We usually think of the camera as an "eye" and the microphone as an "ear," but all the senses exist simultaneously in our bodies.

—BILL VIOLA [1]

For decades, research has focused on elucidating the connection between the forces exerted by flowing blood (hemodynamics) and cardiovascular disease, as well as optimally translating these findings to facilitate clinicians' access to critical patient-specific information. Given the practical constraints of clinical workflows, there is a need to balance precision and detail of the information with the speed of communication and comprehension.

In this context, and framed around the Biomedical Simulation laboratory's (BSL) aim of understanding why cardiovascular diseases such as atherosclerosis [2] and aneurysms [3] tend to develop in areas of complex blood flow associated with arterial branches and bends, in a 2007 article in Leonardo authors Steinman and Steinman described the use of medical imaging and computational fluid dynamics (CFD) toward "the pursuit of aesthetic agreement in the [visual] depiction of these patient-specific CFD simulations and the consistency with traditional medical imaging expected by the clinicians" [4]. Since then, the flow phenomena under investigation became more complicated and opaque to the visual representations we had evolved.

A product of the fortuitous meeting of artist Peter Coppin and scientist David Steinman at a local, student-run visualization symposium in 2011, this paper details the collaboration between BSL and Coppin's Perceptual Artifacts Lab (PAL), resulting in development of blood-flow representations. Building upon the age-old legend of Narcissus, the beautiful and self-absorbed hunter from Boeotia who fell in love with his own image, and the nymph Echo, whose voice and presence he ignored to his perdition, we show how the visual paradigms we developed together, around the ideas of caricature or cartooning, were adapted to sonification in order to progress from strictly visual to aural and bimodal representations. This paper also presents how this collaboration, through the recruitment of students with dual backgrounds in art and sciences, contributed to strengthening their transdisciplinary skills.

More than a decade ago, the authors proposed establishing a basis for scientific exploration of blood-flow dynamics intertwined with the visual arts. Here they present a case study showing how paradigms they codeveloped for visually abstracting cerebral aneurysm blood flows were extrapolated to sonification and bimodal representations, and how a close interdisciplinary partnership was effected by guiding engineering students versed in the arts and artists adept with digital technology toward final outcomes greater than the sum of their parts.

Evolving Image

The search for the best way to understand and then explain motion and flow have preoccupied both artist and scientist for centuries, with medical images evolving from simple anatomical drawings to the elaborate computer-mediated renderings of today. Prior to the advent of digital representations, the two breakthroughs in visual exploration of the unseen body from which our work benefited were the publication of Andreas Vesalius's De Humani Corporis Fabrīca (1543) and Wilhelm Roentgen's discovery of the X-ray (1895). While Vesalius's anatomical illustrations remarkably exemplified established cultural and social conventions, X-rays opened up new visual explorations in both the scientific (medical) and artistic worlds [5].
For both scientific and lay publications, as well as traditional forms of presentation to the clinician (i.e. printed reports), the initial approach was translating simulations of time-based 3D blood flow into 2D images by selecting a particular frame or sequence thereof. The challenges were twofold: the sheer density of information created by the time-varying nature of the phenomena and the possibility of generating confusing or equivocal images owing to spatial complexity. This conundrum led to a number of additional lines of inquiry, not least seeking inspiration from the visual arts [6,7].

As its research focus shifted toward examining the more dynamic blood-flow patterns in cerebral aneurysms, the BSls original attempts at 2D conversion of the 3D simulations echoed Eadweard Muybridges locomotion series [8]. The same case study was, as well, the basis for the exploration into a variety of ways of visually representing clinical data: from the original engineering imaging (saturated with information but difficult to decipher for a viewer with a different professional background) to techniques inspired by the clinical literature (Color Plate D, top). The number and variety of images illustrating different aspects of flow at the same moment in the cardiac cycle, and based on the same CFD data, imposed the need for a compact mode of representation that nonetheless would provide

CARICATURE AND CAROUSEL

Starting from the above-mentioned BSls aneurysm case study, and informed by perceptual-cognitive research explored in Coppins PhD research [9], two strategies for representing 4D structures (time-evolving 3D structures) quickly emerged: the caricature and the carousel (Fig. 1).

Our clinical case, an entanglement of simultaneously changing visual features, invited our use of caricature to amplify features required for decisions by reducing less relevant features [10], thus increasing information salience. We placed these in sequence, akin to a comic strip, thereby lessening cognitive effort by reducing the need to hold animated events in working memory. Sequential images have long been used to communicate complex ideas, at least as far back as the Lascaux cave drawings. As we applied the way in which panels are arranged sequentially (to display spatiotemporal events without animation, as if “outside of time”) to the cyclical nature of the phenomenon (repeated during a cardiac cycle), considering the need of the clinician to quickly access vital information (for diagnosis and treatment choice), the prototype of the carousel emerged.

The carousel is not new to communication in either scientific or artistic settings. A prominent example of its scientific use is Étienne-Jules Mares zoetrope, while artistic examples abound as well. In the field of biomedical illustration, however, presenting a clinician with the patients blood-flow data in the form of a static carousel was an entirely novel approach. Meanwhile, because blood flow is such a highly dynamic process, its visualization involves a high level of complexity due to transformations between states (as represented in the still frames). Research has indicated that when a series of events is depicted via a row of sequential images, the viewer mentally envisions the transformations, thus filling the gaps in the succession of represented states [11].

Building on Scott McClouds Understanding Comics [12], the use of this gap (gutter) in trying to simplify the depiction of a sequence of events became the basis for our future visual representations [13]. To reduce ambiguity during transformations, the convention of adding “trace lines” between caricatured frames was introduced in early sketches by Coppin (Fig. 1A). Taking a cue from Shannon information theory [14] by attempting to reduce uncertainty through the use of marks to show specific configurations between frames, as well as Gibson’s theory of affordances [15], and being mindful of physically possible actions implied in the process depicted in the illustration, the carousel took shape (Fig. 1B).

At this point, a biomedical illustrator/graduate student recruited to PAL and working closely with a BSL postdoctoral fellow under Coppins guidance, began to develop visual abstractions inspired by a variety of BSls flow visualizations, as well as natural phenomena (e.g. river flows) [16]. As shown in Fig. 2, when unencumbered by the limited affordances of engineering visualization software, the artist could use skillful

![Fig. 1. Early sketches showing (A) a comic strip-style representation of vortex flow details at discrete times, with ribbon-like traces through the "gutter" to more precisely depict the temporal evolution of the vortex cores, (B) the carousel prototype later derived from the visual conventions of (A). (© Peter Coppin)](http://direct.mit.edu/leon/article-pdf/doi/10.1162/leon_a_02009/1950836/leon_a_02009.pdf by guest on 08 August 2021)
retouching, highlighting and compositing of the original data representations to visually separate vortex structures from the clutter, while indicating their overlap and continuity. Theory suggested strategies not exposed by artistic influences alone, e.g., the decision to render change-variation between events (Fig. 2, Rings 2–3) was informed by the idea that perceptual systems evolved to detect environmental change-variation [17].

A limiting step was, of course, the impracticality of relying on hand-retouched images in a situation that requires rapidity and repetition, which led to the recruitment of a BSL/Pal graduate student conversant in both engineering and art who used computer graphics (CG) and computer-vision motion-tracking techniques to reproduce the illustrative styles and techniques in a data-driven way [18]. The result was not only an automated channel for producing visualizations and probing them interactively in real time but also an effective vehicle for exploring artistic possibilities (Fig. 3).

INTRODUCTION OF SOUND

Sound as a diagnostic technique has been used since antiquity. The entwined relationship of healthy physiological processes and pathological ones with the sounds of the body, and their parallel to music, has been acknowledged throughout history [19]. To us, key moments are Josephus Struthius’s transcription of bodily sounds into musical notations (1540), followed by Leopold Auenbrugger von Auenbrugg’s 1761 treatise on (externally provoked) percussion the body, and René Laënnec’s 1819 invention of the stethoscope for auscultation (listening to body sounds produced in cavities or by tissues). Interest in such aural diagnosis waned with the 1895 discovery of the X-ray but waxed again in the 1950s with the development of practical medical ultrasound techniques.

Doppler ultrasound (DUS), applied to blood-flow imaging, allows identification of areas of disturbed flow by distinguishing the changes in sound, with each type of sound corresponding to a particular flow pattern, depending on the vessel geometry (branching, curvature, etc.). DUS signals are inherently bimodal: The human-audible signal is a direct result of the Doppler shifts of the moving red blood cells, which are converted to velocities and displayed, concurrently, as a spectrogram [20].

BSLs earliest attempts at adding sound to an image was to literally mimic DUS acquisitions from CFD data, as a teaching tool intended to help medical students and imaging technologists learn how to associate DUS sound characteristics with CFD-visualized flow patterns [21]. During this time, visual artist Javiera Tejerina-Risso approached BSL for some of its patient and simulated images, and the result was the project True Blood, consisting of an installation of video monitors showing blood-flow visualizations synchronized organically with the rhythmic sound of sea waves [22]. Tejerina-Risso’s artistic gaze, distanced from that of the clinic, led to a stunning and suggestive result that managed to convey the phenomenon of pulsating blood in a truly visceral way. This successful artistic approach to representing clinical
By the mid-2010s, research from the BS l had shown that however, due to the intricacy of the sonification process, soundscapes emerged from the same original source [24]; fied data from a carotid artery CFD model, associating a specific exploit generated a soundscape based on raw velocity vector ing. The intent was to give a sense of the actuality of flow in-and a sound artist who had previously sonified protein fold- ing. They were accurate but devoid of any evocative energy. data made evident the lack of range of our visualizations: along with lack of funding, the project was put on hold.

**BIMODAL REPRESENTATION**

By the mid-2010s, research from the BS l had shown that high-frequency flow instabilities might be the rule rather than the exception for cerebral aneurysms [25], and that sequential visual representations alone would not serve to discriminate intricate flow details from one case to another without sacrificing the depiction of overall gross flow pat- terns. Recognizing the ear’s ability to discriminate frequency content better than the eye, we elected to pursue bimodal representations “to augment the visualization by permitting a user to visually concentrate on one field, while listening to the other” [26].

The precursor of sonifying cerebral aneurysm data was the intraoperative recording of blood flowing through a cerebral aneurysm by neurosurgeon and biophysicist Gary Ferguson in 1970 [27]. His study, based on historical applications of auscultation [28], took the concept one step closer to the source, by listening to and recording the sounds, known clinically as “bruits,” through a microphone placed directly onto the aneurysm during open-skull surgery. Four decades later, the observation of visual similarities between velocity-time traces from direct numerical simulations of aneurysm turbulence [29] and the signals recorded by Ferguson ulti- mately led to our current project, which aimed at merging a sound designer’s interpretation with medical simulations and the trained clinical eye.

Toward this end, and as part of PAL’s broader research in inclusive design and auditory displays [30], an electroacous-ician doing graduate work in drama and performance studies was tasked with the challenge of “scoring” BS l’s flow visualizations as one might score a film. Consistent with the caroussel’s focus on identifying the evolution of critical vor- tices, our choice of sonic aesthetics was aimed at creating a sonic “caricature” of blood flow, by which we mean generat- ing a soundscape built upon fluid sounds that intuitively con- note turbulent (high-frequency fluctuating) versus laminar (smooth, ordered) flows. We eventually settled on “windy” and “bubbly” sounds, providing an intuitive and evocative complement to the visualizations [31].

While these sonifications were decidedly not data driven, the synthesizer patches upon which they were based were intentionally designed to be driven by adjustable parameters that could conceivably be mapped to fluid mechanical vari-ables. That challenge was taken up by an engineering mas- ter’s student (and classically trained pianist), who integrated spectral analysis of the CFD velocity data into an interactive prototype linking open-source flow visualization and audio synthesis software [32], allowing implementation and explo- ration of various sonic prototypes [33] concomitantly with the flow patterns that were driving them (Color Plate D, bot- tom) [34]. To evaluate the ability of these “sonic caricatures” to maintain the nuances of the underlying CFD “signals,” we performed a preliminary user study that demonstrated an improved ability to sort aneurysm cases by flow complexity using sound versus conventional engineering visualizations alone [35].

Most recently, this work came full circle when a BSl post-doctoral fellow [36] used the insights from spectrograms to isolate and caricature high-frequency vortical structures from a complex cerebrovascular flow in order to visually highlight intermittent high-frequency vortex-shedding phe- nomena (Fig. 4) [37].

**CONCLUSIONS**

This case study outlines a path taken over the last 15 years by the BSL. Since the initiation of a structured collaboration with PAL, projects have built upon experience in CFD visual- ization integrated with the skill and expertise of cognitive scientists, designers and visual and sound artists, with the goal of informing a clinician of rapid flow changes while giving a sense of the space and context within the blood vessel. In this new pursuit, we were “careful to maintain or renegoti- ate links with everyday listening habits & cultural listening experiences” [38], along with taking inspiration from artistic explorations of body sounds [39].

This collaboration afforded an environment where in- formed artists could freely express their interpretation of patient data alongside scientists with an understanding and appreciation of the arts. The co-supervision of students, chosen for their multidisciplinary backgrounds, has been an in- tegral part of the process of generating knowledge, while the creative process was guided and encouraged by the two lab directors. This collaborative design spiral has continued with the recent recruitment of an engineering master’s student/ musician who developed an interest in psychophysics and human factors engineering during his undergraduate years [40].

We should note that the aim of this art-science collabora- tion is not the production of artworks, although such may be a fortuitous by-product (e.g. Fig. 3). We hope, however, that, like the artistic collaboration that seeded BS l’s original interest in sonification, our work may inspire other artists and future artworks. Finally, we must emphasize that the BSL/PAL collaboration is not a one-way street. Our collabor- ative efforts in sonification emerged out of PAL’s interest in improving the accessibility of charts and graphs for blind and low-vision learners [41], who, as PAL students, helped us counteract our visual fixations. For example, what began as creating auditory display analogs of foveal and peripheral vi- sion became the use of binaural audio to simulate being sur- rounded by auditory cues from different locations of a virtual...
ground plane, wherein a user navigating the display could be keenly aware of nearby data, but alert to directional cues provided by distant data [42], an idea that was later adapted to aneurysm CFD data [43]. Conversely, the constraints of the carousel have forced us to think about ways of mapping 3D structures onto planes, and such “cartographic” approaches currently being explored by the BSL have paralleled, and fed back into, PAL’s own explorations of flat-mapping and skewed perspectives to understand how blind and low-vision individuals mentally construct maps of the 3D world. Such cross-pollination is a prime example of the benefits of seemingly dissimilar disciplines working together in a collaborative manner.

Acknowledgments

We are grateful to the artists and students who have contributed, directly or indirectly, to the evolution of these ideas and works, for the financial support of the Ontario Research Fund’s Centre for Innovation in Information Visualization and Data Driven Design, and to the Natural Sciences and Engineering and Social Sciences and Humanities Research Councils of Canada. Finally, we thank Silvia Casini and Shiralee Saul for their encouragement and editorial advice.

2 Fatty plaques in artery walls, whose rupture ultimately causes most heart attacks and strokes.
3 Saccular outpouchings of arteries in the brain, thought to occur in 1/30 adults, whose rupture causes death or severe disability in the majority of cases.
13 McCloud’s work became a boundary object for bridging BSLs and PAL’s disciplinary worlds and establishing a kind of protoframework to describe the properties of representations. Other such boundary objects, already familiar to all authors, included Marcel Duchamp’s Nude Descending a Staircase, No. 2, Constantin Brancusi’s Bird in Space and numerous works of Umberto Boccioni, which served as touchstones for discussing static representations of motion.
20 In the next section, the spectrogram will be seen to become a kind of nexus for our bimodal representations.


34 This intentionally parallels the approach we described in going from “one-off” artistic renderings to an interactive CG tool for exploring aesthetic prototypes in visualizations.


36 Thangam Natarajan, also an accomplished illustrator who created the explanatory illustrations and animations for BSL/PALs entry to the 2018 National Science Foundation Vizzies competition (see “Brain Aneurysms and Blood Flow Dynamics”: https://youtu.be/ncAW0WoHdfl [accessed 20 May 2020]).


40 Located in a Department of Mechanical and Industrial Engineering, BSL benefits precisely such interdisciplinary crosstalk.

41 And, more generally, for inclusive design.


Manuscript received 22 September 2019.

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COLOR PLATE D: NARCISSUS AND ECHO: REFLECTIONS ON AN ART-SCIENCE COLLABORATION

(top) Visualizations of an aneurysm CFD dataset depicting blood-flow patterns from a single instant in time. From left to right, visual conventions evolve from strictly engineering (vectors, contours) to more intuitive particle pathlines to clinical “slipstream” benchtop experiments to, finally, clinical angiography [44]. (© Biomedical Simulation Lab)

(bottom) Screenshot from interactive bimodal prototype [47]. Main screen at left: conventional pathline visualization of aneurysm flow patterns; small sphere indicates (adjustable) size and location of sample volume, from which sonifications were generated. Bottom right: velocity vs. time “signal” from sample volume (here showing evident high-frequency fluctuations), which undergo moving-window Fourier transforms into their component frequencies over time, visually displayed as spectrogram (top right). Component frequencies drive banks of pitched oscillators and tuned resonance filters. (© Biomedical Simulation Lab and Perceptual Artifacts Lab) (See the article in this issue by Steinman, Coppin and Steinman.)