similarities between science and art we walk a very fine line between scientific rigor (when defining and explaining concepts) and flexibility of interpretation (when applying them to individual patients) [9].

Pedagogical simplicity is inevitably achieved at some cost of verisimilitude.

—F.C. Holmes [10]

In our quest for clarity we strive to maintain the balance of making our data accessible without trivializing our efforts [11]. Correspondingly, we must avoid simplification to the detriment of accuracy. For example, in the classical representation of an aneurysm shown in Fig. 1a, blood is shown to enter the aneurysm from the right (distal) end, swirl clockwise and exit through the left (proximal) end. In still frames from a visualization of one of our first patient-specific CFD simulations we can see blood-flow patterns superficially similar to the idealized case (Fig. 1b). However, when viewed from a different perspective (Fig. 1c), the blood is seen to enter the aneurysm through both the proximal and distal ends. Detailed knowledge of how blood moves in and out of the aneurysm is crucial in selecting a treatment, and, as our slightly more realistic representation shows, this movement is more complicated than the simple pedagogical representation suggests.

Anatomically realist presents challenges for displaying information, as accuracy and rigor are not always guarantors of clarity. As Fig. 2 demonstrates, the traditional engineering representation of flow using flooded contour and vector field plots is clear to scientists and perhaps aesthetically appealing to the layperson, but not all clear to medical students, physicians, technologists or the public at large. In the absence of the conventional planes of symmetry implicit in idealized models, the choice of cut planes to render 3D flow dynamics in 2D becomes somewhat arbitrary and capricious. Furthermore, time as depicted here as a series of individual frames seemingly divorced from one another lacks continuity. This apparent wealth of information thus comes at the expense of communication and understanding.

The problem of representing 3D motion in 2D print is of course not a new one. As we have already mentioned, artists have struggled with this problem for centuries. The need for clarity in this field limits our choices; therefore we strive to exploit representations of blood flow that are familiar to the clinician. For the case depicted in Color Plate G No. 1, our solution was to consciously mimic the experimental slipstream visualization techniques [12] promoted by Charles Kerber, an eminent neurosurgeon with a keen interest in the study of blood-flow dynamics. The 3D context now becomes much clearer, and, although we have lost the detailed depiction of the complex vortical flow structures identified in Fig. 2, the complexity of flow in the aneurysm is still evident in the mixing of the differently colored slipstreams. The temporal evolution of flow, depicted here in a manner that echoes spontaneously the classical Muybridgian approach, also becomes much clearer.

**Despite the fact that the human body has not changed radically, both its perception and its portrayal are continuously changing.**

The scientist and the artist, each at his own work, are in some real sense pursuing the same aim and by methods having in common than is usually admitted.

—Martin Johnson [13]

When challenged by the tension between the novel concept and novel representation, we have chosen to promote the concept of a very complex patterned flow by adopting traditional conventions and adapting them to our needs. For example, when painters were hired to draw anatomical atlases, the convention they were supposed to obey was “red from the heart, blue to the heart.” As illustrated in Color Plate G No. 2a, we exploit this con-
within the portion of the artery where viewer the presence of retrograde flow
vention as a means of conveying to the
time undergoes virtual X-ray imaging to highlight the
and so there is a real danger if the nu-
to highlight the pursuit of aesthetic
sues or organs without the restrictions
computer simulations allow us to anticipate changes within tis-
whether we are telling the truth with
mechanical data underlying a compelling
in vivo, indirect comparisons of the
pression their representations of medical
minds of the public and experts
brings into the conditions of natural phe-
its own creation. As alluded to
of the body's
in the desire to be understood by
animals alike” [18]. In our society, where
researcher that it can fool humans and
and organs.
in vivo data collection, which
physiological processes can thus be
that they decipher the biological code
measure detailed blood-flow dynamics di-
ations obviously has its advantages and
are used ubiquitously for their
able to manipulate and alter percep-
universally the only means available to us to
physiological phenomena (“noting everything normal and
they are talking the truth with
the organ/tissue, as well as of the bodily con-
taken together, these examples serve
to highlight the pursuit of aesthetic agreement in the depiction of these
characteristics of the blood-vessel, (b) The corresponding frames from the clinical angiograms acquired for
this patient [29]. (© IEEE)

In Fig. 3 we go one step further in
exploiting the links between computer-
generated and routine clinical repre-
sentations by “virtually” imaging a
patient-specific CFD model in the same
way that the patient was imaged clinically.

As we have shown, the use of computer-
generated images derived from CFD sim-
ulations obviously has its advantages and
is definitely a step forward in the creation of optimal “windows” into the unseen human body. The principal advantage is

**ADVANTAGES OF COMPUTER-GENERATED VISUAL REPRESENTATIONS**

*Science reorganized its conception of the living body . . . to reflect the body’s new status as a mobile, living system.*
—Lisa Cartwright [14]

**CHALLENGES FACED BY THE IMAGER**

Where cinematography enhanced or oc-
casionally replaced sensory acuity, com-
puter enhancement or simulation goes
further by replacing the recorded image
with its own creation. As alluded to above, in the desire to be understood by
a wide audience and concomitantly make
the information available for both train-
ing and diagnosis/treatment purposes,
we are faced with challenges within two
essential issues: (a) scientific truth and
clarity; and (b) aesthetics and conven-
tions.

Paul Hartal has written, “The painted image has such an enormous power over the
observer that it can fool humans and animals alike” [18]. In our society, where
images are used ubiquitously for their
ability to manipulate and alter percep-
tions, the generation of images for edu-
cational and diagnostic purposes bears
great responsibility. Scientists, and by ex-
tension their representations of medical
data, are in an exceptional position ow-
ing to the public’s implicit trust of their profession [19]. In our field, data may be
used to make life-or-death decisions,
and so there is a real danger if the nu-
merical data underlying a compelling
representation is false or incorrect. In
In the biomedical sciences, it is becoming increasingly easy to create powerful images that can trick the observer into mistaking them for reality.

Aware of this power, one needs to be very careful when dealing with these images and the concepts they represent. Science, whether its practitioners will it or not, is in this regard akin to religion. Like religious imagery, the scientific and medical images herewith promote a new set of theories, principles, ideas and values. In Marx’s terms, religion is “the opiate of the masses” who are “coerced to mindlessly buy into a belief system” [21]. Over the centuries, religious art was used to convey religious myths and church doctrines, as well as to express abstract concepts while depicting seemingly accurate renditions of the world. Today mass media are used to “disseminate the same texts, images, and sounds to millions of citizens—thus assuring the same ideological beliefs” [22]. One can therefore ask, is science a new type of religion, in that it addresses the masses and tries to “coerce into mindlessly buy into a belief system” that is not necessarily innate to them [21].

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6. Except for relatively trivial cases, equations governing fluid flow cannot be solved by hand. Computational fluid dynamics circumvents this by dividing a complex domain into thousands of smaller and simpler elemental shapes, each of which is then governed by a simpler equation. However, because these elements are connected to one another, thousands or even millions of equations must be solved together, a feat achievable in practice only by the use of computers.


9. “The interesting thing about art is that it doesn’t have to have a utilitarian value . . . . [Artists] can indulge those things that are not rigorous.” M. Bond, “The Art of Knowledge: An Interview with Keith Tyson, Winner of Last Year’s Turner Prize,” New Scientist (20 September 2003) pp. 44–47.


11. “Victor Weisskopf has described as a ‘destructive element’ within the community of science the low esteem in which clear and understandable presentations is held.” Root-Bernstein [7] p. 72.

12. In this in vitro approach, colored dyes having the same density as the fluid medium are injected into the same vessel as the organ to be studied, and a certain quality of cleanness; others identify it as beauty in science is equated with simplicity, harmony and a certain quality of cleanness; others identify it as 'artistic activity is a form of reasoning.' R.S. Root-Bernstein, "The Sciences and Arts Share a Common Creative Aesthetic," in Alfred Tauber, ed., The Elusive Synthesis: Aesthetics and Science (Dordrecht, the Netherlands: Kluwer Academic Publishers, 1996) p. 74.


16. Cartwright [2] p. 26. It is important to appreciate the difference between the perception of scientific cinematic recording as "documentary" (i.e. involving no manipulation) versus scientific moving images created on the computer (i.e. realistic simulations derived from real-life data having undergone two conversions: from data collected from the individual patient to numerical data [binary code]; and then from the numerical data into images). The concern we face is: Which one of the two is more accurate, reliable or closer to reality? The former is a recording of the organ (albeit through the angle of the "recorder"), while the latter involves the processing of objective data by a non-biased machine.

17. That is, collection of organs/bodies parts is limited to suit the practical needs of the microscopist: frog legs, rabbit ears, chick embryo choroidallantoic membrane, mouse mesentry, etc.


23. Propaganda here refers to "false representations to lure people into holding beliefs that may compromise their own interest." Sturken and Cartwright [1] p. 21.


25. "There is a self-conscious limit to the artistic fora; however, for the images addressed to a scientific audience are, in a sense, conservative: whereas colour embellishes the dramatic effects used for popular audiences, journal articles and professional presentations largely eschew such bold images and less dramatic, monochromatic pictures are used." Tauber [7] p. 4.

26. Following discussions with our colleagues, we noted a tension between two perceptions: For some, beauty in science is equated with simplicity, harmony and a certain quality of cleanness; others identify it as 'artistic activity is a form of reasoning.' R.S. Root-Bernstein, "The Sciences and Arts Share a Common Creative Aesthetic," in Alfred Tauber, ed., The Elusive Synthesis: Aesthetics and Science (Dordrecht, the Netherlands: Kluwer Academic Publishers, 1996) p. 74.


30. From Steinman et al. [28].


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Dolores Steinman was trained as a pediatrician and went on to doctoral and postdoctoral research in cancer cell biology. An accomplished photographer, she is particularly interested in the role of the arts in medicine and dedicates her efforts to bringing together the local scientific and artistic communities. Dr. Steinman worked as a research associate at the Robarts Research Institute and is currently a Volunteer Art Docent at Museum London.

David Steinman spent the last decade as a scientist at the Robarts Research Institute, working to integrate the fields of computational modeling and medical imaging. Necessity being the mother of invention, he spent much of this time thinking of ways to present complex data to colleagues, collaborators and the community at large. Dr. Steinman is currently an associate professor of mechanical and biomedical engineering at the University of Toronto.