TELEMEDICINE

Applications of information and communications technologies have become increasingly widespread because of the rapid development of microelectronics and computers. One of the most important applications is the use of advanced telecommunications and computer technologies to improve health-care services and systems. Telemedicine—which combines many innovative information technologies that integrate research areas in human–computer interaction, data storage, processing, and compression with communications networking to improve health care—has been recognized as a way to provide an effective and versatile solution to many of the intransigent problems in health-care delivery.

A formal definition for telemedicine has recently been adopted by the Institute of Medicine (IOM), Washington DC. In the report developed by a 15-member committee of the Institute of Medicine, the term *telemedicine* is defined as "the use of electronic information and communication technologies

Table 1. Definitions of Telemedicine Consulted by the Institute of Medicine Committee

Proposer and Reference	Definition
Van Goord and Christensen (2), cited in Gott (3), p. 10	The investigation, monitoring, and management of patients, and the education of patients and staff using systems which allow ready access to expert advice, no matter where the patient is located
Weis (4), p. 151	The use of telecommunications techniques at remote sites for the purpose of enhancing diagnosis, expediting research, and improving treatment of illnesses
Kansas Telemedicine Policy Group (5), p. 1.6	The practice of health care delivery, diagnosis, consultation, treatment, transfer of medical data, and education using . . . audio, visual, and data communications
Grigsby et al. (6), p. 1.3	The use of telecommunication technology as a medium for providing health care services for persons that are at some distance from the provider
Council on Competitiveness (7), p. 6	The use of two-way, interactive telecommunications video systems to examine patients from remote locations, to facilitate medical consultations, and to train health care professionals
Perednia and Allen (8), p. 483	The use of telecommunications technologies to provide medical information and services
Bashshur (9), p. 19	An integrated system of health care delivery and education that employs telecommunications and computer technology as a substitute for face-to-face contact between provider and client
Office of Technology Assessment (OTA) (10), p. 224	The use of information technology to deliver medical services and information from one location to another
Physician Payment Review Commission (PPRC) (11), p. 135	An infrastructure for furnishing an array of individual services that are performed using telecommunication technologies
Lipson and Henderson (12), p. I-1–4	Telemedicine encompasses all of the health care, education, information and administratie services that can be transmitted over distances by telecommunications technologies
Puskin et al. (13)	The use of modern telecommunications and information technologies for the provision of clinical care to individuals at a distance and the transmission of information to provide that care

to provide and support health care when distance separates the participants" (1). The committee adopted this definition of telemedicine after consulting a number of suggested definitions. A list of these definitions is shown in Table 1 (2–13). The committee identified three common elements in these definitions: (1) information or telecommunications technologies, (2) distance between participants, and (3) health or medical uses.

The adopted definition of telemedicine includes all three common elements and covers a broad context in terms of both technologies employed and application areas considered. Traditionally, video conferencing is perceived as the defining technology for telemedicine, and the clinical application is considered as the defining mode for telemedicine. However, the adopted definition encompasses a wide variety of forms of communication, including telephone conversation, still-image transmission, and medical file electronic access. The definition of technologies also includes computer-based capturing, manipulating, analyzing, retrieving, and displaying of the related data and information. Both clinical and nonclinical uses of telemedicine are considered in the definition. In general, clinical applications of telemedicine involve patient care such as diagnosis, treatment, and other medical decisions and services. Nonclinical applications of telemedicine involve non-decision-making processes such as continuing medical education and management meetings. The boundary for clinical and nonclinical applications often cannot be clearly defined, because remote learning and consultation by participants will result in the application of acquired knowledge to future diagnostic and treatment decision-making processes. The third element, the geographic separation or distance between the participants, is the defining characteristic for telemedicine. In many cases, it is the separation of participants, not the distance between the participants, that requires telemedicine to overcome problems associated with patient care.

The concept of health-care services performed over a distance first appeared in 1924 in an imaginative cover for the magazine *Radio News.* The cover showed a "radio doctor" who could talk with the patient by a live picture through radio links (1). However, the technology to support such a visionary concept namely, television transmission, was not developed until three years later, in 1927. According to a recent reivew, the first reference to telemedicine in medical literature appeared in 1950 (14) and described the transmission of radiological images by telephone over a distance of 24 mi. The interactive practice of telemedicine began during the 1960s when two-way, closed-circuit microwave televisions were used for psychiatric consultation by clinicians at the Nebraska Psychiatric Institute (15). Following the Nebraska program, several other telemedicine programs were developed in the 1960s. Some of these early programs aimed at improving health services in remote populations that traditionally had limited access to quality health care. One such early attempt was sponsored by the US Department of Health, Education and Welfare, the National Aeronautics and Space Administration (NASA), and the Lockheed Company and was called the Space Technology Applied to Rural Papago Advanced Health Care (STARPAHC) program (16). The program offered medical care through a mobile health unit (MHU), a medically equipped van that traveled over a prescribed route through the Papago Indian Reservation in the Sonora Desert, west of Tucson and south of Phoenix, Arizona. The MHU clinic and a fixed clinic at Santa Rosa, Arizona were linked via telemedicine facilities to a hospital in Phoenix. Other programs aimed to improve health services in urban emergency and urgent situations (17,18). Although these pioneering telemedicine efforts demonstrated both technical and medical feasibility and received enthusiastic appraisal from the health-care recipients (16), the issue of cost-effectiveness was debated at a premature stage by telemedicine authorities, especially the major funding agencies. The prevailing fear was that as the technologies for telemedicine became sophisticated, the cost of telemedicine would increase (15). Such fear has been proven to be unfounded. Many applications of telemedicine are considered to have the potential to reduce health-care costs or to reduce the rate of cost escalation (1). The rapid advances of modern communications and information technologies during the 1990s have been a major driving force for the strong revival of telemedicine today.

The development of telemedicine has depended on the associated enabling technologies. One of the reasons that first-generation telemedicine projects did not succeed is that the technologies available at the time were, by today's standard, relatively primitive. The rapid advances in digital compression, fiber optics, and computer miniaturization and portability and their application to telemedicine systems were not even predicted during the early stage of telemedicine system development. In the case of communications, dedicated telephone lines were used in many telemedicine projects. However, such lines could only transmit slow-scan analog images, and digital compression techniques were not incorporated into the first generation of telemedicine systems. The recent rapid advances in digital communications, computer technology, and information science have provided a much broader range of enabling technologies for today's telemedicine systems. For example, the original telephone-based communications mode has now reached very high capacity because of the revolutionary development in computer modem design. The transmission bandwidth of the telephone line is now more than 10 times greater than it was during the 1960s (19). Other modes of modern communications, such as the integrated services digital network (ISDN) and asynchronous transfer mode (ATM), have been playing increasing roles in telemedicine systems. These new communications technologies enable the telemedicine system to operate with more flexibility and at a higher efficiency. In addition to these more advanced communication technologies, developments in digital compression (especially digital audio and video compression), and computer networking (in particular the Internet), have injected much needed versatility into the design of today's telemedicine systems. These greatly improved technologies and, more important, the decreasing cost of these technologies have allowed a wide-scale implementation of telemedicine.

The clinical applications of telemedicine have been adapted by a wide range of medical specialties and health-care disciplines. Many of the current telemedicine applications involve the transmission of medical images for diagnosis and treatment. Two such primary image-related applications are teleradiology and telepathology. *Teleradiology* can be defined as the practice of radiology from a distance, and the initial interest in teleradiology as a practical cost-effective method of providing professional radiology services to underserved areas began some 30 years ago. Early teleradiology was considered as an alternative to recruiting radiologists for remote and isolated communities; it facilitated local patient care and avoided the unnecessary transport of patients to distant hospitals. However, until recently, technical deficiencies in the hardware, software, and telecommunications links have hindered the acceptance of teleradiology by radiologists and other physicians (20,21). *Telepathology,* on the other hand, was developed more recently, during the late 1980s, and is still in its infancy compared with teleradiology. Two significantly different and competing techniques are currently used in telepathology: dynamic imaging and static imaging. *Dynamic imaging systems* provide real-time video imaging capability via a remotely controlled light microscope and a broadband communications link. With dynamic imaging systems, telepathologists are able to operate the microscope remotely via a keypad, mouse, or other input device so that the systems approximate the usual techniques of pathological examination. *Static imaging systems* are usually based on less expensive conventional telephone lines to transmit a limited number of still images. In this case, the consulting telepathologists are virtually excluded from the process of selecting the microscope fields for imaging. Other clinical applications of telemedicine include teledermatology, teleoncology, telepsychiatry, and more generally, the delivery of quality primary medical care to remote and isolated populations.

The nonclinical applications of telemedicine have received increased attention because of rapid developments in the telecommunications industry and the deployment of the National Information Infrastructure (NII). In such cases, telemedicine systems are often employed to enhance educational and management activities through video conferencing and multimedia presentations. It has been recognized that nonclinical uses of telemedicine for educational and administrative activities will also contribute to the effectiveness of many clinical applications, especially when the clinicians gain greater familiarity with the telemedicine technologies through nonclinical uses. Examples of nonclinical uses of telemedicine include continuing medical education, on-line health-care information resources, coordinating research at multiple sites, and video conferencing for administrative meetings (1). With Internet and World Wide Web resources, health-care information can be readily obtained for the formal and informal provision of medical advice, and continuing medical education can be implemented at multiple sites with effective multimedia presentations. Health-related research may also be conducted over telemedicine systems based on the patients' data collected and distributed at multiple sites to maximize the use of all available data. For health-care administrations, video conferencing for managers of integrated health-care systems allows such meetings to combine evaluation with quality monitoring.

More recently, public health has been identified as another nonclinical application of telemedicine with great potential. Public health for the most part is massive information transfer, teaching people how to find clean water, wash, and change lifestyles as well as disease monitoring. Telemedicine systems in the future will be able to provide the connectivity needed for mass education on disease prevention and the global network needed for disease monitoring. Such nonclinical applications of telemedicine can contribute to the improvement of human health on a global scale.

TECHNOLOGIES FOR TELEMEDICINE

As defined previously, telemedicine is the application of information and communications technologies to health care. As a result, the development of telemedicine has largely been constrained by the balance of the supply and demand of technologies applicable to various telemedicine applications. The degree to which a particular telemedicine application is able to develop is depends greatly on the development of appropriate technologies associated with the application. In general, the development of telemedicine applications are constrained by three fundamental aspects of information and communications technologies: information-carrying capacity, communications media, and information processing and digital technologies. These technologies determine the availability, quality, and affordability of many telemedicine applications.

The information-carrying capacity of a communications system is called *bandwidth.* Bandwidth measures the amount of information that can be carried at one time through the communications system. The advances in digital communications have offered various possibilities to transmit health care–related information over communications systems with very high information-carrying capacities. Usually, however, a communications system with higher bandwidth tends to be more expensive to install and maintain. Therefore, the demand for information-carrying capability, or bandwidth, depends on the needs and resources of the telemedicine users. Many recent advances in information and communications technologies have sought to increase the capacity of various communications systems by improving transmission media and by configuring the information in such a way as to reduce bandwidth requirements. The core modern information and communication technologies applicable to telemedicine are digital communications, digital video and video compression, digital imaging, and multimedia integration.

Digital Communication

The telecommunications industry is moving rapidly toward digital systems for various applications. This is because digital systems can easily facilitate more efficient transmission, more accurate signal reproduction, and more flexible information multiplexing. All these characteristics of digital communications will benefit the further development of telemedicine systems. The more efficient transmission of a digital communications system can reduce the cost of transmission and therefore may spawn new applications in telemedicine. More accurate reproduction of the digital transmission will improve the quality of the received information and hence the quality of the telemedicine services. More flexible information multiplexing offers the integration of audio, video, and data signals into multimedia information so that more greatly enhanced telemedicine services can be made possible.

Historically, telemedicine was developed to overcome health-care problems arising from geographic separation between people who needed health care and those who could provide it. Naturally, telemedicine applications have relied on existing telecommunications networks and technologies to resolve the geographic-separation issues. Depending on the nature of the telemedicine information to be transmitted, a particular type of communications media and network may be selected so that a trade-off between the costs of and the need for timely connection can be achieved. Many telemedicine applications have depended on the public switched telephone network (PSTN) to transmit both time-critical and non-time-critical health-care information from one place to another. The carrier systems for such information transmission may include traditional telephone service, T-1 carrier systems, and ISDN.

The telephone network has several major advantages over the other two, more advanced technologies for some telemedicine applications. These advantages include ubiquity, relatively low cost for installation, and low cost per use. In addition, modern telephone systems offer a range of flexible services that have emerged during the past decade. Among them, telephone conferencing offers the opportunity for relatively large numbers of people who are geographically dispersed to meet together by phone. Voice-mail enables the transmission of voice messages when instant response is not required. Fax service facilitates the transmission of material on paper via the telephone system. With currently available computer modems, the exchange of electronic mail, data, documents, and even images can now be easily accomplished through the telephone system. In the near future, the videophone will provide more versatile and low-cost communications services for telemedicine participants.

The T-1 carrier system was the first successful system designed to use digitized voice transmission over the telephone network (19). It was first developed to resolve the problems with the old analog telephone systems so that the system would be able to increase call-carrying capability and improve transmission quality. The first step of development was the deployment of mixed analog and digital transmission capabilities so that end users could use analog transmission through the twisted pair cable on the local loop while the interoffice trunks were operating through digital carriers with digital switching systems. As the T-1 system evolved from the old analog telephone system, some of the features of the old telephone system remained compatible, such as the four-wire circuits in the local loop and full-duplex capability. However, many digital characteristics have been introduced in the T-1 carrier system. These characteristics include pulse-coded modulation (PCM), time-division multiplexing, framed format, bipolar format, byte-synchronous transmission, and channelized or nonchannelized services. With these digital technologies, the T-1 carrier system is able to provide a basic rate of digital transmission at 1.5444 Mbps, the rate of the digital signal level 1 (DS1) as defined by the time-division multiplexing hierarchy. This rate of the digital link is the result of multiplexing 24 standard 64-kbps PCM signals, also known as DS0 digital signals. With these higher-capacity transmission links, many telemedicine applications are now able to transmit time-critical high-bandwidth requirement information, such as live video signals, over the telephone network via T-1 carrier systems.

The original motivation for the development of the T-carrier system was to provide lower cost and better quality dial-up telephone services. However, the technologies that evolved from such developments form the basis for a full end-to-end digital network, (ISDN), to support the simultaneous transmission of voice, data, video, image, text, and graphics information. ISDN provides a wide range of services using a limited set of connection types and multipurpose user–network interface arrangements (19,22). ISDN is intended to be a single worldwide public telecommunications network to replace existing public telecommunications networks that are currently not totally compatible among various countries (23). There are two major types of ISDN with different capacities: narrowband ISDN and broadband ISDN (BISDN). Narrowband ISDN is based on the use of a 64 kbps channel as the basic unit of switching with primarily a circuit-switching mode of transmission supported by frame-relay protocols. BISDN offers very high data rates at the order of hundreds of Mbps with primarily a packet-switching mode of transmission supported by asynchronous transfer mode (ATM) protocols. Narrowband ISDN provides the transmission bandwidth ranging from 64 kbps to 1.544 Mbps, while BISDN provides broader transmission bandwidth, ranging from 44.736 Mbps, or DS3 in the digital signal hierarchy, to 2.48832 Gbps, or OC-48 in the optical carrier hierarchy in the synchronous optical network (SONET). Narrowband ISDN offers these services: (1) speech, (2) 3.1 kHz audio, (3) 3 kHz audio, (4) high-speed end-to-end digital channels at a rate between the basic rate of 64 kbps and the super-rate of 384 kbps, and (5) packet-mode transmission (24). BISDN offers a variety of interactive and distribution services, including (1) broadband video telephony and video conferencing, (2) video surveillance, (3) high-speed file transfer, (4) video and document retrieval service, (5) television distribution, and (6) potentially many more future services (24). Depending upon a particular application and cost-effective consideration, a telemedicine system may employ either narrowband ISDN or BISDN to accomplish desired health-care tasks. The development of ISDN enables a telemedicine system to encompass a much wider variety of applications, ranging from interactive videoconferencing-based diagnosis and treatment to the transfer of patient records and other health-care-related documents for consultation and management.

Digital Video and Video Compression

As noted, video conferencing is considered the defining technology for telemedicine. Recent rapid development of video technologies, especially digital video and video compression, have enabled telemedicine to continue its strong revival.

Video refers to visual or pictorial information, which includes both still images and image sequences. Most common examples of video include television and motion pictures. The recording, storage, and transmission of video signals has traditionally been handled in analog form. Rapid advances in computer and communications technology, however, have exposed the limitations of traditional analog video. In particular, the analog video lacks interactivity and is difficult to be integrated with computer systems that accept and process digitized information and modern communications systems that transmit digital signals. As a result, efficient digital representation of the video signal has been extensively studied to take full advantage of the remarkable developments in digital communications and computer systems. Digital video is a coded sequence of data that represent the intensity and color of successive discrete points along the scan lines. Details in the digital representations of video signal are beyond the scope of this article and can be found in Refs. 25 and 26.

Digital video offers many advantages over its analog counterpart. Digital video allows the existence of video at multiple resolutions in the spatial and temporal domains, interactivity suitable for search and retrieval of video databases, variable-rate transmission based on user demand, and more important, integration of digital video with other digital media, such as digital audio, text, and graphics, for true multimedia computing and communications. All these benefits of digital video create new opportunities for a telemedicine system to integrate a high level of interactivity and flexibility into routine health-care activities, such as efficient patient-information gathering, computerized therapy management, and automatic patient follow-up. These new opportunities are not possible with telemedicine systems that are based on analog communications. Because digital video typically requires huge storage and transmission bandwidth capacities, however, a fundamental issue is the development of video compression algorithms and the implementation of compression in hardware. For example, digital video requires a much higher data rate and transmission bandwidth than digital audio. For compact disk (CD)–quality digital audio, the data rate is about 700 kbps, while for a high-definition television (HDTV) signal, the data rate will be about 550 Mbps. Without appropriate compression, the sheer size of digital video will overwhelm many current storage and transmission systems. Therefore, video compression is a key technology that determines the cost and the quality of the interactive video transmission, which, in many cases, can determine the quality of the health-care service in a specific telemedicine system. The temporal, spatial, intensity, and color resolutions required by specific telemedicine applications along with available communications channel bandwidth often dictate the desired compression performance. For example, the ISDN line with a data rate of 384 kbps may be adequate for face-to-face discussion among health-care providers. However, remote real-time high-fidelity display of cardiological ultrasound image sequences would need a 45 Mbps communications channel. The video-compression requirements for these two applications would be quite different.

Compatibility among applications and manufacturers is often essential for the exchange and successful transmission of video data among different systems. As a result, several video-compression standards have recently been developed. Two major categories of such standards are reviewed here: (1) Standards H.261 and H.263 for video conferencing applications and (2) the MPEG series, including MPEG-1 for CD read-only memory (ROM) access, MPEG-2 for HDTV, and MPEG-4 for the true multimedia communications standard that encompassess audio coding, video coding, multiplexing of coded data, coding of text and graphics, and audiovisual scene composition.

An understanding of these video-compression standards starts with JPEG, a standard for coding single-frame color images developed by the International Standardization Organization (ISO) Joint Photographic Experts Group (JPEG). Compression of image data without significant degradation of the visual quality is usually possible because images often exhibit a high degree of spatial, spectral, and psychovisual redundancies. Spatial redundancy is due to the correlation among neighboring pixels. Spectral redundancy is due to the correlation among color components. Psychovisual redundancy is due to perceptual properties of the human visual system. For video signals, the compression algorithms also take advantage of the temporal redundancy due to usually very high correlation between neighboring frames. For the compression of still-frame images, the process is generally composed of three steps: (1) transformation, (2) quantization, and (3) symbol coding. The transformation in the JPEG standard is the discrete cosine transform (DCT), which is employed to pack the energy of the image signal to a small number of coefficients. As a result, the image can be well approximated by a small number of DCT coefficients. The quantization is needed to generate a finite number of symbols from originally continuously valued coefficients, while the symbol coding assigns a code word, or a binary bit stream, to each symbol generated by the quantization step. Intuitively, the coarser the quantization, the fewer the number of symbols. Higher compression can be used for coarser quantization; however, there is more degradation in the visual quality of the compressed image. In the case of symbol coding, variable length codes are usually employed to minimize the average length of the binary bitstream by assigning short code words to more probable symbols. Huffman and arithmetic coding techniques are used as variable length coding in the JPEG standard (27).

In the compression of video signals, motion compensation is a basic technique to reduce the temporal redundancy of the image sequences. This is also the major difference between image compression and video compression. The temporal redundancy is due to the fact that there usually exists certain portion of an image that changes little from one image frame to the next. In the H.261 standard, which is the video-compression standard developed for videoconferencing by the International Telecommunication Union–Telecommunication Standardization Sector (ITU-T), block-based motion compensation is performed to compute interframe differences. In this case, image data in the previous frame are used to predict the image blocks in the current frame. Only differences, typically of small magnitude, between the displaced previous block and the current block need to be coded. As in the case of JPEG, DCT and variable-length coding techniques are employed. However, interframe differences, instead of the frame itself in the case of JPEG, are transformed with DCT and coded with variable-length coding. The development of the H.261 standard began in 1984 and was completed in late 1989. This video-compression standard was developed for the application of videoconferencing over low-bit-rate ISDN lines with target bit rate of p times 64 kbps, where p is between 1 and 30. Only two image formats are assumed: common intermediate format (CIF) and quarter-CIF (QCIF). CIF images consist of three components: luminance Y and color differences C_B and C_R. The size of a CIF image is 352 pixels per line by 244 lines per frame. Since the H.261 standard is designed for real-time communication, it uses only the closest previous frames as a prediction to reduce the coding delay. In summary, the H.261 standard is a compromise among coding performance, real-time requirements, implementation complexity, and system robustness. This standard has been implemented in various videoconferencing products. Many telemedicine systems with interactive video services are based on real-time videoconferencing system over ISDN lines with the H.261 standard.

Standard H.263 was defined by the same group that developed the H.261 standard. The activities of the H.263 standard started in 1993 and was adopted in 1996. The main goal of Standard H.263 was to design a video coding standard for applications with bit rates of less than 64 kbps. Examples of such applications include video data transmission over the public service telephone network and the mobile network in which the video bit rates range from 10 kbps to 24 kbps. Since Standard H.263 was built on top of Standard H.261, the main structure is essentially the same. However, Standard H.263 offers several enhanced techniques over Standard H.261. These enhancements include the support of more image formats, the use of half-pel motion compensation, three-dimensional variable length coding, and a variable quantization step at each microblock. With the H.263 standard, telemedicine systems will have extended options in the choice of video transmission channels, the selection of image formats, and a much-improved picture quality at low-bit-rate transmission. It also opens up a new opportunity for telemedicine to use mobile communications, which may be very much desired in emergency and battlefield situations.

In parallel to the efforts by the ITU-T standards, the ISO Moving Picture Experts Group (MPEG) has developed both audio- and video-compression standards that can compress many types of video sources for storage and transmission on various digital media, including compact disk, remote video database, video-on-demand, digital television, and network video. The MPEG committee started its activities in 1988 and the MPEG-1 standard was approved by the end of 1992 (27). The MPEG-1 standard has been developed for the storage of digital video and its associated audio at about 1.5 Mbps on various digital storage media. The target application for the MPEG-1 standard is the interactive multimedia system, in which video data can be decoded in real time to allow random access and fast forward/reverse with reasonable coding/decoding delays. In some telemedicine applications, in which interactive access to the desired video database is required, the MPEG-1 standard will be able to play a very important role. To reach the target bit rate of 1.5 Mbps, the input video is usually down-sampled to MPEG standard input format (SIF) before compression. The SIF consists of noninterlaced frames of 352 pixels by 240 lines at a frame rate of 30 frames per second, with a 2 : 1 color subsampling both horizontally and vertically. The compression approach of the MPEG-1 standard uses a combination of JPEG and H.261 standards. In particular, the MPEG-1 standard also employs a block-based two-dimensional DCT to exploit spatial redundancy as in the JPEG and H.261 standards. However, the MPEG-1 standard uses bidirectional temporal prediction to achieve higher compression than the H.261 standard, which employs only forward prediction.

The second phase of the ISO MPEG standard, MPEG-2, began in 1990 and was approved as an international standard in 1994. Standard MPEG-2 provides a video coding solution for applications not originally covered or envisaged by the MPEG-1 standard. Specifically, the MPEG-2 standard was given the charter to code interlaced video at bit rate of 4 Mbps to 9 Mbps and provide video quality not lower than National Television Systems Committee (NTSC)/Phase Alternation Line (PAL) and up to that of International Radio Consultative Committee (CCIR) 601 (26). Emerging applications, such as digital cable TV distribution, networked database services via ATM, digital video tape recorder (VTR) applications, and satellite and terrestrial digital broadcasting distribution, were seen to benefit from the increased quality expected from the MPEG-2 standardization phase. Work was carried out in collaboration with the ITU-T SG 15 Experts Group for ATM video coding and in 1994 the MPEG-2 Draft International Standard (which is identical to the ITU-T H.262 recommendation) was released. The specification of the standard is intended to be generic—hence, the standard aims to facilitate the bitstream interchange among different applications, transmissions, and storage media.

Basically the MPEG-2 standard can be seen as a superset of the MPEG-1 coding standard and was designed to be compatible with MPEG-1: every MPEG-2–compatible decoder can decode a valid MPEG-1 bitstream. Many video coding algorithms were integrated into a single syntax to meet the diverse application requirements: prediction modes were developed to support efficient coding of interlaced video, and scalable video coding extensions were introduced to provide such additional functions as embedded coding of digital TV and HDTV and graceful quality degradation in the presence of transmission errors.

The MPEG-2 standard offers enhanced capability of many telemedicine applications. At the higher bit rate of MPEG-2, a telemedicine system can take advantage of emerging video communications services to provide more flexible services and expand some remote medical consultation services over ATM, satellite, and terrestrial digital broadcasting distributions. Since the MPEG-2 standard targets mainly HDTV and digital TV applications, telemedicine applications will benefit greatly the superior video quality in terms of both spatial and temporal resolution. Such high-quality video will enable telemedicine to tap many new applications that otherwise cannot be explored, among them real-time transmission of some high-resolution teleradiology images and telepathology images.

Anticipating the rapid convergence of telecommunications industries, computer, TV, and film industries, the MPEG group officially initiated a new MPEG-4 standardization phase in 1994—with the mandate to standardize algorithms and tools for coding and flexible representation of audiovisual data that are able to meet the challenges of future multimedia applications (28). Four major future needs are identified and addressed in the development of the MPEG-4 standard: (1) universal accessibility and robustness in error-prone environments, (2) high interactive capability, (3) coding of natural and synthetic data, and (4) high compression efficiency. Bit rates targeted for the MPEG-4 video standard are between 5 kbps and 64 kbps for mobile or PSTN video applications and up to 2 Mbps for TV and film applications. The release of the MPEG-4 International Standard was targeted for late 1998.

Although the MPEG-4 standard encompasses a much wider scope of applications than telemedicine systems intend to accommodate, it will have a great impact on the quality of many telemedicine applications. These applications may include (1) video-based telemedicine services over the Internet and Intranets, (2) telemedicine video transmission over wireless channels, such as an in-hospital mobile network and combat-field wireless links, (3) a video database search in heterogeneous network environments, including various medical image storage facilities and hospital medical record management environments, and (4) virtual-reality applications in health care such as remote visualization and image-guided surgery. As the demand for more sophisticated multimedia applications in health care grows and computer and communications systems integration continues, various video coding standards that have been developed or are currently under development are expected to facilitate enhanced telemedicine systems as well as improved health-care services.

Digital Imaging

Imaging devices have been an integral part of health-care service, especially diagnosis, since its very beginning. Many imaging devices have actually been invented primarily for medical applications. Traditional media used to record static diagnosis images include sheet and roll film for radiography and photography while traditional media used to record dynamic images include movie film and videotapes. Modern medical imaging devices often create digital images directly. These digital imaging modalities include computer tomography (CT), magnetic resonance imaging (MRI), single-photon emission computer tomography (SPECT), and positron emission tomography (PET). For the images and videos acquired with traditional media to be exchanged over the telemedicine network, they must be converted into digital format by an appropriate digitization process to preserve the required image quality for diagnosis. A typical 11 in. $\times$ 17 in. chest film requires at least 2000 $\times$ 2000 pixels and an optical dynamic range of at least 4000 to 1 (12 bits) to represent the image adequately (15). The compression of medical images is often needed for telemedicine applications to reduce the storage and transmission costs and to reduce access time. Various image and video compression techniques and standards have been discussed previously. However, many of these generic compression techniques cannot be directly applied to diagnostic images as they employ lossy compression schemes.

The American College of Radiologists and the National Electrical Manufacturers Association (ACR-NEMA) sponsored and developed the Digital Imaging and Communications in Medicine (DICOM) Standard to meet the needs of manufacturers and users of medical imaging equipment, particularly computer radiography (CR), CT, MRI, and picture archiving and communication systems (PACS) for interconnection of devices on standard networks. The DICOM standard also provides a means by which users of imaging equipment may assess whether two devices claiming conformance are able to exchange meaningful information. As the DICOM is a standard for the transmission of radiological images from one location to another for the purpose of interpretation or consultation (29), it will have a great impact on development of telemedicine systems. In addition to personnel qualifications, licensing, and quality control, the standard includes equipment guidelines for digitization of both small and large matrix images, display capabilities, and patient database requirements.

The DICOM standard allows digital communications between diagnostic and therapeutic equipment and systems from various manufacturers. Such connectivity is important to cost effectiveness in health care and therefore is crucial to the development of cost-effective telemedicine systems. Telemedicine systems with the DICOM standard can provide radiology services within facilities as well as across geographic regions. Therefore, they gain maximum benefit from existing resources and keep costs down through compatibility of new equipment and systems. For example, workstations, CT scanners, MR imagers, film digitizers, shared archives, laser printers, and computers from multiple vendors and located at one site or many sites can talk to one another by means of the DICOM standard across an open-system network. As a result, medical images can be captured and communicated more quickly and the health-care providers in a telemedicine system can make diagnoses and treatment decisions more quickly. In summary, digital imaging and the related DICOM standard are able to facilitate an improved quality of health care through a networked telemedicine system.

Multimedia Integration

Today's telemedicine systems have evolved from simple video conferencing between the service provider and participant to integrating multiple types of media into a coherent medical information system for the service provider to optimize decision making in the diagnosis and treatment process. In general, multimedia resources enable telemedicine system developers to integrate a high level of interactivity into routine health-care activities, such as patient-information gathering, problem solving, therapy management, and treatment follow-up. The integration of multimedia in a telemedicine system is characterized by computer-controlled production, manipulation, presentation, storage, and communications of several types of different media. Such integration enhances the value of the telemedicine system in that the traditional audiovisual world has been augmented by the processing of a variety of health care–related information to reinforce the diagnostic and treatment decision. It creates new opportunities for home-based multimedia integrated telemedicine systems, in which patients are able to monitor, treat, and learn more about their own health problems through the manipulation of a wide variety of health-related information. A telemedicine system with multimedia integration capability offers additional opportunities for health-care providers to explore medical options that cannot be accomplished through traditional face-to-face health-care services.

One specific area in which multimedia integration can play an important role is the coherent interpretation of patient data obtained from either direct or indirect patient observations. Direct observation of a patient may produce the data obtained from senses such as sight, sound, touch, and smell and through interaction with the patient. Indirect observations of a patient may be accomplished through diagnostic instruments, including many medical imaging devices. These observations may be compared with the patient's health history to derive the progression of changes for a specific health problem. In the conventional health-care setting, the clinician usually makes verbal notes and marks some sketches to characterize the observations. With multimedia integration tools, quantification of the patient data, such as computational analysis of the diagnostic images, becomes possible. Such quantification allows objective comparisons of the patient data at the follow-up examination and enables consistent treatment protocols even when the patient is assigned to a different health-care provider at the follow-up examination.

Another application for multimedia integration is the management of the electronic medical record. With multimedia integration, electronic patient medical records, including those acquired at a remote site, can be shared on-line in a telemedicine system among physicians, patients, and specialists, as well as off-line to facilitate consultation and second opinions. The management of the electronic medical records through multimedia integration has been made possible since, in a telemedicine system, the primary patient data can be electronically captured as images, videos, sounds, graphics, and text. In addition, the networked telemedicine systems allow sharing of patient data that may be located away from the service site or distributed at several sites.

Finally, multimedia integration is the key to access to Internet resources, including continuing medical education and case consultation. Since the Internet offers hyperlinked multimedia information for either public or restricted access, it may be an integral part of a telemedicine system to provide access for the general public to medical education or for a restricted pool of participants to provide sharing of specific medical information. It is anticipated that the potential for multimedia integration will be further expanded in many information systems, including various telemedicine applications.

In summary, the convergence of communications and computer technologies has shaped a wide range of new telemedicine applications. As the technologies advance to new levels, new applications will transform the daily routine of a health-care provider and offer enhanced service quality.

HUMAN AND POLICY CONTEXTS OF TELEMEDICINE

The success of the telemedicine system does not depend exclusively on technological infrastructures. Technological infrastructures are necessary conditions for the implementation of telemedicine systems. However, they are not sufficient conditions for implementation. An important factor that influences the success of a telemedicine system is the human infrastructure, which can be complex (30). In fact, it has been reported that most failures of telemedicine programs are associated with the human aspects of implementation (31). Several factors have been identified that could impede the acceptance and adoption of telemedicine, including the documentation of benefits for clinicians and patients, incorporation of telemedicine with existing practices, operation of the equipment by participants, assessment of needs and preferences (32), and government policies (1). As telemedicine practice involves both patients and health-care providers, the success of an advanced system will eventually be determined by human participants, not the technologies that support the system.

The documentation of benefits for clinicians and patients is in fact a cultural and social factor. The benefits for the clinician may include professional image and health-care quality improvement. In terms of professional image, the adoption of relatively new technology such as telemedicine by the clinicians may be regarded poorly by their peers, even though in many cases, the quality of the care has indeed been improved. Documentation on how telemedicine can help improve professional image and quality of health-care service is greatly needed. The benefits for patients have been better documented, especially in the case of enhancing rural health care through telemedicine. However, more efforts are needed to educate patients and customers about the benefits of a well-staffed and well-equipped central hospital in a telemedicine system. Such benefits are evident when multimedia integration of patients' data can be made possible by a telemedicine system so that an optimal medical decision can be derived.

The next three issues are human factors. First, it is often difficult to incorporate telemedicine with existing practices. Interactive applications require primary-care and consulting practitioners at different locations to be present simultaneously to take advantage of a real-time system. This is quite different from the existing practice, in which consulting by peers is usually performed asynchronously. Many telemedicine systems are centrally located, requiring health-care providers to travel from their traditional location of practice to use the systems. With practical and affordable multimedia desktop workstations soon to be widely available, it will be easier to incorporate telemedicine into the existing mode of health-care practice.

Second, the operation of telemedicine equipment is usually not user friendly. The difficulties associated with this issue include the initial installation of the telemedicine system and continual maintenance and upgrading. In general, health-care providers lack sufficient time to learn how to use complicated hardware and software, which usually require quite extensive training. This problem is further complicated by many information technology products that are designed from the perspective of the technology developer rather than that of the end user. As a result, users can find it very difficult to operate telemedicine equipment, and such problems can affect the quality of health care in a telemedicine system.

Third, the assessment of needs and preferences is inadequate. The needs of patients and medical practitioners are often not well communicated to the developer of a specific telemedicine system. The needs of patients include health status and problems while the needs of practitioners include individual and organization characteristics, capacities, and objectives. The preferences are related mostly to health-care providers. Often, a practitioner would prefer a certain form of presentation of patient data to make a comfortable decision. Those preferences, however, may not be possible as a result of technical limitations and financial considerations. As such needs and preferences are usually individual, it will be a challenge to develop effective methods and tools for assessing them and to provide technology that can incorporate them. A continual exchange between the users and designers of telemedicine systems is critical to their success.

In addition to these human factors, the success of telemedicine also depends on public policies at both federal and state levels. One recent federal policy that will shape the future of telemedicine is the Telecommunication Bill of 1996. The part of the policy most relevant to telemedicine is the assurance of universal communications services at affordable rates for rural, high-cost, or low-income areas. Even though the National Information Infrastructure initiative includes more elements than just telemedicine, such a policy presents an incentive for the development of telemedicine systems, especially when many telemedicine systems are designed to enhance health-care services for rural and underserved areas. State policies provide mixed incentives for the development of telemedicine. For example, policies regarding professional licensure have been greatly challenged by telemedicine. In particular, the medical practice through telemedicine complicates the decision as to whether the practitioner should be licensed if the practitioner and the patient are located across state lines. Existing state laws usually require that any out-of-state physician who diagnoses and treats a patient in the state to be licensed in that state. Most states also provide an exception that allows physicians licensed in that state to consult with physicians from other states or even other countries, and this exception could be applied to some telemedicine applications. State policies on consultation exception are not uniform, however, and many of them limit the exception to one-time or occasional consultations. Furthermore, some states even have amended or are considering amending physician licensure to prohibit out-of-state physicians from practicing without a license in that state (33,34). The inflexible or over-restrictive licensing policies of many states have a negative impact on the development of telemedicine systems. A national legislation that would create a national telemedicine license seems unlikely, unless telemedicine can prove itself despite regulatory obstacles.

Several other policy issues also have impact on the development of telemedicine. These include policies on privacy, confidentiality, and security; payment policies for telemedicine practice; and policies on the regulation of medical devices. Privacy and confidentiality issues also exist in conventional health-care practice, but the electronic recording, storage, transmission, and retrieval of patient data in a telemedicine system increase opportunities for infringing on patients' privacy and confidentiality rights. Payment policies for telemedicine practice must also be addressed. In fact, insurer and health-care restrictions on fee-for-service payments to physicians for telemedicine consultations could hinder the growth of telemedicine development. Issues include lack of information on the value of telemedicine compared with conventional service and uncertainty about whether telemedicine would cause excess service use or increase inappropriate use. The policies on the regulation of medical devices have been handled by the federal Food and Drug Administration (FDA) mainly through the Center for Devices and Radiological Health (CDRH). Many of the devices used in telemedicine have been regulated by CDRH to ensure that these devices are safe, effective, and properly manufactured. Most devices are hardware equipment such as medical imaging devices and can be appropriately regulated. However, the regulation of software used to transmit, store, process, display, and copy medical images is more complicated. The FDA is currently still exploring new policies that can better regulate software.

CONCLUSION

Telemedicine applications can expand the availability and accessibility of health care and improve the quality of medical services. Telemedicine is not a single technology or a small group of related technologies. Instead, it is an integration of many communications and information technologies. Key technologies in telemedicine include digital communications, digital video and video compression, digital imaging, and multimedia integration. In addition to technical infrastructure, human factors will also have a profound influence on the success of telemedicine.

Telemedicine will continue to evolve; the development of communications, computer, and information technologies is still moving forward at an unprecedented pace. There are great opportunities for telemedicine to improve diagnostics, therapeutics, and education in health care. However, great challenges remain. In particular, social, cultural, and legal obstacles must be overcome to achieve the maximum potential of telemedicine.

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