Advanced networks and computing in healthcare

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ABSTRACT

As computing and network capabilities continue to rise, it becomes increasingly important to understand the varied applications for using them to provide healthcare. The objective of this review is to identify key characteristics and attributes of healthcare applications involving the use of advanced computing and communication technologies, drawing upon 45 research and development projects in telemedicine and other aspects of healthcare funded by the National Library of Medicine over the past 12 years. Only projects publishing in the professional literature were included in the review. Four projects did not publish beyond their final reports. In addition, the authors drew on their first-hand experience as project officers, reviewers and monitors of the work. Major themes in the corpus of work were identified, characterizing key attributes of advanced computing and network applications in healthcare. Advanced computing and network applications are relevant to a range of healthcare settings and specialties, but they are most appropriate for solving a narrower range of problems in each. Healthcare projects undertaken primarily to explore potential have also demonstrated effectiveness and depend on the quality of network service as much as bandwidth. Many applications are enabling, making it possible to provide service or conduct research that previously was not possible or to achieve outcomes in addition to those for which projects were undertaken. Most notable are advances in imaging and visualization, collaboration and sense of presence, and mobility in communication and information-resource use.

INTRODUCTION

Key themes or characteristics of advanced network and computing applications in healthcare are described in this article. They were identified through a retrospective review of National Library of Medicine (NLM) sponsored application research in three initiatives the NLM undertook as the lead government agency for high-performance computing in healthcare. Some applications were proofs of concept, while others examined costs, effectiveness, and other outcomes related to healthcare practice, education, and research. Nineteen projects were funded in the 1996–1999 Telemedicine Initiative, 15 in the 1998–2002 Next Generation Internet Initiative, and 11 in the 2003–2007 Scalable Information Infrastructure Initiative. Most entailed building communications infrastructure and required additional time to complete. Some received extended funding. They included a range of academic and clinical specialties and programs in telemedicine, scientific collaboration, medical education, and disaster management. Many of the cutting-edge applications in the earliest initiatives are now commonplace, while some of the latest ones, only recently concluded, still test technology limits.

The National Research Council Report,[1] Networking Health: Prescriptions for the Internet, underscored the potential of networks in health this way:

> Although health-related web sites garner considerable media attention, they represent only a small sampling of the ways in which the internet can be used in health, itself a large sector embracing healthcare, public health, health education, and biomedical research. Because the internet, in theory, can link all participants in the health community, it can be used to improve consumer access to health information and healthcare, to enhance clinical decision-making and improve health outcomes .... to improve the education of medical professionals, enhance public health surveillance, and facilitate biomedical research. In each of these domains, specific applications can be envisioned in which the internet is used to transfer text, graphics and video files ... control remote medical or experimental equipment; search for needed information; and support collaboration, in real time, among members of the health community. (p. 3)

Networking Health: Prescriptions for the Internet was very influential in spawning NLM's Next Generation Internet and Scalable Information Infrastructure Initiatives, just as NLM's earlier Telemedicine Initiative grew partially from earlier reports by the National Research Council and Institute of Medicine.[2 3] These NLM-sponsored reports raised questions about the technical network capabilities health applications demand, how they differ from those in other sectors, and what experiments and demonstrations are needed to learn about the requirements and benefits of health applications that the initiatives addressed. Ten themes concerning the use of advanced networks identified in project reviews are presented that provide a landscape view of network applications in healthcare today.

Diversity theme

One of the most striking aspects of NLM funded projects is their diversity. The numbers of health specialties and applications represented exceed the number of projects because of the work's interdisciplinary nature and because many projects developed multiple applications. Varied applications were anticipated in Networking Health: Prescriptions for the Internet, but the projects could have turned out otherwise. Their variety suggests that most areas of healthcare could benefit from using advanced networks.

Applications ranged from multimedia websites for providing and interlinking consumer health, personal health records, patient education, and clinical guidelines,[4–18] to the use of two-way interactive video, 3D imaging, and haptic (tactile) tools for telemedicine, surgical education, and implant modeling.[19–33] They included projects linking physicians to patients at the bedside[34–39]; connecting families from their homes to their babies and professional staff in neonatal intensive care units[40–43]; developing electronic medical record systems with multimedia capabilities, clinical decision support and patient monitoring and education facilities[44–50]; leveraging existing videoconferencing telemedicine infrastructure for continuing medical education[51]; deploying wireless technologies for disaster management[45 52–63]; and transmitting video of patients and other data from ambulances en route to emergency rooms.[64 65] Projects demonstrated the feasibility of a distributed database enabling medical records and imaging studies to be portable when patients relocate[66 67]; determined the viability of telemedicine network applications to reach underserved rural[68–78] and urban populations[79–81]; and established collaboratories allowing clinicians at diverse sites to conduct tumor boards[82–84], collaboratively research rare diseases[85 86], and work together in real time and to jointly control applications for developing databases and learning objects on human development.[87–89] They involved experimentation with acquiring, archiving, and sharing radiologic images,[90–96] using expert systems to generate alerts of drug interactions,[97 98] and testing real time 3D video's potential for providing remote consultation to paramedics.[99–101]

Projects included the medical specialties of anatomy and surgery,[19–33] cardiology,[68 69 102] dermatology,[72 73 76] embryology,[87 89] emergency medicine,[52–65 77 80 99–101] family practice medicine,[49 50 74 75 103 104] genomics,[105] geriatrics,[36 39] neonatology,[40–43] nephrology,[34 35] neurology,[85–88 92 105] oncology,[82–84] ophthalmology,[79 80] otolaryngology,[102] pediatrics,[68 69] pharmacology,[97 98] psychiatry,[70 71] and radiology.[9 31–33 66 67 90–96]

Specificity theme

Many aspects of healthcare do not need advanced networks. This theme does not contradict the first, since many routine health applications work over standard networks. But there are special healthcare problems where advanced networks become paramount. In one project, for instance, physicians were connected from their clinic and homes to a nursing facility to provide 24×7 coverage by videoconference. The technology was not needed for reporting usual medications and vital signs,[37] but became essential when patients' conditions changed dramatically or they fell.[36]

As image quality increases and technologies are used representing data in three dimensions, more advanced networks are required for asynchronous data transport and manipulation of large files.[28 90] Moreover, certain areas of remote routine care, such as echocardiography,[68 69] neurologic exams, and gait analysis require sufficient network capacity for real-time motion. Real-time video also is important in telepsychiatry,[70] emergency medicine,[99 100] and disaster management.[53 62] Video transmissions from ambulances allow physicians to assess patients and begin interventions immediately,[64 65] while those from disaster sites enable commanders to obtain accurate real-time data on the unfolding conditions.[53 62]

Quality theme

Network quality of service (QoS) is as important as bandwidth in healthcare. Although greater bandwidth reduces the probability of congestion, network capacity and QoS are not synonymous, since data still can be lost or corrupted. Bandwidth management is vital, however, even in disaster situations where mobile, low-capacity network technology with reduced power requirements is deployed[57 61] and where land lines may be down and cellular systems overwhelmed.[57] Codecs, methods of compressing video, can lower bandwidth requirements, but excessive compression reduces quality and introduces latency and jitter. Neurologic exams and echocardiogram interpretation[68 69] are examples where smooth motion is needed, and when haptic feedback is required for remote surgery, even less latency can be tolerated.[21] Quality of service also is important in non-life-threatening situations. Workflow interruptions and delayed communication can frustrate scientists and clinicians collaborating online.[82 83] Students observing surgeons doing virtual operations and feeling movement with haptic devices will not learn much if movement is delayed or erratic.[21]

Effectiveness theme

A sampling of project outcomes shows that advanced network applications in healthcare can be highly effective.

- Baby CareLink, a project connecting a neonatal intensive care unit by video to parent's homes and using a patient centric web interface with educational materials, demonstrated shorter stays, greater satisfaction, and earlier discharges. All babies in the project were discharged directly home, while 20% in a no-video control condition had to be discharged to community hospitals first.[40–42]
- A teledermatology project in rural areas where referral rates by primary care providers to dermatologists were inappropriately low because local specialists were lacking found that video and store and forward technologies to access distant specialists reversed the trend, improving care while reducing the number of in-person visits.[72]
- A project sending patient data, including real-time video transmission, while patients were in transport to the hospital demonstrated that the data were sufficient for physicians to identify patients having strokes and to begin interventions immediately upon arrival, halving treatment time.[64 65]
- A project developing technology for real-time 3D views of patients found that first responders made fewer errors and had greater confidence when physicians gave them advice in a 3D proxy condition than when it was given by 2D videoconferencing.[99 100]
- A project developing applications for disaster management demonstrated computer-based, mobile communication systems captured data just as well as paper-based systems with superior ability to monitor and track victims.[60]
- An ophthalmology telemedicine study demonstrated that digital imaging combined with remote consultation by video could be used for initial screening of eye disease.[79 80]
- Controlled studies of telepsychiatric counseling, tele-echocardiography, and telemedicine consultation of children with neuromuscular disorders demonstrated that outcomes were equivalent when these services were delivered in person or by telemedicine.[68–71] Moreover, there were significant reductions in time to render service and in costs.
- Studies involving the use of networks for immersive 3D imaging found that students who had successfully completed a standard anatomy lesson made further dramatic knowledge gains that continued over time because 3D visualizations enabled them to understand concepts that were only partially learned initially.[32]
- 3D embryo image data and animations showing development of organs over time were used to determine how certain organs develop and to clarify what constitutes normal and abnormal development.[87–89]

Advanced network applications have had additional indirect and unanticipated benefits. For example, a remote dermatology project found that patients felt they had a physician's undivided attention more in telemedicine consultations than those in person.[76] The project assessing videoconferencing for remote consultation with dialysis patients found they felt they had greater access to physicians who would otherwise visit the dialysis center less frequently.[35] A tumor board project found that distributing conference sessions over multiple sites allowed more staff attendence.[83] Some telemedicine studies also demonstrated time and cost savings for providers, patients, or both, and high levels of utilization and patient satisfaction due to increased access and convenience.[68 76]

Enabling theme

The network infrastructure established in most projects produced applications enabling other outcomes. For example, network connectivity enabled multicenter and multinational clinical trials for rare diseases where there usually are insufficient patients to study at any given location,[85 86] making it easier to pool data to increase reliability, confidence, and probability of clinical conclusions about the diseases. Advanced networking enabled physician access to archives of previous medical records and mammogram imaging studies carried out in cities from which patients had moved. The archives contributed to continuity of care and served as a teaching resource.[66] Networks also provided a way for embryology experts to collaborate across institutions to develop and annotate databases, create educational objects, and provide instruction to students at universities lacking faculty.[87]

NLM-funded telemedicine projects enabled entrée to previously underused healthcare services[72] that often required great effort and expense to access.[76] Some involved utilizing large statewide telemedicine networks and multiple services,[68–70 76–78] while others involved local[53 57 82 83] national,[20 66 87] and even international partnerships.[82 85 86] The varied projects funded in Iowa and Missouri demonstrated how advanced networks could extend access to healthcare in rural underserved areas,[68–70 76–78] and one project demonstrated how the technology could be used to extend healthcare to underserved urban populations.[79 80]

Many projects developed products or techniques that could be adopted elsewhere. For example, the Baby CareLink application could be replicated today using Skype or other free, low-bandwidth videoconferencing software. Three-dimensional anatomical viewers created for Visible Human and other data sets are online or exist as independent applications that can be adopted by others.[19 25] The open-source personal electronic-medical-record system,[18] real-time prescription-checking technology,[97 98] online annotation tools for digital mammography,[67] methods for electronically tagging and monitoring disaster victims,[60 61] creating colorized three-dimensional images from radiologic data for teaching and surgical planning,[28] and animations depicting embryo development[88] are other examples.

Imaging and visualization theme

Technologies for high-resolution image capture for diagnosis and volume rendering of 3D images from 2D scans have been available for a while, but advanced networks allow sharing and interacting with the data in real time from remote sites. Seamless, reliable image sharing over advanced networks was demonstrated in the project assembling cases from various sources for multisite tumor boards,[82] the project for multinational clinical trials enabling pooling data from around the world for meaningful analysis,[85 86] and the projects leveraging the Visible Human datasets of complete human male and female anatomy.[19 27] Other projects developed a large visual databases of human embryology[87] and radiology images.[90–94] Advanced networks made it possible to distribute and federate databases at different sites, eliminating the need for large, central repositories.[29 66]

Collaboration and sharing theme

Advanced networks can foster collaboration. Many projects were inherently collaborative, given the nature of the work and varied expertise required, and some were cross-institutional, not just interdepartmental. For example, Stanford University developed 3D anatomy and surgical simulation resources working with the University of Wisconsin at La Crosse[19–21] and later with schools in Canada and Australia. George Mason University's effort to develop an embryology visual database and related teaching resources included faculty and staff from the University of Illinois at Chicago, the Johns Hopkins University, the Oregon Health Sciences University, the Armed Forces Institute of Pathology, the Lawrence Livermore National Laboratory, and Eolas Technologies.[87 88] All projects concerning disaster management required working with first responders and public health departments.[55 58] Some projects supported existing collaborations, such as tumor boards, to eliminate travel time and cost,[83] while others were new collaborations to develop information resources or applications.[87 96] Projects created new collaboration tools and adapted existing ones.[31 32 87 88]

Presence theme

Sense of presence and telepresence can be dramatically extended by advanced networks, especially in telemedicine where real-time video allows physicians and patients to interact remotely. While patients may rate telemedicine and in-person consultations similarly[71] and feel they receive more attention in telemedicine consultations,[76] providers and patients may view a sense of presence differently. Providers may believe telemedicine consultations yield ample data, while patients may be concerned they were examined sufficiently.[35] Less obvious areas where sense of presence can be important include scientific collaboration,[87] distance learning,[20 32] and disaster management.[53] In many of these contexts, being able to simultaneously share tools and applications augments sense of presence, making interaction at a distance more like in person.

Many projects extended presence. Experts at diverse locations collaborating in real time were able to reach consensus segmenting embryo structures using mark-up tools that they could hand off virtually.[87] Similarly, surgeons and physicians can interact with 3D radiologic datasets in real time to reach consensus on appropriate treatments when visualization applications are combined with interactive video.[31] 3D visualizations created from 2D clinical data can also be streamed as video creating immersive environments for surgical planning and teaching,[32] and 3D video streams with head tracking allow physicians to move in relation to the screen and view patients from varied perspectives.[101] Video from cameras situated at disaster sites can be stitched together to provide operations managers more realistic views.[53] Haptic devices provide tactile feedback enabling medical modelers to fashion cranial implants with precise fit using stereolithography machines, by-passing the expensive, time-consuming steps of physical sculpting and mould making.[33]

Mobility theme

Several projects investigated nomadic network applications and the deployment of ad hoc networks, especially those researching emergency medicine and disaster management. An early telemedicine project multiplexed analog cell phones to send video of patients from ambulances to emergency rooms,[64] and disaster projects tested deployment of mini wireless ad hoc networks upon arrival at disaster scenes.[60 61] The latter also demonstrated video transmission from remote-controlled drones, transmission of information from monitoring devices placed on patients in the field,[61 62] and use of global positioning systems to identify locations of victims and first responders.[52 62] Mobility was a factor in projects monitoring unattended ambulatory patients in emergency rooms and those sending video wirelessly from handheld devices in clinics or from videoconferencing devices that could be wheeled into patient's rooms.[37 45 96]

Integration/accommodation theme

Devices for monitoring vital signs, triaging patients, and for providing haptic feedback had to be integrated into the developed applications.[32 60 61] Wireless networks and devices had to be integrated with wired ones,[37] and the capabilities and range of standard wireless networks sometimes had to be extended.[60 61 64] Software often had to be integrated instead of hardware, especially in projects linking multimedia information into medical records[44 46] and electronic medical records to online libraries.[103] Finally, integration had to be addressed at a social and organizational level so that the applications developed would fit into the normal workflow of health professionals.[55 83]

Many integration issues remain that are barriers to widespread adoption of many of the innovations developed and researched. Some are technology-related, but others are exogenous to the technology itself.[80 81] The so-called 'last mile' problem remains a factor in many contexts where network bandwidth and quality of service are available nearby but not at the point where it is needed. This problem is prevalent in rural and underserved areas that can especially benefit from networked delivery of healthcare and related information and education services, but it also occurs in settings relatively rich with network resources. Another technology problem is that many of the applications are still platform-dependent, requiring specific hardware, operating systems and levels of technology expertise. Further work is needed to make some applications turnkey systems.

Security is a problem that is, partially, technological but also due to policy and those administering it. All the telemedicine projects and those using databases and electronic medical records had to address security which was the focal point for several projects.[15–17 38 74] There were antagonisms between applications involving collaboration and security, since the former give access to networks the latter are intended to block. Investigators mentioned firewall problems and differing mindsets of those involved with collaboration and security, but these were usually not publicized, with some exceptions.[80 81] Collaboration tools need to be more secure, and network security tools need to better accommodate access, since security features can make applications more difficult and discourage use.[14]

Workflow integration is another problem with technology and non-technology aspects. Applications can disrupt work, especially if new and experimental. Refining applications to make them less platform-dependent, easier to use, and more turnkey will help, but the fact remains that any technology application, even when integrated into the work environment, will still require work to be done differently. Users should be involved in the refinement and workflow integration process, and trained appropriately. Similarly, interoperability is a hybrid technology/non-technology integration problem, especially in projects that employed electronic medical records. The varied systems have to have mechanisms for exchanging and sharing data, but users and developers need to agree on standards and have incentives for complying with them.

Perhaps the greatest non-technology barrier to adoption of network applications involves trust. For example, clinicians have issues concerning data integrity and transparency when distributed patient record systems are integrated.[104] Staff working with collaboration tools may dismiss or have relaxed attitudes about security, but those working with security may be too rigid. They need to work together to enable collaboration and outside network access in secure ways. Finally, there are legal, social, and economic concerns about telemedicine licensure, privacy, and reimbursement.[18 73 80] If a patient going out of state to receive care is not a problem, why is a physician coming virtually to a patient from out of state an issue? These problems are political, requiring various constituencies to agree on policy. They are not resolved by research.

CONCLUSION

Although many routine aspects of healthcare do not require advance networks, there are special problems in a range of healthcare specialties that require their use. Advanced network applications can directly and indirectly affect health outcomes. They improve ways the healthcare community can share resources and interact with patients, students, and each other by providing ways to distribute information, collaborate, and operate in a more mobile environment. They also present challenges to developers, end users, and network administrators because they often change how networks are managed and healthcare is provided. Advanced networks are not static, and neither are the needs of healthcare. Some of the cutting-edge applications funded under NLM's first Telemedicine Initiative are now commonplace, and improvements in wireless networks, optical networking, and tools for allocating bandwidth offer new research opportunities.

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