Telehealth on Advanced Networks

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Abstract

We address advanced Internet for complex telehealth applications by reviewing four hospital-based broadband telehealth projects and identifying common threads. These projects were conducted in Australia under a 6-year research project on broadband Internet applications. Each project addressed specific clinical needs and its development was guided by the clinicians involved. Each project was trialed in the field and evaluated against the initial requirements. The four projects covered remote management of a resuscitation team in a district hospital, remote guidance and interpretation of echocardiography, virtual-reality-based instructor–student surgical training, and postoperative outpatient consultations following pediatric surgery. Each was characterized by a high level of interpersonal communication, a high level of clinical expertise, and multiple participants. Each made use of multiple high-quality video and audio links and shared real-time access to clinical data. Four common threads were observed. Each application provided a high level of usability and task focus because the design and use of broadband capability was aimed directly to meet the clinicians' needs. Each used the media quality available over broadband to convey words, gestures, body movements, and facial expressions to support communication and a sense of presence among the participants. Each required a complex information space shared among the participants, including real-time access to stored patient data and real-time interactive access to the patients themselves. Finally, each application supported the social and organizational aspects of their healthcare focus, creating and maintaining relationships between the various participants, and this was done by placing the telehealth application into a wider functioning clinical context. These findings provide evidence for a significantly enhanced role for appropriate telemedicine systems running on advanced networks, in a wider range of clinical applications, more deeply integrated into healthcare systems.

Key words: *technology, telecommunications, telehealth, e-health, extreme environments, policy, telemedicine, telesurgery*

Introduction

Advanced networks, also known as next-generation Internet or next-generation networks, will provide quality-of-service-based network connections to ensure that the users get the network characteristics, for example, bandwidth and latency, that they have requested. These can be defined as "packet-based networks able to provide services including telecommunication services and able to make use of multiple broadband, quality-of-service (QoS)-enabled transport technologies and in which service-related functions are independent from underlying transport-related technologies."[1] Applications using an advanced network, therefore, can be designed for the intended purposes based on a known network service rather than being designed around the constraints of a slow or unpredictable network. Advanced networks such as Internet2 in the United States,[2] Trans Eurasia Information Network (TEIN2) in the Asia-Pacific region,[3] and the Centre for Networking Technologies for the Information Economy (CeNTIE) in Australia[4] are generally being operated as research networks.

The features of advanced networks can impact on telemedicine in a number of ways. The higher bandwidth can improve temporal and spatial resolution in video displays, providing a greater sense of presence, as well as providing several video channels for multiple simultaneous views. Improved quality of service permits telemedicine to be used to support time-critical procedures such as surgery and critical care.[5] While not a direct consequence of the use of advanced networks, improvements in user interfaces will be needed to ensure that this more complex technology does not adversely affect workflow for clinicians, or require extra staff to operate it. A telemedicine system incorporating a user-centric task-oriented user interface, running over an advanced network, comprises an "advanced telemedicine system."

In this article, we look at four telehealth research projects in which the applications have been designed for an advanced network. These range from pure teaching, through emergency and intensive care applications, to tertiary-level postoperative outpatient clinics. The application domains were defined by the clinicians who then worked with us to guide the development of research prototypes and conduct field trials in clinical settings. When the results of these field trials are brought together, we see patterns that illustrate our approach to conducting telehealth over the next generation of Internet.

While the CeNTIE project built a nationwide experimental advanced network and used it to support project development,[4] each of the projects described in this article was deployed on networks outside the CeNTIE network, in most cased leased from commercial suppliers.

Much of the research in advanced telemedicine systems has been focused on proof-of-concept and the results have been presented as demonstration events at conferences and clinical meetings. Examples include a teaching presentation of laparoscopic gynecological surgery between California and Australia,[6] surgical teaching sessions connecting Australia, Singapore, and Japan,[7] a California-wide surgical teaching case study,[8] and a series of live surgical presentations between Japan and Korea.[9] In this last article, the authors state that "high quality moving images are mandatory for surgical training and consultation." Clinical applications such as critical care have made little use of advanced networks and are still seen as emerging applications.[10]

In contrast, the four examples presented in this article were designed as prototypes for actual clinical situations. They were designed from user-led requirements analysis to target highly specific applications. They addressed complex clinical or teaching situations with high levels of human–human interaction and real-time interaction with multiple diverse data sets. They were deployed as research prototypes in their clinical settings and were evaluated in terms of the wider application domain in which they were embedded.

Materials and Methods

This article is an exploration of the implications for telehealth on advanced networks based on the findings from four specific projects. The "materials" for this article are therefore the projects themselves and their evaluations, especially those elements that are common across the four projects, and from which implications can be drawn for future applications on advanced networks. This will necessarily limit the details of the individual projects and their evaluations, and readers are encouraged to refer to the references for more detailed descriptions.

The four projects that form the observational basis of this article are summarized in *Table 1*, and each will be briefly described.

VIRTUAL CRITICAL CARE UNIT

Local hospitals outside the major cities often have staff with little experience in emergency care. The Virtual Critical Care Unit (ViCCU®)[11,12] provided expert guidance from a tertiary hospital to the resuscitation team at a small rural hospital. The remote specialist was able to guide the resuscitation team using high-quality video and audio together with vital signs information. A total of four cameras provided views of the room, the patient, a document pad, and close-ups using a mobile hand camera or head-mounted camera. The specialist could choose any two of these views for high-quality transmission. This transmission used Digital Video over IP[13] (a variant of Motion JPEG). Unlike standards such as H.264 or MPEG, this codec uses no interframe compression, minimizing latency, and producing broadcast quality images (720×520 pixels). The audio channel was sampled at 48 kHz, producing CD-quality sound. Communication was via leased fiber on a commercial network, and used approximately 70 Mbps bandwidth. The cameras, displays, and vital signs signals were transmitted and received with equipment mounted on a trolley that was placed at the foot of the patient's bed (*Figs. 1* and *2*). The design permitted the resuscitation team and the remote specialist to interact in precisely the same way as they would if the

Table 1. Summary of the Centre for Networking Technologies for the Information Economy Telehealth Systems

SYSTEM	APPLICATION DOMAIN	EVALUATION BASIS
Virtual Critical Care Unit (ViCCU®)	Emergency medicine	Clinical trial and long-term implementation
ECHONET	Intensive care	Clinical trial and long-term implementation
Collaborative surgical training	Surgical training	Demonstrations and controlled trial
Remote outpatient consultations	Outpatient pediatric consultation	Pilot trial in clinical setting

ViCCU®, Virtual Critical Care Unit.

Fig. 1. The Virtual Critical Care Unit peripheral node located in a resuscitation bay of a hospital emergency department.

specialist were physically present. This system underwent an 18-month clinical trial in 2003–2004, which was separately evaluated for clinical effectiveness[14] and for technical design.[15]

ECHONET

Tasmania is a small Australian state with limited specialist coverage outside of the capital city, particularly in echocardiography, which is an important tool in intensive care and emergency care. This system allowed the specialist on duty at the Royal Hobart Hospital to conduct an echocardiography examination on a patient at a regional hospital, thereby avoiding difficult and expensive patient transfer. The EchoCardiographic Healthcare Online Networking Expertise in Tasmania (ECHONET) system[16] is a mobile system that provides high-quality videoconferencing and simultaneous video data transmission from the patient's bedside (*Fig. 3*), using the same codec as the ViCCU® (see above). Two high-quality video channels (a camera plus an external input such as a computer or ultrasound scanner) could be sent from each site. It was also possible to initiate a three-way connection. It was designed to support a range of activities that included bedside Intensive Care Unit (ICU) consultations, grand rounds teaching, echocardiography, and formal teaching. All activations were user initiated (there was no on-site support) and a graphical user interface was designed to facilitate use by untrained staff. Three connected units were deployed: two in the ICUs of North West Regional Hospital (Burnie) and Royal Hobart Hospital, respectively, and one in the Cardiology Department of Royal Hobart Hospital. A 9-month clinical trial was conducted.

COLLABORATIVE VIRTUAL REALITY SURGICAL TRAINING

This work addressed the high level of interpersonal communication involved between instructor and student in teaching the surgical approach to a particular procedure and critiquing the student's understanding. This approach used virtual reality technology for conceptual learning rather than skills training and used shared access to three-dimensional anatomical models with visual, auditory, and haptic interaction simultaneously for both the instructor and student.[17] While student and instructor could each have both hands conceptually in a shared virtual world, they could individually be located in separate places and connected by the Internet. The purpose of this work was to shorten the early learning curve for surgical trainees prior to them attending specialist training courses, and in principle the trainees could complete this early instruction at their local place of work. Two versions of the system were produced. One used a soft-tissue case study (removal of the gallbladder) with the haptic interaction representing the tool–tissue interactions, and this was presented at meetings over intercontinental distances from Australia to North America (*Fig. 4*). The second used temporal bone surgery as its case study, with the haptic device representing a bone drill (*Fig. 5*). This system was trialed with 11 basic surgical trainees at a Temporal Bone Surgery course conducted in Melbourne, Australia and is currently being commercialized.[18–20] In addition to shared access to the data in the virtual world, the system provided a two-way high-quality video and audio link between the participants for face-to-face discussions.

Fig. 2. The Virtual Critical Care Unit specialist node.

REMOTE OUTPATIENT CONSULTATIONS

Complex surgery at a tertiary hospital can generate several years of outpatient follow-up, especially for pediatric surgery. Where the hospital has a large catchment, this can require days of travel for the patient and family. This project explored delivering those consultations at a local or regional hospital via a telehealth link. This system delivered whole-of-room telehealth using three static cameras for room coverage, several specific cameras to support patient examination, and shared tablet displays for interactive discussion of image, video, and radiology data (*Figs. 6* and *7*).[21,22] For communication, the system used commercially available hardware to support video over an IP network using MPEG-4. One camera was a self-contained unit that delivered a motion JPEG packet stream. A month-long pilot trial within the Royal Children's Hospital in Melbourne, Australia, conducted 44 outpatient consultations with a telehealth phase followed by a face-to-face phase. This trial was evaluated with observational and questionnaire data from the patients/family, the surgeons, and the clinic assistants.

Results

EVALUATION

All systems were trialed with end users (medical personnel) in appropriate clinical settings, and were evaluated by a variety of instruments that included log books, interviews, questionnaires, and task performance. One project (ViCCU®) was evaluated separately and independently for technical design[23] and clinical outcomes.[14] The various instruments used for evaluation are shown in *Table 2*.

The evaluation methodologies were chosen according to the anticipated outcomes of the respective trials; hence, it was not practical or possible to use common instruments. However, there was considerable pooling of resources for the evaluations, resulting in, for example, similar formats for instruments such as questionnaires.

The scope of this article was not to separately evaluate each project (these have been, or will be covered in further articles) but to examine, through a slightly less formal process, findings related to several or all of these projects. Such findings may be applicable to future telemedicine applications on advanced networks. The findings below have been based on a combination of questionnaires and interviews with participants in the projects.

The studies are not easily amenable to a formal meta-analysis, but the evaluations revealed a set of common themes in the systems' impacts, comprising:

- Usability and task focus
- Presence and media quality
- Working in a complex information space
- Social and organizational—creating and affecting working relationships

They will now be discussed in more detail as they relate to the application demonstrations.

USABILITY AND TASK FOCUS

Point of care telemedicine systems require a high degree of patient focus, since the telemedicine consultation occurs in the patient's presence, often while the treating physician is carrying out or

Fig. 3. An ECHONET unit being operated at the bedside of an intensive care unit patient.

supervising procedures for patient care. In designing our applications we interpreted this requirement in terms of:

- usability so that operating the system requires little mental effort
- preserving team-based work practices
- high media quality to mimic physical presence

All systems were designed around a specific application in an iterative, user-centric process, rather being developed in a technology-centric way. Once the clinicians were familiar with what the technology was capable of, they were free with suggestions which in most cases could be incorporated into the design, which was trialed. While increased usability made the systems conceptually simpler, the underlying technology usually became more complex.

For systems with multiple participants, the level of designed usability varied with each group of participants. The remote outpatient consultation system had two basic user groups: the clinicians (surgeons and clinic assistants) and the patients and families. While all clinicians received some training, this was of course not possible for patients and their families, but most of this second group found the system very easy to use.

PRESENCE AND MEDIA QUALITY

For the clinician, there are many advantages of a co-present, face-to-face interaction with a patient. There is the opportunity to engage

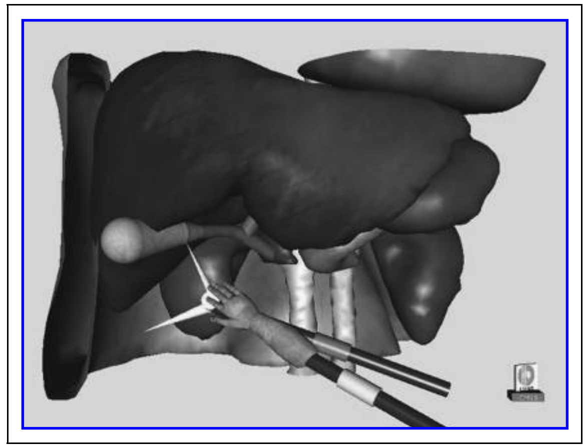

Fig. 4. Screen shot from the gallbladder surgical simulator.

in a multisensorial interaction with the patient and there are many cues that are difficult to convey via a video link. A clinician might engage with more than just the patient; the interaction might include the care team and the patient's family; sometimes all of these occur simultaneously. Apart from conveying clinical information and diagnosis based on observation of and interaction with the patient, the interaction builds up a sense of mutual trust between the participants, based on the quality of that interaction. The clinician builds up confidence in diagnosis and management, based on the quality of

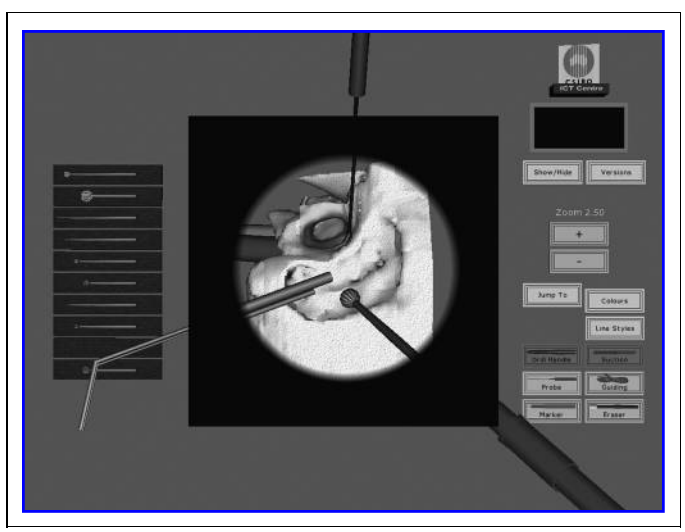

Fig. 5. Screen shot from the temporal bone drilling simulator.

Fig. 6. The remote outpatient consultations "patient" node.

information on which that management is based. Finally, of course, the clinician does not have to deal with technology in order to interact.

These factors have limited the use of telemedicine in point-of-care situations, especially in time-critical patient management. The strong sense of presence inherent in using advanced telemedicine systems (especially ViCCU®, ECHONET, and remote outpatient consultation) appears to overcome many of the objections to the use of telemedicine in critical care situations. It is important to note that the bandwidth required for a strong sense of presence is usually more than that required for a medical diagnosis, and this aspect of telemedicine is usually ignored when assessing its efficacy. So while the use of telemedicine obviously reduces the sense of presence, advanced telemedicine systems can restore this sense, lowering one of the barriers to the wider diffusion of telemedicine.

Fig. 7. The remote outpatient consultations specialist node. (Photograph courtesy Royal Children's Hospital, Melbourne)

All four applications involved performing over a distance a collaborative task that would normally be done with all participants co-located.

There was an expectation that high media quality would enhance the sense of presence among the participants. Presence is the subject of a number of studies outside of telemedicine, and several definitions exist. For example, Heeter[24] describes three aspects of presence:

- Physical presence: the sense of being in one place or environment.
- Social presence: the feeling of being connected to other people in the place or environment.
- Environmental presence: the extent to which the environment itself appears to know that you are there and reacts to you.

In the ViCCU® study, we focused on the "physical" definition of presence, and employed a methodology based on the Witmer and Singer definition of presence to confirm this.[25] This method relied on a number of questions in the final questionnaires to verify that participants felt as if they were physically present with the remote participant. These questions verified that a feeling of "presence," according to this definition, existed for these participants.

Although the design aim in all systems was to mimic some aspects of physical presence, such physical presence is not necessarily the "gold standard." For example, physical co-presence is neither necessary nor possible for collaborative surgical training due to space limitations in the physical surgical field. With the remote outpatient consultation, the participants all had unobstructed access to the image and video data seen by the clinician. The patients and families reported a much better understanding of the situation during the examination of the patient and during discussion of the proposed management plan than they had in conventional face-to-face consultations. These two examples show the value of the sense of presence in the context of the task, and the value of sharing the context of the task among the participants.

Approximately 1 in 5 ViCCU® users (clinicians) expressed a preference for specialist consultations to take place via ViCCU,® compared with physical presence of the specialist. This reflected

Table 2. Evaluation Instruments

	SAMPLE	LOG BOOKS	INTERVIEWS	VIDEO RECORDINGS	QUES-TIONNAIRES	TASK PERFORMANCE	CLINICAL OUTCOMES
ViCCU®	18-month clinical trial; 503 activations		✓		✓		✓
ECHONET	9-month clinical trial; 84 activations	✓	✓		✓		
Virtual surgical training	11 trainees each receiving 1 hour tuition & ½-hour assessment		✓	✓	✓	✓	
Remote outpatient consultations	44 consultations, each ½-hour		✓	✓	✓	✓	✓

ViCCU®, Virtual Critical Care Unit.

ViCCU®'s ability to preserve some of the autonomy of the team caring for the patient, and to restrict the specialist's role to an advisory one.

WORKING IN A COMPLEX INFORMATION SPACE

Many of the systems described are designed for consultation on all aspects of a patient's care plan, rather than consultations on particular specialities (such as pathology). As such, the relevant information space is inhomogeneous, and can consist of written records, traces of vital signs, patient appearance and demeanor, images from several modalities, background demographic information, and many other sources. In emergency medicine, some of this information is generated in real time during the consultation. The information space in the trials described here included shared displays from the hospital's Picture Archiving and Communication System, camera views of images, paper medical records, monitoring equipment and, importantly, live video views of the patients themselves. In some aspects of critical (e.g., intensive care), vital signs records are viewed on different time scales to review trends or specific short episodes.

The surgical training application involved a limited information space, since there were defined learning outcomes in each case. Nevertheless, the rich media channel provided opportunities for complex extra teaching or case-based material that could also be provided on demand.

In the remote outpatient consultation example, the information space—tablet displays showing interactively annotatable views of images, radiology data, and live video of the patient—was shared between the surgeon and the patient and family so that the patient and family saw exactly the scale and quality of data that was in front of the surgeon. The surgeons used the pen and tablet displays to point at and draw over the images and video to explain the history and current state of the patient's condition, to explain and justify the future treatment plan, and to enlist the agreement and commitment on the part of the patient and family to this plan.

Even in the applications not specifically designed for educational outcomes, the ability to convey complex information resulted in educational outcomes through telementoring of procedures, case-based discussions of patients, as well as some formal training sessions.

SOCIAL AND ORGANIZATIONAL: CREATING AND AFFECTING WORKING RELATIONSHIPS

Two of the applications (ViCCU® and ECHONET) were specifically designed to enhance collaboration between clinical departments that were similar in clinical speciality (Emergency and Intensive Care, respectively) but differed significantly in size, and therefore in ability to provide specialist services. In both cases, the primary aim was to permit specialists in the larger department to "virtually" attend the point of care in the smaller department, and provide guidance on patient management, which remained the primary responsibility of the smaller department. The aim was to facilitate a high level of collaboration, without compromising autonomy. This appears to have been achieved in these two hospital pairs, although there are inevitable adjustments in working relationships brought about by the increased facility for collaboration. An example is the anecdotal finding that nurses in the Emergency Department at Blue Mountains Hospital were empowered through being able to participate in discussions between the local specialist and the Nepean specialist using the ViCCU® system.[14] This was facilitated through the ability of ViCCU®'s high media quality to support group interactions. In the ECHONET project, specialists at North West Regional Hospitals were reassured as to their level of care through benchmarking against a tertiary referral hospital. In both cases, an expected longer term outcome was improvement in the perceived status of a posting to a regional hospital for junior specialists.

The findings from all of the systems are summarized in *Table 3*.

Discussion

Telemedicine's potential to transform healthcare delivery on a system-wide scale is far from being realized; this is one aspect of the relatively slow uptake of information and communications technologies in healthcare.[26] The projects described in this article set out to show how advances in technology, based on the use of advanced networks, can extend the range of clinical services that can be delivered over a distance.

The applications and configurations included real and virtual shared environments, and included systems that were exclusively clinical, exclusively educational, or capable of both functions. The clinical systems were designed for point of care application, some in very time-critical, stressful clinical environments. There was also a mixture of systems with both asymmetrical nodes and networks of identical user interfaces. These demonstrations offered a unique opportunity to extrapolate from a number

Table 3. Summary of Evaluation Findings Categorized by Application and Success Criteria

	VICCU	ECHONET	COLLABORATIVE SURGICAL TRAINING	REMOTE OUTPATIENT CONSULTATIONS
Usability; design for application; task focus	Strong feature of design process Complex design Easy to use without training Evaluation found users easily maintained patient focus	Multipurpose Can use without instructions Good patient focus	Need to mimic actual surgery Immersive so filled sensory fields facilitating task focus	Families: easy because of the close match to the normal consultation experience Clinicians: easy because of close match between system design and the target patient group
Presence and media quality	Preliminary study shows strong role of "presence" Many favorable comments on media quality	Good comments on audio, video quality Provides remote specialist with all the information they would perceive from the foot of the patient's bed	Multimodal nature of communication Haptics supports situated learning	Participants rated the video support for conversations highly Tablet/pen support for clinical data was better than for face-to-face consultations
Working in a complex information space	ViCCU® shown to provide accurate and complete patient information with which to provide advice to BMH staff	Comments—"can see all the things you would see at the end of the bed"	Shared identical viewpoint into a virtual 3D model Multimedia background information on demand	Designed for complex information space—multiple media—shared information access
Social & organizational—creating & affecting working relationships	Improved inter-hospital relationships and better understanding of the roles and competencies	Seen as improving relationships between two hospitals	Potential for training over long distances demonstrated	Creating relationships between surgeons and remotely located clinic assistants

ViCCU®, Virtual Critical Care Unit; BMH, Blue Mountains Hospital.

of experiments to the potential for the next generation of telemedicine systems.

Specifically, the experimental systems described in this article used advanced technology to create systems whose demonstrated features included enhancements in usability, "presence," the ability to work in complex information spaces and improving social and organizational relationships. These benefits have implications for how advanced telemedicine systems can play a significant role in healthcare.

Usability and patient focus mean that telemedicine systems can be more easily incorporated into clinical protocols, with minimal need for special training or on-site support, especially in point-of-care applications. This will make such systems more easily applied in high-stress situations such as critical care, and will create confidence on the part of staff who need to use the systems.

Decision making in medicine requires a high degree of trust among participants; these can include the patient, their immediate family, the patient's immediate clinical carer, as well as other consulting clinicians. When part of this network is separated by distance, loss of the sense of presence can reduce the willingness of these participants to trust the judgment of those not physically present. Our experience has been that creating a high sense of presence among participants not physically present can form an important component of this "trust," and contributes to users' willingness to make critical decisions based on interaction over a distance. Our systems have created a few data points in quantifying the role of presence in telehealth, and indicate that acceptance of telehealth in critical decision-making processes is enhanced by a strong sense of presence, supported by high-quality media. The media quality requirements for trust may exceed the requirements for diagnosis.

While high-quality video and audio creates a sense of presence, medical decision making and training involves accessing a complex, multimedia information space. Our projects had different levels of integrating the clinical information space with the video and audio links that supported a sense of telepresence. The remote outpatient consultation succeeded in integrating the video support for interpersonal communication with diagnostic video of the patient and access to archived radiology data. We believe that integrating complex information spaces into systems with high telepresence remains one of the major research challenges in telemedicine.[10]

Health systems are now facing major issues of providing high-quality specialist healthcare into geographically scattered populations, using an increasingly stretched workforce. Previous studies, especially in critical care applications, have shown the importance of personal networks and informal information exchanges among health professionals.[27,28] The ability of advanced telemedicine systems to support such informal exchanges and to create wider communities of collaborating health professionals will be a vital element in addressing some of these issues. Once again, this can be achieved with advanced telehealth systems whose specifications exceed those for diagnosis alone.

This article provides evidence for an enhancement to the range and quality of services that can be delivered by telemedicine if health systems are prepared to increase their investment in telehealth. Moreover, we assert that the additional costs are justified on the basis of the outcomes that can be delivered. The costs of upgrading telemedicine technology appear not only in equipment and network costs. There are changes in workload, especially at the system "hubs," and organizational changes will need to ensure that such issues do not prevent the benefits of advanced telehealth systems from being realized. There is a need to not only change the way health system administrators think about telehealth, but also to provide evidence and quantification of the benefits. Most cost–benefit studies in telehealth have been too focused at a local level, but advanced telehealth systems will require more global, system-wide thinking with appropriate new business models.[29] Lack of broadband infrastructure remains a barrier at present, but the rapid development and implementation of broadband networks should mean that this barrier will disappear in time. Examples of such widespread availability already exist in such countries as Korea.[30]

In summary, the transition to advanced networks, if accompanied by changes in user interface informed by user-centered design processes, will permit telemedicine to play a more central role in healthcare delivery, especially in critical care and other point-of-care applications.

Telemedicine has the potential to improve healthcare through better use of medical expertise. The systems described in this article have given several pointers as to how telemedicine might evolve to meet the immense challenges of providing quality healthcare in the 21st century.

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