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Virtual Reality in Medicine: A Personal Perspective

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***Abstract*:** This personal perspective is an attempt to look at the role and impact of virtual reality (VR) as related to medicine and medical practice over the past 10-15 years. A similar treatise was recently published (Robb, 2002) in much shorter form. This more complete version is still not intended to be, nor can it be, fully comprehensive and inclusive of all developments or viewpoints. It is primarily based on the author's experience and opinion. Although such a review begs for many references to published works, that too is eschewed in the interest of preserving, for better or worse, the single view of the author in this article. Only seven references are included which contain copious other references to much of the material touched upon in this essay. To the extent that one can learn from history, this synopsis will also fall short, not so much due to lack of confirming references, but rather because the impact of VR in medicine has been an evolutionary culmination of digression and progression that has resulted in some success and useful contributions but also some wasted time and resources.

***Keywords*:** virtual reality, medical imaging, interactive visualization, procedure validation.

1. Introduction

Facts are in evidence that in the past 15 years or so, there has been remarkable intrusion by advanced technology into the world of medicine and healthcare, including virtual reality technology. This treatise will summarize but a few of the more obvious and egregious pitfalls and only some of the generally acclaimed progress of VR in medicine during the past 15 years. These are listed in Table 1.

Table 1. Some problems and progress of VR in medicine.

Problems	Progress
wire frame models	surface and volume rendering
primitive geometry-"cartoons"	true anatomic volume scanning
rigid models only	deformable models
artificial surfaces	photo-realistic texture mapping
high latency	rapid computing-interactivity
2-D display only	high-resolution 3-D display
no tactile or other senses	haptic and aural devices
difficult image segmentation	image registration/fusion
artificial intelligence	augmented/mixed reality
no "Killer App"	virtual endoscopy, surgery planning
crude robots	high precision robots
magnetic trackers, tethered	untethered optical trackers
poor communication	education/training, telemedicine
no software toolkits	comprehensive software
lack of standards	emerging standards
lack of validation	improving validation

VR has a relatively short history (Burdea and Coiffet, 1994). One reasonable starting point coincides in the early 1960s with the development of the "Sensorama Simulator". This device placed the user in a surrounding visual and audio field to provoke a sense of immersion in the scene. The device was marginally successful as an oddity in the entertainment industry. More significant and useful developments followed this nascent stage. To mention a few, the development of the first head-mounted display in 1966, and in the early 1970s the development of high resolution screens for generating realistic scenes in flight simulation. The military rapidly adapted this technology in flight simulators, developing flight helmets and other interactive simulators to train pilots and other military personnel. A great amount of this work was unpublished. Other contributions to VR came in the early 1980s with the development of LCD-based head-mounted displays and in 1982 with the first VR system, called VIVED or "Virtual Visualization Environmental Display". This system consisted of a mini-computer, a graphics system and a magnetic non-contact tracker. Feedback devices also began to appear in the 1980s, including the first sensory gloves. In the late 1980s, another system called VIEW for "Virtual Interface Environment Workstation" was developed incorporating 3-D virtual sound and some of the very first surface renderings instead of wire frame graphics.

2. Medical Virtual Reality

Medical VR began in the very late 1980s (Akay and Marsh, 2001). In 1989, the first simulated surgery procedure for doing tendon transplants was published. In 1991, an abdominal surgery simulator was reported and, in 1993, detailed graphics of highly realistic images of the human torso, including deformable models, was published. The advent of the Visible Human Dataset from the National Library of Medicine in 1994 generated a large number of efforts to produce more realistic simulations of a variety of medical procedures. A hysteroscopy simulator using haptics was developed and published in 1995. Virtual endoscopy had its beginnings in the middle 1990s with simultaneous developments by several groups. By the late 1990s, a wide array of VR devices and systems were being developed for and used in medicine. Haptic input-output devices, tracking and navigation instruments, and high resolution head-mounted displays permit trainers and surgeons to perform highly realistic surgical simulations and rehearsals. More recently, incorporation of realistic physical properties into deformable models, ultra-high resolution displays, more sensitive haptic devices and intelligent mapping of physiological properties onto anatomy have moved virtual reality into the mainstream of medical technology research, and useful clinical applications have begun to appear (Satava, 1998).

Interactive visualization and virtual reality technology have opened new realms in the practice of medicine. Virtual reality refers to a human-computer interface that facilitates highly interactive visualization and control of computer generated 3-D scenes and their related components with sufficient detail and speed so as to evoke sensorial experience similar to that of real experience. VR technology permits computed 3-D and 4-D images obtained from medical and biologic imaging systems to be faithfully transformed into patient specific anatomic models, with physical and functional properties added as appropriate, providing interaction with and manipulation of the realistic models with intuitive immediacy similar to and sometimes indistinguishable from that of real objects, all employed in specific clinical tasks and applications. Figure 1 illustrates this paradigm for deriving clinical applications from patient specific body scans. In medical VR, the viewer can "enter" the body to take up any viewpoint, anatomic objects can be dynamic - either in response to viewer actions or to illustrate normal or abnormal function - and other senses can be synergistically engaged, such as touch and hearing (or even smell) to enrich the simulation. Applications extend across a vast range of scale from individual molecules and cells through the varieties of tissue to organs and organ systems, including functional attributes of these systems, such as biophysical and physiological properties (Robb, 2000). Medical applications include anatomy instruction, enhanced diagnosis, and treatment planning, rehearsal and execution. The greatest potential for revolutionary innovation in the teaching and practice of medicine and biology lies in dynamic, fully immersive, multisensory fusion of real and virtual information data streams. Although this technology is still being refined, vastly increased computational capabilities have facilitated major advances, and there are several practical applications involving varying levels of interactivity, immersion and sensory experiences that are now possible (IEEE, 2001). These applications will have a significant impact on medicine and biology now and in the near future. These applications require an intimate and immediate union of patient-specific images and models with other real-world, real-time data. It may well be that the ultimate value of VR in medicine will derive more from the sensory enhancement or augmentation of real experience than from the simulation of normally-sensed reality. This variant of VR is often referred to as AR (Augmented Reality) or sometimes MR (Mixed Reality).

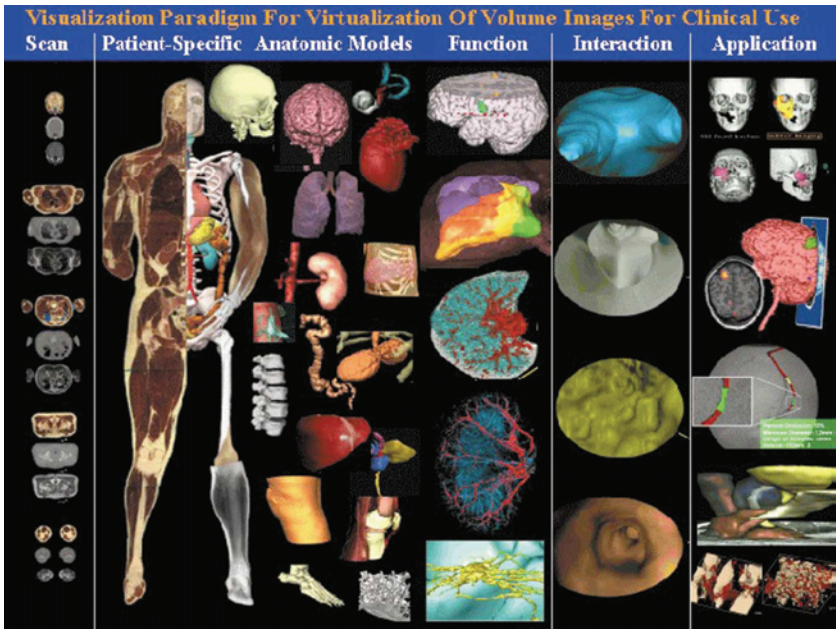

Fig. 1. Visualization paradigm for virtualization (computer modeling) of advanced high spatial and temporal resolution volume images of the body for clinical applications. Future scanning systems will provide image data for every region of the body, ranging in size from cells to organs. Functional properties and physical characteristics will be fused with these anatomic and micro structures to provide rapid and accurate analysis of structure to function relationships, including expression of cell function at the organ level, connecting specific micro-cellular level mechanisms and/or abnormalities with specific diseases and malfunctions at the macro-organ level. Such capabilities will provide synchronous detection, differentiation and treatment of disease that will become the evolutionary successor of current image-guided diagnosis and therapy.

In spite of numerous "fits and starts", progress has been sufficient to deploy VR technology in the operating or procedure room to provide the physician or surgeon with on-line, intra-operative access to and viewing of 5-D volume images of the anatomic regions of interest, along with associated physiological functions, all translated faithfully to the patient on the procedure table. Pre-operative volume image data and models can be fused with real-time data in the procedure room to provide enhanced visualizations of dynamic functional processes as well as anatomy, to make on-line measurements and generally to manipulate, control and guide interventional procedures (Robb, 2001). Accurate tracking devices for reliable interactive navigation in such procedures have only recently become available. In the past, magnetic trackers were seriously compromised by the "unfriendly" metallic environment in the procedure room, and often required the physician to be tethered to the device. Free-standing optical and very recent metal-immune magnetic tracking/navigation systems are now providing working solutions. Not withstanding the pitfalls, current VR-based capabilities have largely dispelled the formative notion that virtual reality must include three inseparable components, namely 1) immersion, 2) interaction and 3) imagination. Participants in modern VR environments no longer need to "suspend disbelief" to make VR useful. Immersion and interaction are readily achieved by advanced technology which render the simulations and environments so realistic and responsive as to minimize or negate the need for imagination or conscious effort to suspend disbelief. VR techniques have also evolved to a three-fold stratification of types. First, simulated reality which involves an imitation or a model of real objects and procedures. Examples of simulated reality in medicine are virtual endoscopy and virtual surgery planning (see Fig. 2). The second stratification is augmented reality, which is a fusion of simulated and real time data. Image guided surgery and computer-aided interventions are examples of augmented reality (see Fig. 3). Fully synthetic reality refers to an optimized, totally artificial, yet absolutely faithful, environment and procedures and tools that replace or significantly augment actual procedures. Examples of optimized synthetic reality are telepresence surgery and robot manipulator performers (see Fig. 4).

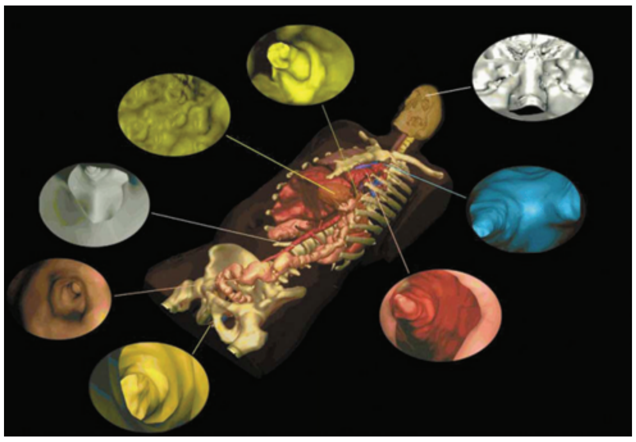

Fig. 2. Virtual endoscopic views within various anatomic structures within the body. Such views can be obtained for any region for the body from rapid 3-D volume scans.

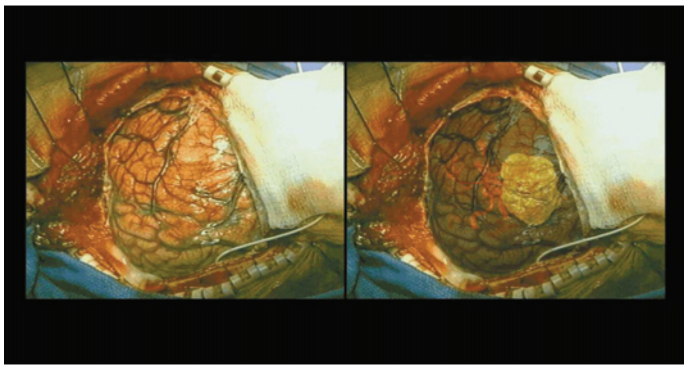

Fig. 3. Augmented reality wherein live video image of craniotomy (left) are registered and fused with computed 3-D images of tumor and cerebral vessels during neurosurgery. Such visualizations provide useful navigation and tumor targeting and accurate cytoreduction margins during an operation.

Fig. 4. Synthetic reality allows surgery to be realistically planned, rehearsed and/or remotely conducted using highly interactive visualization, haptic and robotic controls, such as is possible with this two-handed haptic and 3-D visualization system (courtesy of Dr. Naoki Suzuki, Jikei University, Tokyo).

3. Evolution of Virtual Anatomy and Functions

Over the past decade, a taxonomy of generations of virtual anatomy and functions has also evolved, marking at least five generations, as shown in Table 2.

Table 2. Taxonomy of generations of virtual anatomy and functions.

Generation	Properties	Examples
1	Geometry	3-D organs, body shapes
2	Elasticity	Tissue deformations, kinematics
3	Physiology	Fluid flows, muscle dynamics
4	Microanatomy Cells	Organelles, neurovascular
5	Biochemistry	Endocrine, immune system

The first generation of VR anatomy actually started in the 1960s and 70s, involving 3-D geometric shape representation of body and organs and other anatomy. This generation contributed to an early major pitfall in VR, at least in medicine. Wire frame drawings and rigid modules were "neat", but not really useful. Often oversimplified geometries were used to represent even complex body shapes. To compound the problem, the models were displayed on low-resolution 2-D displays. The hype surrounding artificial intelligence and expert systems in the 1960s and 70s also mislead many who looked to this "new science" to make up for the shortcomings of simplistic biologic models. It was the wrong solution to the wrong problem. The second generation added more sophistication to these models, providing elastic properties, which permitted tissue deformations and kinematics. Initially this was too crude for medical applications, but these capabilities became sufficiently realistic to be useful in the late 1980s and early 1990s. This was progress. Then physiology and even more complex physical properties were added to the simulations and anatomic models to more accurately depict structure and function, providing realistic and useful simulations of fluid flows and muscle dynamics, for example. High resolution, high performance graphic displays, along with true volume rendering, stereoscopic and immersive display formats, significantly advanced the usefulness of these higher order models. More recently, micro-anatomy models and cellular mechanics simulations have been possible with the advent of 3-D microscopic imaging systems in the 1990s (e.g., confocal microscopy and optical coherence tomography). Highly detailed simulations for study of cells and organelles and other microstructures and their functions have been developed (see Fig. 5). This

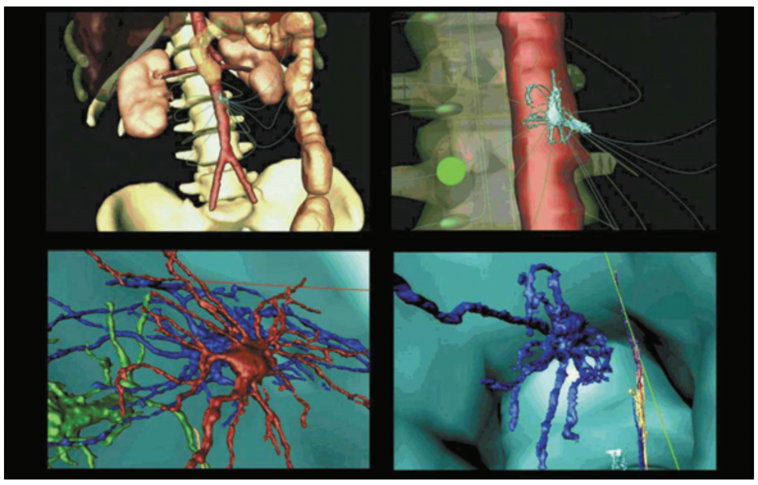

Fig. 5. Synthesis of cell models into gross anatomic framework by using Visible Human Male torso model. Upper left panel shows gross anatomy of spine and dorsal root at centimeter scale. Upper right panel shows magnified view of synthesized conductance pathway through dorsal root toward mesenteric ganglia. Lower panels show two groups of neurons within ganglia at micrometer scale. The individual neurons are modeled and rendered from confocal microscope data, just as macrostructures (e.g., the brain) are produced from computed tomography or magnetic resonance imaging scans. Virtual endoscopic fly-throughs along the conduction pathways can be produced, beginning at the gross anatomy level for spatial context, proceeding to finer and finer resolutions through magnification of field of view, and ending in virtual exploration within single cells.

represents very exciting progress. The future generation, the direction where virtual anatomy and function must eventually go, is to accurately represent in simulations biochemistry and metabolic functions at the molecular level. Such capabilities will permit study and understanding of fundamental biologic processes and systems, such as the endocrine and immune systems. We have not yet reached this stage of sophistication.

4. Pitfalls and Progress

Arguably, one of the greatest pitfalls experienced by researchers and practitioners in medical VR early in the past decade or so has been the relative isolation of workers in the field, and lack of communication among them. Another pitfall was the false notion, at least originally, that sufficiently realistic simulations without validation could augment medical procedures in ways that would be acceptable to physicians. Much work was done in the early days of medical VR with unrealistic models based on analytical geometry rather than true anatomical geometry, with artificial textures applied and no physical properties included. Even though such primitive efforts could be expected at the beginning, they were often promoted as useful without validation for way too long, to the detriment of the field. Because of such fallacious efforts, VR in medicine became unfairly stereotyped as "science fiction" - a waste of time in terms of making any positive contribution to the practice of medicine.

However, as the years have marched on, more and more reports on practical applications and careful evaluations of VR methods and devices in medicine have penetrated the scene. This author believes this has been a good thing, rendering the field more inclusive of clinicians - an important goal that has become marginalized. Scientists and engineers can occupy hours and days sharing their theories and gadgets, but dialogue with physicians is eventually essential if these are ever to be useful. Innovative technology and clever ideas are still an important part of the VR research and development, but the applications "promised" for several years are now being delivered - a welcome trend.

In the early 1990s, computer graphics played a large part in the VR publications, and there were virtually no clinical applications. Presentations consisted largely of innovative VR tools and how they might be used clinically, but no real bridges were built. Descriptions of software packages for producing 3-D visualizations and renderings were common. Although the potential was obvious, no "Killer App" had yet emerged in published reports. This lack of a validated, clinically useful application insured that progress toward a realization of the promise of VR in medicine would languish for a period of time, in spite of a continuing stream of "neat new stuff". In the mid 1990s, a wider variety of VR technologies and approaches began to emerge, including working systems that showed real promise in clinical applications. For example, surgery training, planning and rehearsal systems, rehabilitation applications and virtual endoscopy were potentially valuable VR-based procedures and tools that were beginning to have a measurable impact on the practice of medicine. "Killer Apps" were on their way. The published themes symbolized the advances in development of VR in medicine that were being made in the field, and many papers were presented with proven VR technology and clinical applications, including immersive displays, haptics, robotics, high precision manipulators, telemedicine, telepathology, virtual biopsy and augmented reality in the operating room. This trend migrated moderately away from the original theme of cutting edge science only. Again, this author contends this is good, logical and should continue on balance. By the year 2000, papers were appearing on multidimensional approaches, biointelligence, advanced deformations of models, data fusion, realistic mapping of structure and function, all established the meeting again as a forum for exposition of state-of-the-art technology and its promise in medicine. A retrospective look at the field, such as this, also tempts a prospective look at the future of virtual reality in medicine. The present overview finds itself in the saddle of these two perspectives.

A significant contributor to pitfalls and progress in medical VR over the last decade has been developments (or not) in medical imaging. The field of medical imaging enjoyed continued improvements in resolution, speed and differential clinical applications in the past 20 years. However, issues of image latency, interactivity and validation have proven challenging. The speed of image acquisition and computation has almost followed Moores Law (doubling of performance/output every 18 months) over the last decade. The amount of detail that can now be presented at interactive rates, even near real-time rates, is several-fold higher than that available in 1990. There has been similar improvement in the photo-realistic quality of the images used in simulations and augmented reality scenarios and in the sensory responsiveness and interactivity of the systems. Even so, this increase does not obey Moore's formula. Improvement has often been slow and fraught with difficulties. Similarly, although there has been great progress in data processing, e.g., multimodality registration, volume rendering and quantitative measurement, image segmentation and classification is still the Achilles heel in achieving practical routine use of medical images. Even though medical images have improved significantly in quality, they are still relatively "noisy" in terms of absolute and reproducible quantitative representation of bodily tissue properties, making methods for automatic, rapid and reproducible segmentation of desired features from medical image scans very difficult. There are some niche successes for certain algorithms, modalities and tissue types, but the "Killer App" in image segmentation has yet to be developed. When it is, Moore's Law may well be applicable to the rate of progress that will ensue.

5. Needs and Solutions

What is needed to avoid some of the pitfalls and blind alleys that have occurred in the past is a concerted effort on due diligence. The needs and requirements for augmenting or replacing certain clinical tasks with virtual reality technology needs more attention. Table 3 summarizes some guidelines for assessing needs and requirements of clinical procedures based on new technology.

Table 3. Guidelines for assessing needs and requirements for new clinical procedures.

• Based on real needs and expectations
• Clinically relevant, improves outcome
• Equipment/procedure safety
• Reliability and accuracy
• Ease of use, modularity, versatility
• Training, maintenance
• Standards and monitoring
• Validation and evaluation
• Cost vs. benefit

Proposed new methods should be based on real clinical needs and align with the expectations of physicians. The method(s) should be relevant to problems without satisfactory current solutions and that have distinct promise to improve outcomes. Safety of the equipment and procedures needs to be documented and demonstrated. Reliability, accuracy, ease of use, modularity and versatility of the method or procedure are all important factors to consider and document. Lack of comprehensive software toolkits for rapid prototyping and testing of VR methods, procedures and devices has impeded progress. Conversely, recent availability of such resources has significantly empowered the field and moved it forward. One must consider several practical issues commonly associated with new methodology, including the training of new users and the maintenance of new systems and/or devices. Conformance to existing standards or development of new standards is often crucial to success. Standards in VR have been slow to develop, but emerging conventions (e.g., VRML) are promising. Validation and evaluation are critical, as is careful assessment of cost versus benefit. Without question, one of the greatest pitfalls and inhibitors to reduction to practice and routine use of new methods and technologies involving imaging and virtual reality in medicine has been the lack of adequate scientific and clinical validation. The general approach to validation that scientists routinely take is a necessary but not sufficient first step, involving a sequence of mathematical simulations, phantom studies and testing on synthetic data derived from real data. Such evaluation can quantitatively characterize the performance and error margins of a new method. Such results should then be compared to ground truth or gold standards, if available, and multiple trials and comparisons conducted with existing standard methods targeted for replacement.

In addition to this scientific validation, scientists must interact with physicians who are expert in the specific clinical application, and consider an additional set of both objective and subjective factors for evaluating new methods. These are indicated in Table 4.

Table 4. Considerations for validating new technology for clinical applications.

Objective Factors	Subjective Factors
Sensitivity (resolution, detection, texture)	Physician Acceptance (familiarity, practicality, interactivity)
Specificity (localization, size, shape, type/classification)	Patient Acceptance (physical and psychological comfort)
Reproducibility (exam, conditions, image processing)	Computer vs. Human Performance (trust factor)
Artifacts (false positives, false negatives)	Insurance (third party payers)
Local Relationships (inclusion, adjacent vs. distant)	Research Studies (retrospective, long term)
Time (diagnosis, treatment)	Exclusivity Value (relative merits of unique features)
Cost (exam expense, throughput)	
Outcome (survival, morbidity, cure)	

The last item in Table 4, Exclusivity Value, involves observation and determination of an absolutely unique feature(s) of a new method that has compelling merit, i.e., no other method can produce the useful measure or effect. In such cases, efforts to get the new method into routine use should be greatly accelerated.

6. The Future

Current and future VR medical research will continue to focus in four main areas: 1) devices and instrumentation, 2) algorithm development, 3) modeling and simulation and 4) application prototyping. Many projects that have been initiated in the last decade will continue into the next decade, including virtual surgery, virtual endoscopy, image-guided diagnosis and treatment, virtual histology and pathology, robotics, manipulations, telepresence, performance assessment, etc. These are predicted to have an ever-increasing positive impact on medicine and healthcare. We will move toward the future successfully, the same as we have done in the past, through a synergistic combination of ideas and tools. Ideas alone are not worth much. Tools that have not been based on good ideas are not worth much, but good ideas and good tools together are the key to future success, and what a bright future it is. Table 5 indicates some of the developments that can be expected in the upcoming decade or two - progress toward realizing fully non-invasive real-time diagnosis and treatment made possible through VR-related technologies.

Table 5. The Future: Non-invasive real-time diagnosis and treatment.

• Multidimensional Dynamic Displays	Ultrahigh resolution, real-time holograms, dynamic immersion
• Image Gloves	Bare hand control, unconstrained gesturing
• Voice Control	Voice pick-up, tracking, recognition, synthesis
• Smart Rooms	Whole body location sensing/tracking
• Smart Clothes	Neural interfaces, bio-signal monitoring (EMG, EEG)
• High Performance Medical Robots	Intelligent, remotely programmable, micro-precision, teletherapy
• Smart Micro-Probes	Miniature devices inserted into body, controllable outside
• Dick Tracy Computers	Wristwatch super-computers, voice programming, real-time models
• Hospital Palmtops	Hand-held device for synchronous diagnosis and therapy

Multidimensional dynamic displays, image gloves for hands-free navigation in virtual space, and voice control will epitomize next generation Mixed Reality and greatly enhance medical procedures. Intelligent rooms and clothing that perform real-time tracking and monitoring will provide comprehensive and instantaneous input for informed, even automated, decision making. Special high precision robots remotely controllable will facilitate effective telemedicine and teletherapy. Moore's law will continue to apply to computers through at least the next decade, although an asymptote in computational performance may be approached within the next couple of decades (not really, DNA computers will maintain the slope!). Real-time model generation capabilities and programming computers in natural language will be possible, and super computers will, in fact, be micro or even nano computers, and used both outside and inside the body. Intelligent diagnostic and/or therapeutic probes will be introduced into the body and either pre-programmed or externally controlled to proceed to the anatomic site of interest - "seek and destroy" nanobots!). Eventually, we will have the kind of totally non-invasive real-time technology that we only see in Star Wars and Star Trek movies - devices that simultaneously perform diagnosis and treatment - sort of "one-stop shopping" (see Fig. 6). Satava's "Door to the Future" (Satava, 1998) may be such a device, but this author believes it will be much smaller than a door - more like a flashlight.

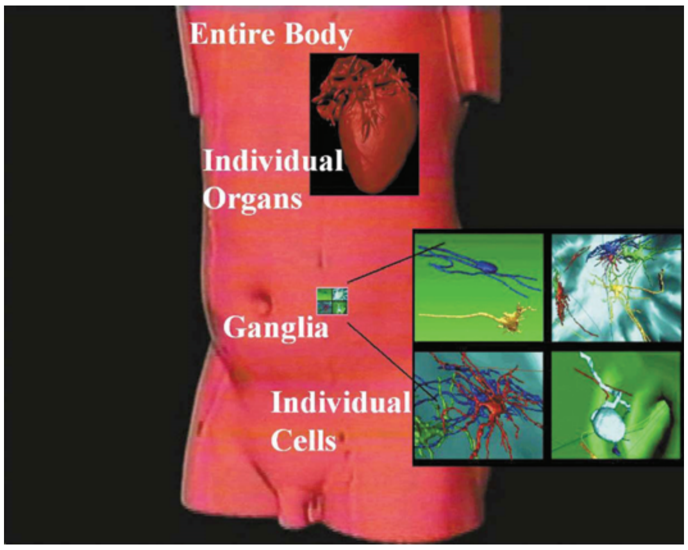

Fig. 6. Synthetic reality will permit rapid navigation and detailed exploration of all regions and objects in the body, from entire torso to individual organs to interstitial spaces to single cells, with instantaneous translocation, if desired, and appropriate scaling provided automatically or as selected by the navigator. Physiologic processes may be observed as well, at systemic, organ or cellular levels of detail. This mode of visualizing anatomy and physiology simultaneously over large differences in size may be referred to as "scale space stitching". Such capabilities will provide highly specific and synchronous diagnosis and therapy.

7. Conclusion

A couple of comments in closing. One of the pitfalls that any progressive age enjoys and suffers is that there are more false prophets than true pioneers (I firmly assert to be neither). We have to more expediently discern those really useful tasks from those that are destined to be useless, and not give heed to those voices that are "full of sound and fury, signifying nothing" (Shakespear's Macbeth). At any given moment in history, it may be challenging to discern the false prophet from the true pioneer. John Lawton said "The irony of the information age is that it has given new responsibility to uninformed opinion." I agree with this. We indeed are in the Age of Information, for better and for worse! One might even refer to it as the Age of Information Overload, so enormous is the magnitude and ready accessibility of the information. We are not well poised to take maximum advantage of the available information. To compensate, some short cuts are taken by the false prophets, resulting in deductions that are not substantiated by good, hard facts and experimentation. Again, that "V" word, validation. The cost of new technology should not be the driving nor limiting factor to future progress. It is important, but if the cost of developing and proving a new technology can be demonstrated with high probability to improve and impact positively healthcare and eventually reduce costs, then fortitude and foresight must prevail to make the required capital investment. There is ample room in the field for true pioneers and visionaries, indeed they are always needed, but there is also need for rationale practitioners who exercise common sense and are committed to reduction to practice. As Carl Popper said "I hold it to be morally wrong not to believe in reality". The degree to which virtual reality will ultimately be successful in improving healthcare and advancing the state-of-the-art in medicine will surely be commensurate with the degree to which we understand reality and are sensitive to it. The reason for this is simple: the object of medicine is the patient, and the patient is real.

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Author Profile

Dr. Richard A. Robb received the B.A. degree in Mathematics in 1965, the M.S. degree in Computer Science in 1968, and the Ph.D. degree in Computer Science and Biophysics in 1971, all from the University of Utah. He is currently the Scheller Professor in Medical Research, Professor of Biophysics and Professor of Computer Science in the Mayo Medical School and Mayo Graduate School. He is Associate Dean for Academic Affairs in the Mayo Graduate School. He is Director of the Mayo Biomedical Imaging Resource at Mayo Foundation/Clinic.

He has been involved in the development and application of computer systems for processing, analysis, and display of biomedical image data for over 30 years. He has been principal investigator on several research grants and has over 300 publications in the field of biomedical image processing, including 5 books and 30 book chapters. He has patented several inventions related to display, manipulation and analysis of computer-generated medical images. He has directed development of comprehensive software packages which provide advanced capabilities for multidimensional biomedical image visualization and analysis in basic research, clinical practice and education. These software packages are used in over 300 institutions around the world and have been licensed to several companies. His continuing interests include design and evaluation of new-generation paradigms for biomedical imaging and visualization systems of the future, particularly for medical treatment planning, minimally invasive clinical procedures, computer assisted surgery, medical education and basic science curricula. He was honored in 2000 with a Named Professorship by the Board of Trustees of Mayo Foundation/Clinic. He received the prestigious award in recognition of his many contributions to medical research and education over a span of 30 years. The endowed professorship, called the Scheller Professorship in Medical Research, cites him as a "respected leader, innovative scientist and caring educator".