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Magnetic Resonance Imaging Research in Sub-Saharan Africa: Challenges and Satellite-Based Networking Implementation

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As part of an NIH-funded study of malaria pathogenesis, a magnetic resonance (MR) imaging research facility was established in Blantyre, Malaŵi to enhance the clinical characterization of pediatric patients with cerebral malaria through application of neurological MR methods. The research program requires daily transmission of MR studies to Michigan State University (MSU) for clinical research interpretation and quantitative post-processing. An intercontinental satellite-based network was implemented for transmission of MR image data in Digital Imaging and Communications in Medicine (DICOM) format, research data collection, project communications, and remote systems administration. Satellite Internet service costs limited the bandwidth to symmetrical 384 kbit/s. DICOM routers deployed at both the Malaŵi MRI facility and MSU manage the end-to-end encrypted compressed data transmission. Network performance between DICOM routers was measured while transmitting both mixed clinical MR studies and synthetic studies. Effective network latency averaged 715 ms. Within a mix of clinical MR studies, the average transmission time for a 256 × 256 image was ~2.25 and ~6.25 s for a 512 × 512 image. Using synthetic studies of 1,000 duplicate images, the interquartile range for 256 × 256 images was [2.30, 2.36] s and [5.94, 6.05] s for 512 × 512 images. Transmission of clinical MRI studies between the DICOM routers averaged 9.35 images per minute, representing an effective channel utilization of ~137% of the 384-kbit/s satellite service as computed using uncompressed image file sizes (including the effects of image compression, protocol overhead, channel latency, etc.). Power unreliability was the primary cause of interrupted operations in the first year, including an outage exceeding 10 days.

KEY WORDS: Magnetic resonance imaging, computer networks, image distribution, wide area network (WAN), brain imaging, satellite-based networks, sub-Saharan Africa, DICOM router

BACKGROUND

As part of an ongoing US NIH-funded study of malaria pathogenesis,[1] a magnetic resonance (MR) imaging research facility was established to enhance the clinical characterization of pediatric patients with cerebral malaria (CM; Fig. 1). Malaria results in the deaths of approximately one million children per year and threatens half of the world's population according to recent estimates.[2] Michigan State University (MSU; East Lansing, MI, USA) collaborates with Queen Elizabeth Central Hospital and University of

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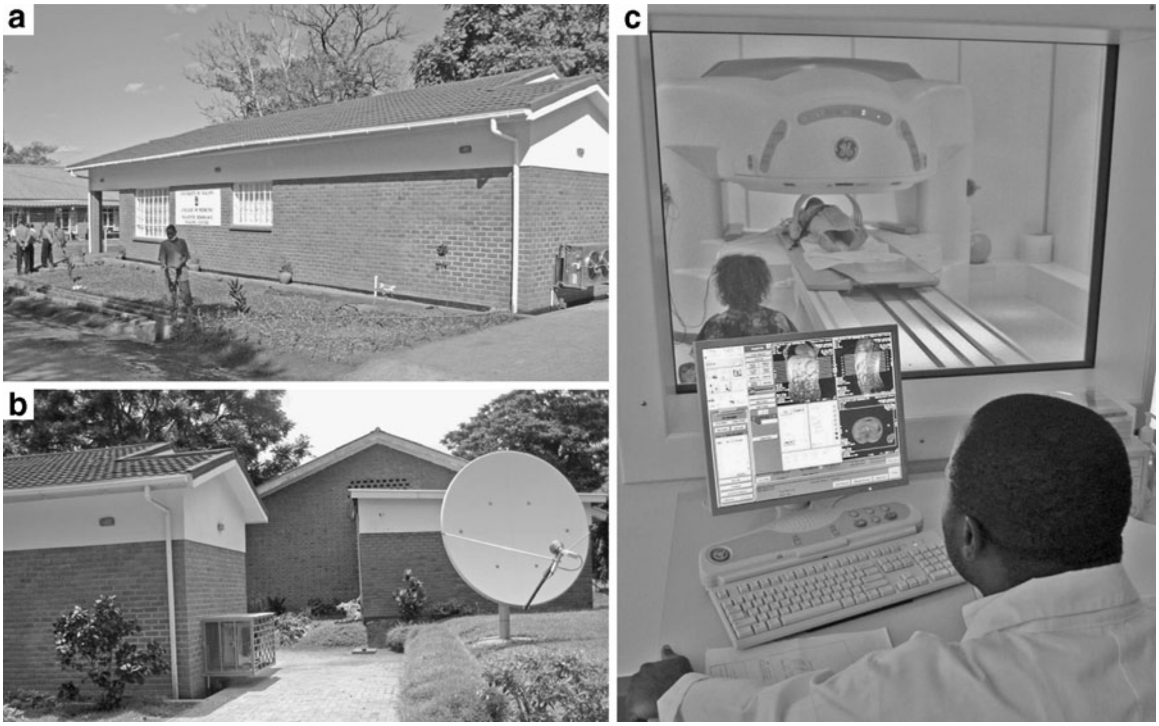

Fig. 1. New public MRI facility in Blantyre, Malaŵi. a An exterior view of the new MRI facility at UNIMA-CoM is shown. b SCPC satellite service provides symmetrical 384-kbit/s bandwidth for digital data transmission (*lower left photo*). c A Malaŵian technologist scans a patient in the 0.35-T MRI scanner (photo by John R. Williams). The MRI facility serves the population of Malaŵi and surrounding areas of Zambia and Mozambique. Malaŵi is a region exhibiting a high rate of fatal cerebral malaria.

Malaŵi College of Medicine (UNIMA-CoM) in Blantyre, Malaŵi to apply neurological MR methods in basic and clinical CM research. Queen Elizabeth Central Hospital was selected as a research site because of its location in a *Plasmodium falciparum*-endemic area experiencing a high incidence of CM and the support of the Malawi Ministry of Health. MRI was identified as the most promising imaging modality for visualization of the pathology likely to be detected in vivo.[3,4] The research program requires daily transmission of lossless-compressed Digital Imaging and Communications in Medicine (DICOM) MR studies from Malaŵi to MSU for clinical research interpretation, quantitative post-processing, and archiving. Other supporting information technology (IT functions—clinical information systems operation, research data collection, Internet protocol (IP) telephony and conferencing, email—are also required. Like much of sub-Saharan Africa, Malaŵi presently has no optical fiber connection to the Internet. The developing country location of this facility presents unusual operational challenges rarely encountered in IT projects in developed nations.

There is scant information in the recent literature or Internet content concerning satellite-based transmission of DICOM images.[5–7] Real-time satellite transmission of compressed analog ultrasound video signals and the use of lossy compression techniques to reduce the quantity of digital data transmitted over a satellite link have been discussed in the literature.[8,9] Application of satellite technology to provide medical services, including imaging, to remote locations such as offshore oil platforms and seafaring vessels has also been shown.[10,11] However, the extraordinary challenges associated with operating an imaging research facility in a remote developing nation and using satellite technology to routinely transmit lossless-compressed DICOM image data have not been examined in the literature.

Satellite-based communications present two consequential problems: an intrinsic ~250-ms up-down propagation time that results from the speed-of-light propagation of radiofrequency signals to and from geosynchronous orbit (35,784 km altitude) and a much higher cost per unit bandwidth than terrestrial networks. This paper presents insights learned during the execution of this project from three aspects: (1) details of the implementation of data networking over an intercontinental satellite-based Internet service for transmission of DICOM image data, technical challenges, and achieved performance metrics; (2) description of the configuration of the operations and the challenges presented by the developing country context; and (3) other IT-related project aspects.

METHODS

MRI Facility Implementation

A new free-standing building housing the MR scanner and associated operations was constructed on hospital grounds with funds donated by the MSU College of Osteopathic Medicine. A permanent magnet-based Signa Ovation 0.35-T MR scanner was enabled by GE Healthcare (Waukesha, WI, USA) and MSU Radiology. Continuous operation of climate control systems is essential to the proper operation of this permanent magnet system, and therefore, the original facility plan included two generators to support continued operation in the event of a sustained power failure. However, the likelihood of a power failure lasting more than 10 days was deemed low, and as a cost-saving measure, it was decided to instead purchase a single generator rated for 250 h of continuous operation before requiring a shutdown for maintenance. The new MRI facility began operation in August 2008. Recruitment and subsequent treatment of patients enrolled in all human subject research described herein was conducted in accordance with the procedures approved by institutional review boards at MSU and UNIMA-CoM, and informed consent from each child's family was obtained.

Configuration of the PCs required at the Malaŵi site was done prospectively at MSU. In order to mitigate delays associated with technology export compliance, PCs were packed in their original containers and shipped by air freight to the site 1 month prior to their scheduled deployment. To speed clearance through Malaŵi customs and provide sufficient documentation to satisfy authorities that the items were donations to Blantyre Malaria Project and therefore exempt from import duties, a copy of the original purchase invoice, an excerpt of the grant application detailing the purpose of the equipment, a customs declaration form, and an executed letter of donation were packed with each shipped box.

Intercontinental Satellite-Based Network Implementation

Figure 2 depicts the implementation of the intercontinental satellite-based data networking between MSU and the Malaŵi MRI Facility. Local area network (LAN) connectivity within the MRI facility was implemented using an Ethernet switch (HP ProCurve 2626, Hewlett-Packard Co., Palo Alto, CA, USA). Imaging studies performed on the MR scanner are transmitted to a DICOM router (ACUO Technologies, LLC, St. Paul, MN, USA), which functions as DICOM image storage, automatically forwards images to a stand-alone DICOM image viewing workstation (Merge Healthcare, Milwaukee, WI, USA) for primary diagnostic reading at the Malaŵi MRI facility, and performs queued image transmissions to MSU.

Remote Internet connectivity was established via C band wireless relay from a very small aperture terminal (VSAT) satellite ground station through the Telstar 10 geosynchronous satellite to the Internet service provider's (ISP) Cambridge, UK facility (AfriConnect, Ltd.). Symmetrical 384-kbit/s service costing approximately US $3,600 per month was selected. The service level agreement with the satellite ISP specifies a minimum of 98.5% uptime. A reciprocal agreement with UNIMA-CoM allows for limited network redundancy by sharing a separate existing UNIMA-CoM contracted satellite Internet service. A rack-mounted PC running Squid (www.squid-cache.org) and DansGuardian (dansguardian.org) software on CentOS Linux (www.centos.org) serves as a bandwidth manager and proxy server to ensure timely delivery of MRI data by prioritizing network traffic types, caching web page content, and filtering undesirable network traffic. The bandwidth manager also provides capabilities to support automatic failover and bandwidth sharing, although this feature has not been utilized. A hybrid router/firewall (Cisco 1811, Cisco Systems, Inc., San Jose, CA, USA) provides network address translation and Dynamic Host Configuration Protocol services for the LAN and

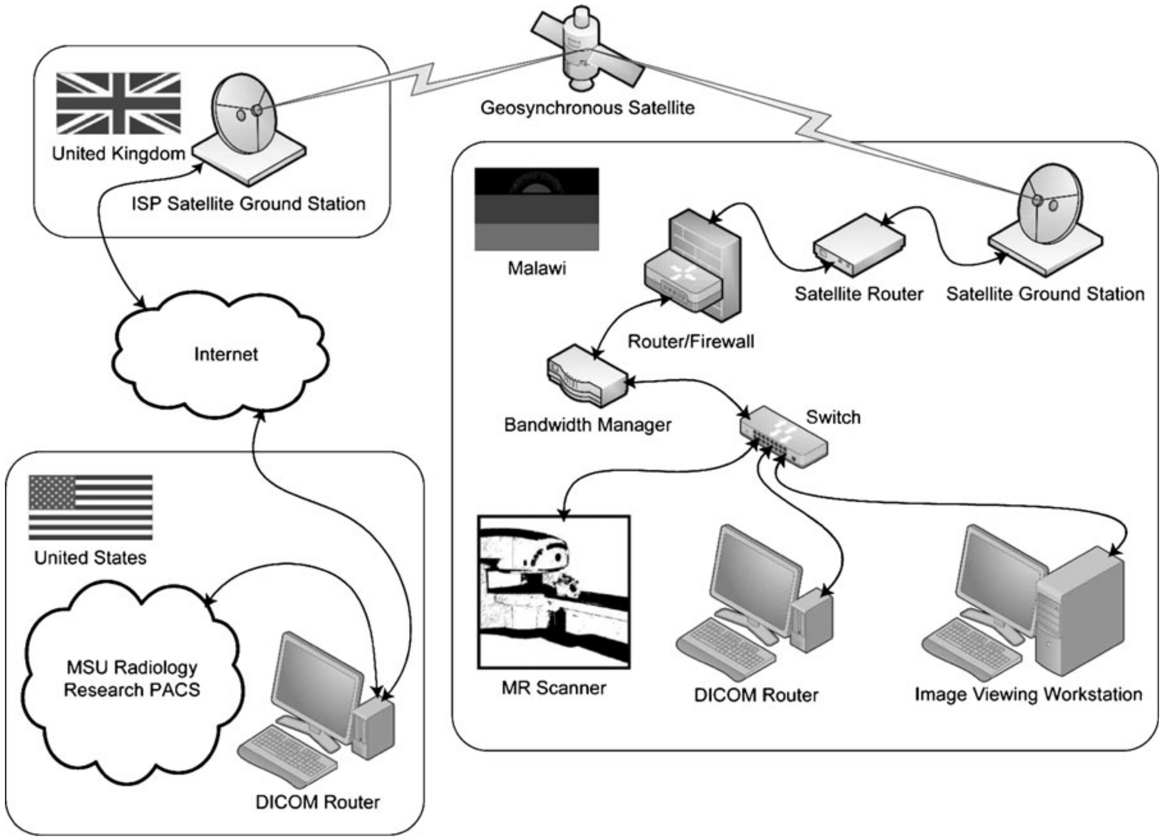

Fig. 2. Schematic of the project network implementation. At the MRI facility in Malaŵi, images are transmitted from the MR scanner to a DICOM router which stores the images and automatically selects, queues, and compresses them and then assures delivery to MSU and the local DICOM workstation. Remote image transmission is performed DICOM router to DICOM router. Data transmission between Malaŵi and MSU is carried out through an intercontinental satellite-based Internet service relayed in the UK and then via the fiber Internet to MSU in the USA. The satellite Internet service is also used for email, file transfer, and remote system maintenance. A DICOM workstation (Merge eFilm) is used for local interpretation of MRI studies at the Malaŵi MRI facility.

excludes unauthorized traffic to protect the LAN from malicious agents. A satellite router (iDirect 5100, Satcom Resources, Avon, CO, USA) performs sophisticated modulation/demodulation functions and implements Transmission Control Protocol and Hypertext Transfer Protocol network protocol acceleration strategies, lossless compression, and Domain Name System caching to minimize apparent link latency and optimize utilization of the available single channel per carrier (SCPC) satellite bandwidth.

Automated encrypted end-to-end transmission of imaging studies is managed by the DICOM routers which are deployed at both the Malaŵi MRI facility and MSU. The long channel latencies of a satellite-based Internet service would impair the usual direct interconnection of a DICOM image storage service class user and service class provider (SCP). The Malaŵi DICOM router functions as a DICOM storage SCP locally, applying configured rules to select studies for transmission to specific destination(s); caching, encrypting, and queuing studies; and handles transmission errors robustly to exchange DICOM images with the remote DICOM router using an efficient proprietary routed network protocol (not the DICOM network protocol described in parts 7 and 8 of the standard). At MSU Radiology, the research picture archiving and communication system supports secondary/research interpretation of MR studies and long term archiving.

MSU technical personnel traveled to the site to coordinate the project launch. DICOM connectivity was established and tested between the modality, viewing workstation, and DICOM router using a temporary network configuration because, although the satellite installation was partially completed, it was stalled due to delays in the delivery of parts. Once satellite connectivity was established, UNIMA IT staff finished the network implementation with remote guidance from MSU staff. UNIMA provides ongoing local IT support for the MRI facility. A conservative satellite bandwidth allocation of 90% for image traffic and 10% for interactive uses was selected to ensure timely transmission of study image data.

Web-based remote administration software (LogMeIn IT Reach, LogMeIn, Inc., Woburn, MA, USA) was deployed on all PCs at the Malaŵi site to allow some configuration and maintenance tasks to be performed from MSU. The LogMeIn software creates a secure connection between any two Internet-connected computers that have it installed, enabling remote access. MSU IT support personnel used LogMeIn to conveniently transfer files and administer the Malaŵi computers interactively as if present at the local keyboard.

Satellite Network Performance Metrics

Image transmission speed experiments were conducted by sending research and clinical MR neuroimaging DICOM studies from the Malaŵi MRI facility and analyzing the recorded activity in the log files of the sending and receiving DICOM router to determine the time elapsed between receipt of the image storage request message and transmission of the outgoing response indicating successful storage of the image for each image. These MR studies consisted of a mixture of ~30% images having a reconstructed matrix size of 256× 256 and ~70% with a matrix size of 512×512. Each image was lossless compressed and decompressed by the DICOM routers. Data from the recorded log files were analyzed and histograms generated using SPSS Statistics 17.0 software (SPSS Inc., Chicago, IL, USA).

Additional experiments were carried out using artificially constructed MR studies to further investigate the characteristics of the communication channel without the confounding influence of variation in the image data being transmitted. Two artificial MR studies, each containing a total of 1,000 identical images with only their DICOM series instance unique identifier (UID) and service–object pair (SOP) instance UID attributes varying, were constructed containing ten series with each series containing 100 images. The first study was constructed from copies of an axial slice from a typical 3D localization scan, acquired using 256 frequency and 128 phase encoding steps, with an image matrix size of 256×256 in the Fourier-reconstructed image. The second study was produced from a typical axial T1 fluid-attenuated inversion recovery source image acquired using 288 frequency and 160 phase encoding steps with a 512×512 image matrix.

Transmission experiments were conducted after the imaging center's business hours to ensure that no other imaging traffic would interfere with the measurements. Performance testing data comprised 10,664 images transmitted in six testing sessions spanning 1 week during Malaŵi nighttime hours, with the images being received seven geographic time zones away in the early evening. Copies of the transmission logs of the DICOM routers at both the Malaŵi site and MSU were recorded prior to each transmission and again afterward. The artificial studies were transferred to the site via the LogMeIn file manager, imported into the viewer application, and transmitted to the DICOM router sequentially, waiting for each transmission to complete and copies of the logs to be recorded before proceeding with the next transmission. Log data were analyzed using SPSS version 17.0. Transmission time for the DICOM router in Malaŵi was determined from the logs as the time between when the image storage request message was sent and a response was received indicating successful storage of the image. Transmission time for the MSU DICOM router was determined as the time between receipt of a request to store an image and transmittal of a response indicating the image was successfully received and stored.

Clinical Study Interpretation and Research Data Collection

In addition to transporting images to MSU for analysis, the satellite network is required to support custom web-based research data collection software entitled NeuroInterp which uses menu-driven graphical forms to capture the physician's interpretation in a structured manner, using quantitative and categorical scores. The current version of this software was developed using C# ASP.NET 2.0 and Microsoft SQL Server Express. As development of this software continues, LogMeIn is

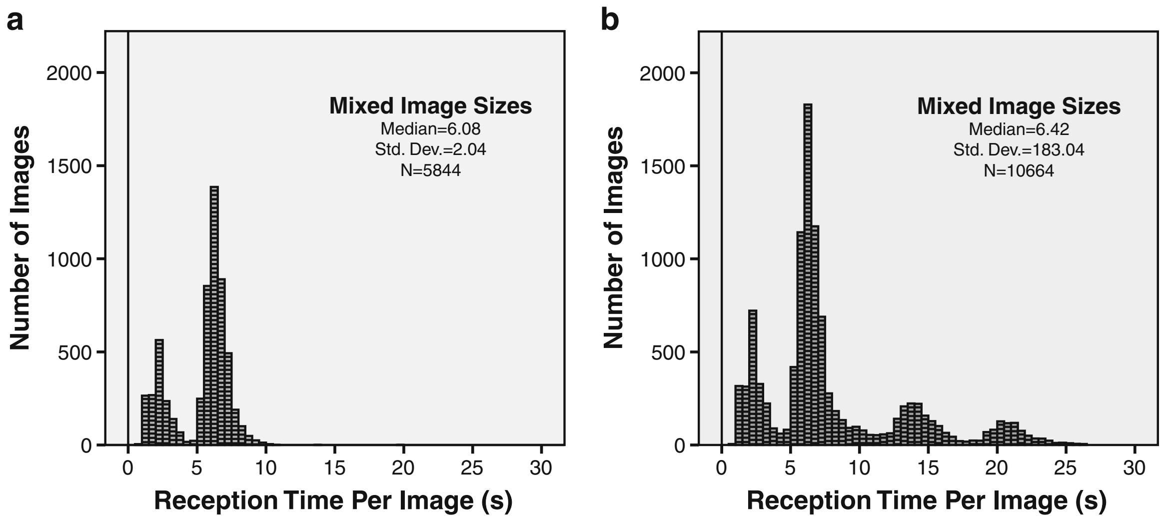

Fig 3. Image transmit time histograms for a mixture of two image sizes. Image transmission time was evaluated by sending large sets of MRI studies from the Malaŵi DICOM router to the MSU DICOM router, containing ~30% 256×256 matrix images and ~70% 512×512 matrix images. a The two peaks in the distribution correspond to 256×256 and 512×512 images. The histogram mode for the 256×256 image is ~2.25 s, and the mode for 512×512 images is ~6.25 s. b Histogram of the overall satellite network performance across all of the timing experiments. Some anomalous behavior occurred during two of the experiments resulting in the two additional peaks probably due to high network error rates incurring packet and or image retransmissions. One outlier measurement with a transmission time of 4.6 h caused the large standard deviation of 183.04 s (outliers are not shown in Fig. 3 plots). Ninety-nine percent of all observed transmissions had a duration less than 23.32 s.

used to perform software updates remotely and manually backup data files.

RESULTS

Performance of the Intercontinental Satellite-Based Network

The histogram of image transmission times shown in Figure 3a demonstrates the typical performance of the satellite network while transmitting a sample of clinical imaging studies between the DICOM routers, with two peaks in the distribution corresponding to 256×256 and 512×512 image matrix populations. The histogram in Figure 3b represents the overall behavior of the satellite network across all of the timing experiments performed using clinical MRI study data. The normal mode for the transmission of a 256×256 image, as measured from the receiving DICOM router at MSU, is ~2.25 s and the mode for a 512×512 image is ~6.25 s in Figure 3a, b. Some anomalous behavior occurred during two of the experiments resulting in the two additional peaks in the image transmission time histogram of Figure 3b not seen in Figure 3a.

Channel transmission behavior was further characterized by experiments conducted using artificial MR studies constructed such that every image in the study has the same pixel data, differing from other images only in its SOP instance UID and series instance UID attributes. Figure 4a, b shows histograms of image transmission times as measured from the DICOM router on the receiving (MSU) end for such an experiment using an artificial MR study containing 1,000 duplicate copies of a single 256×256 axial brain image and a corresponding study containing 512×512 images, respectively. The median time to transmit a 256×256 image was 2.34 s on the receiving side and 3.08 s on the sending side. The interquartile range was [2.30, 2.36] s on the receiving side and [3.02, 3.08] s on the sending side. The range was [1.67, 78.60] s on the receiving side and [2.39, 79.30] s on the sending side due to the presence of a single outlier value. For the 512×512 images (Fig. 4b), the median transmission time was 6.00 s when measured from the receiving side of the link. The interquartile range was [5.94, 6.05] s and the range was [5.25, 8.08] s. Measured from the sending side of the link, the median transmission

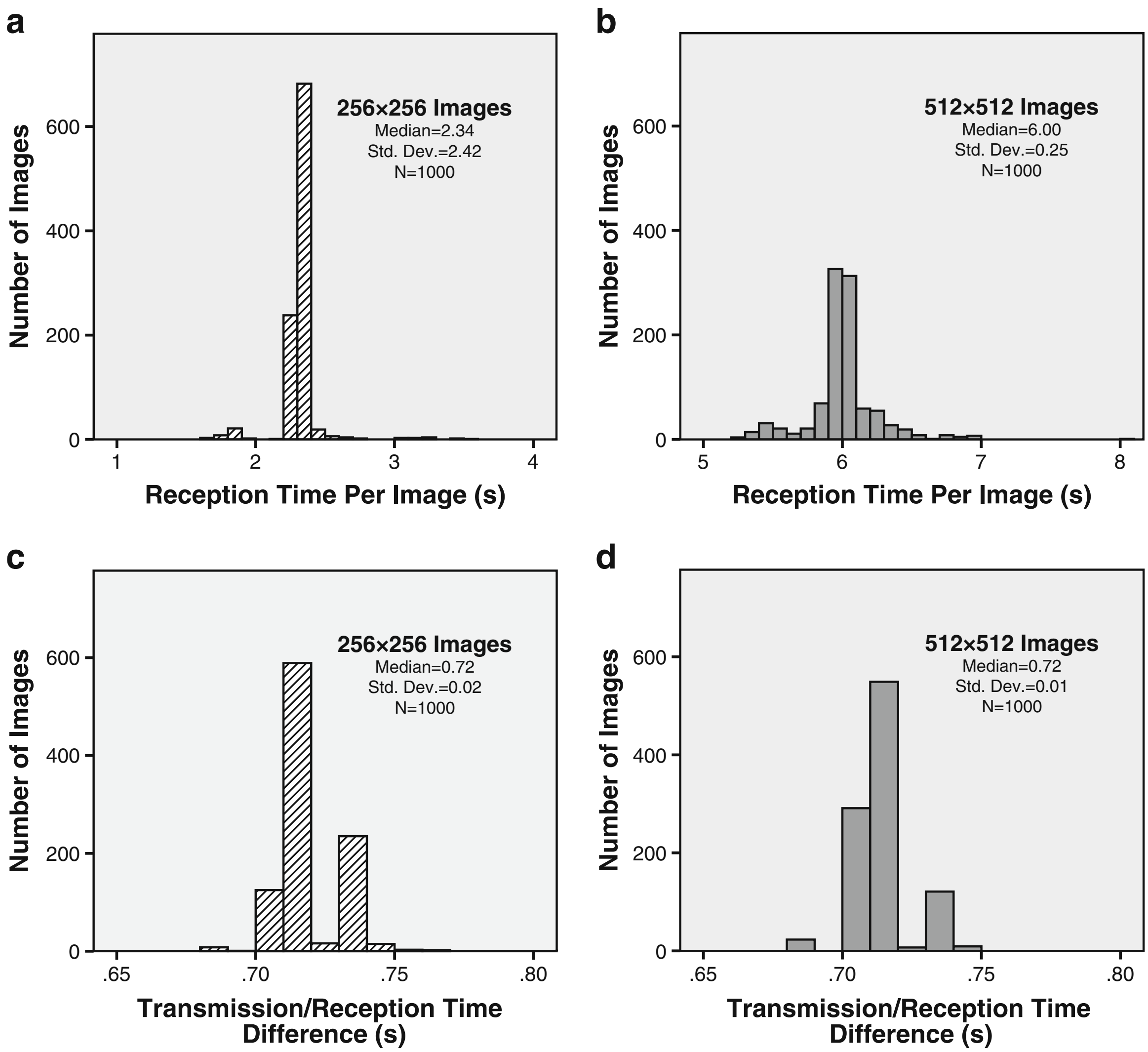

Fig. 4. Image transit time histograms for transmitting a synthetic study comprising 1,000 duplicate MR images that were 256×256 for (a) and 512×512 for (b). c, d The respective differences in transmission time as measured by the sending and receiving DICOM routers. The c and d difference histograms are effectively showing the distribution of round-trip network latency and hence are very similar.

time was 6.70 s, the interquartile range was [6.66, 6.75] s, and the range was [5.95, 8.78] s.

Figure 4c, d shows histograms of the differences between transmission times measured at the sending and receiving routers for the "1,000 duplicate images" experiments with image matrix sizes 256×256 and 512×512, respectively. The median difference in the transmission time measurements taken at the sending and receiving sides of the link for 256×256 images was 0.72 s. The interquartile range was [0.72, 0.73] s and the range was [0.69, 0.91]. For 512×512 images, the transmission time difference has a median value of 0.72 s, interquartile range of [0.70, 0.72] s, and range of [0.69, 0.75] s.

Round-trip latency was also evaluated via Internet Control Message Protocol (ICMP) ping testing. The test, conducted overnight from a PC at MSU to the DICOM router in Malaŵi, measured a minimum ping time of 678 ms, maximum of 1,135 ms, and average of 715 ms for a test consisting of 54,779 transmitted packets. Packet loss occurred in 100 of the packets (0.2%).

Facility Operations: Electrical Power Unreliability

Power unreliability has been the primary cause of interrupted MRI operations in the first year since the opening of the facility. Multiple power outages per day are not uncommon. Power failures temporarily interrupt operations as switchovers to/from diesel generator power are performed. Power losses interrupt magnet operation; satellite, and LAN communications; and air conditioning of the magnet and equipment rooms. In one incident, failure of a step-down transformer on the main power supply for the area resulted in a sustained power loss because there were no spare transformers available in Malaŵi. During the first year of MRI operations, an extended power outage incident occurred when the facility operated on generator power for 10 days, but then had to shut down for several hours in order to service the generator. Continued intermittent power losses and high ambient temperature resulted in degraded image quality that persisted for ~3 days after grid power was restored.

DISCUSSION

This new MRI facility is among the first public MRI facilities in sub-Saharan Africa. Successfully establishing a collaborative research MR facility in a developing country requires surmounting logistical, political, and regulatory complications; limited local technical resources; and human research protection challenges. Delivery delays caused by communication and transportation difficulties must be anticipated and their effect mitigated. The pre-existing infrastructure imposes constraints on system designs and implementation schedules. For example, the lack of local infrastructure for supply of liquid helium along with unreliable electrical power service precluded the use of a higher-field strength superconducting MRI scanner, resulting in the decision to install a 0.35-T permanent magnet scanner. A generous travel budget allocation is necessary to address unanticipated problems and ensure forward progress of the research project.

In the developing world, it is common practice to subcontract the whole job to access labor and resources in the locale of the job site because of inefficiencies associated with travel. More than one level of subcontracting is common. This practice resolves travel problems but complicates project management. Email communication was critically important as a coordination tool, especially for communications with staff at MSU due to the 6- to 7-h time zone difference.

Networking

Prospective budgetary considerations were the primary determinant of the satellite link speed. Dedicated symmetrical satellite service with a fixed bandwidth of 384 kbit/s was chosen instead of an available service with burst capability which permits temporarily increased bandwidth whenever excess capacity is available but features a lower level of guaranteed minimum bandwidth. The rationale for this decision was that, because satellite is the only viable option in the region for high-bandwidth applications due to the lack of a fiber optic connection to the Internet, demand for satellite service would be high and the excess channel capacity needed to enable the satellite burst feature would rarely occur in practice. Furthermore, limited economic resources ensure that subscribers will purchase no more bandwidth than what is minimally necessary to meet their application requirements, resulting in high utilization of the limited satellite capacity.

Some unusual behavior was captured in two of the six experiments performed with clinical imaging studies. In these experiments, two additional peaks appear in the image transmission time histogram shown in Figure 3b, occurring at approximately integer multiples of the center of the large peak seen in normal operation. This suggests that they may represent incidents where transmission errors required complete retransmission of an image one or two times. The reason for the appearance of the delayed transmission time peaks is not known with certainty. Because the measurements were taken at night in Malaŵi during the last days of the wet season, it is reasonable to speculate that the aberrant transmission behavior may have been caused by rain attenuation of the C band satellite signal. However, we did not collect corresponding weather data at the site to confirm or contradict this.

Lossy image compression could not be employed in this project because quantitative parameter estimation post-processing and research study archiving is performed at MSU. Because lossless image compression is applied prior to the transmitting data, the transmit time of 512×512 images compared with 256×256 images is not required to be the 4:1 ratio that would be expected for transmitting uncompressed images. Although the size of an uncompressed 512×512 image is four times larger than a 256×256 image, the lossless compression factor that can be achieved for a given image is more closely related to the information content of the image than the size of the image matrix. For MR images, correlation among adjacent pixels results from the interpolation that occurs in the Fourier image reconstruction process when any acquisition matrix dimension is less than the reconstructed image matrix dimension. The interpolation correlations will make such an image intrinsically more compressible. MR images acquired using matrix dimension(s) smaller that the reconstructed image dimension(s) can be expected to compress more than otherwise. The two images contained in the two artificial studies for testing were acquired as 256×128 and reconstructed as 256×256 and 288×160 reconstructed as 512×512. The 512×512 image will compress by a higher factor than will the 256×256 image, all else being equal. The varying compressibility among the images within the clinical studies largely explains the differences seen between Figures 3a and 4a, b for the corresponding image sizes. The remarkably narrow distributions shown in Figure 4 demonstrate the practical appropriateness of employing the intercontinental Internet for medical imaging.

The transmission time differences between measurements taken from the DICOM router in Malaŵi compared with the router at MSU exhibit an expected behavior. Similarity in Figure 4c, d demonstrates a net additional round-trip protocol exchange measured on the sending DICOM router which corresponds to the average ICMP ping time of 715 ms. This net round-trip likely corresponds to the time for the initiating image storage request message in addition to the concluding acknowledgement of reception of the error-free completed image. The average 715-ms round-trip includes two ~250-ms speed-of-light satellite hop propagations.

Other smaller factors may contribute to the differences between the transmission times measured at the sending and receiving DICOM routers. Detailed information regarding the exact contents of any particular frame transmitted over the satellite was not available because the connection is encrypted and because we opted to analyze router log files, which were convenient to obtain. More robust tools such as network packet sniffers could have provided a more complete description of the network packets transmitted, but at the cost of greatly increased complexity in the subsequent data analysis. Any delay occurring between when a message indicating that image storage has commenced (or has completed) has been received and the time when the value of the system clock is read by the process that logs the event can have an effect on the measurement. Thus, any time the process that performs event logging is interrupted by the operating system scheduler or blocks for synchronous input/output (I/O), the reported time of day could be increased.

Despite the limited mix of MRI procedures used in our testing—principally brain procedures—stating some overall performance metrics could be useful for planning purposes by others. The mix of clinical image sizes averaged ~30% 256×256 images and ~70% 512×512 images. End-to-end networking performance is largely determined by the satellite portion of the network due to its low symmetrical 384-kbit/s data rates and ~250-ms latency. Given these conditions, the observed aggregate speed of the transmission of clinical MRI studies between the DICOM routers averaged 9.35 images per minute. This represents an *effective* channel utilization of ~137% of the 384-kbit/s satellite service as calculated using uncompressed image file sizes (including the beneficial effects of image compression, as well as the costs of protocol overhead, channel latency, and all other inefficiencies).

After completion of the satellite Internet service implementation, the availability of skilled IT staff at UNIMA was a crucial factor in successfully completing configuration and maintenance of the facility network.

Telephony

The expense of international calls made telephone communication undesirable prior to successful satellite installation. Voice over Internet Protocol (VoIP) telephony software (Skype, Skype Technologies S. A., Luxembourg) was tested after completion of the satellite implementation and a connection was successfully established; however, changes in our current bandwidth allocation scheme are needed in order to provide adequate audio quality without excessive transmission delay. After characterizing the end-to-end image transfer performance and daily volume of studies produced at the facility, it became clear that bandwidth allocation constraints may be relaxed to allow future improvements in the quality of VoIP service and web access without undue impact on the timely availability of imaging studies. Furthermore, VoIP across our dedicated satellite link enables communication during public cellular phone service outages which occur sporadically.

Dealing with Unreliable Electrical Power

Electricity Supply Commission of Malaŵi (ESCOM) generates and distributes power in Malaŵi. Due to insufficient power generation capacity, ESCOM is compelled to conduct power-shedding programs in which portions of the power grid are temporarily shut down every week to prevent system overload. The power-shedding programs are expected to continue for several years until ESCOM can obtain sufficient capacity to meet demand. Although service is typically restored within 2 h, the mission-critical nature of the MRI facility and the days required to achieve magnet thermal stability necessitate a reliable system for backup power generation.

Power supply instability is especially problematic for permanent magnet-based MRI equipment in a tropical climate. The thermal stability of the permanent magnet depends upon reliable power for air conditioning. A sustained power outage can cause image quality problems which persist following power restoration, resolving only when thermal equilibrium is reached.

CONCLUSION

This project established an MRI facility to support pediatric cerebral malaria research and general patient care in Blantyre, Malaŵi and the surrounding area. Satellite networking infrastructure providing symmetrical 384-kbit/s Internet service was implemented to achieve practical intercontinental transport of DICOM image data via the Internet. The aggregate transmission rate of clinical DICOM brain MRI studies averaged 9.35 images per minute. Operational difficulties have been largely caused by unreliable electrical power utility service. Careful consideration, using historical electrical power reliability information, should be given to facility planning and design to survive extended power interruptions as well as frequent shorter interruptions.

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