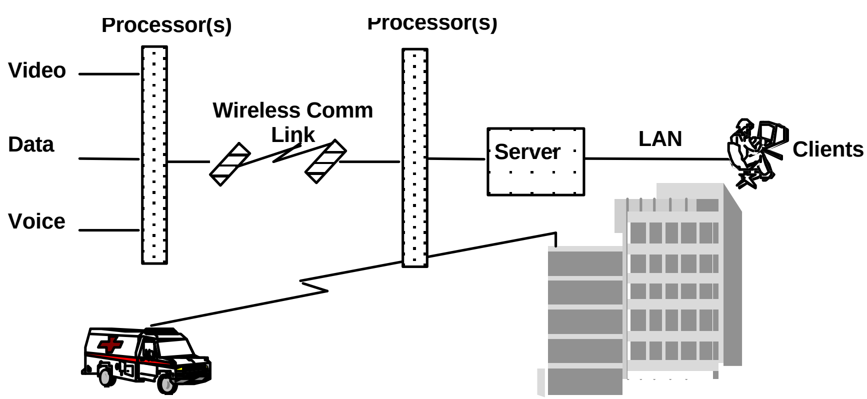
Final Report

Mobile Telemedicine Testbed

Health Applications
for the
National Information Infrastructure



National Library of Medicine
Project N0-1-LM-6-3541
15 Aug 1998

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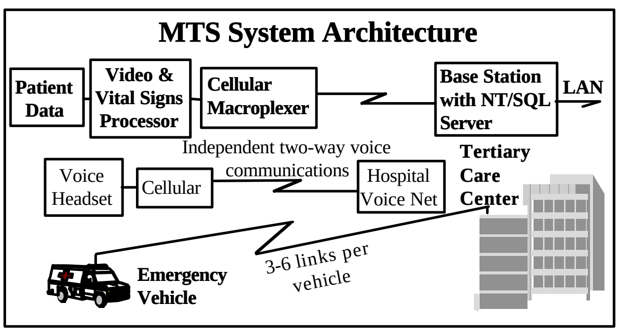
1. EXECUTIVE SUMMARY

Overview

The objective of the Mobile Telemedicine System (MTS) project was to determine the feasibility of transmitting real-time vital signs data and video images from enroute ambulances to the receiving trauma center via digital cellular communications. The goal was to improve the quality and timeliness of care provided during the prehospital transport phase of the “golden window” immediately following insult or injury and to provide better information to the emergency department staff prior to arrival at the hospital.



Clinical Evaluation Model

The project focused on speeding the treatment of brain attack (acute ischemic stroke) patients. Because treatment of brain attack is time critical, options are constrained by the delay between symptom onset and definitive diagnosis. Using the mobile telemedicine system to transmit diagnostic information enroute shortens delays to therapeutic treatment, increasing the available treatment options and improving patient outcomes.

Acute Ischemic Stroke

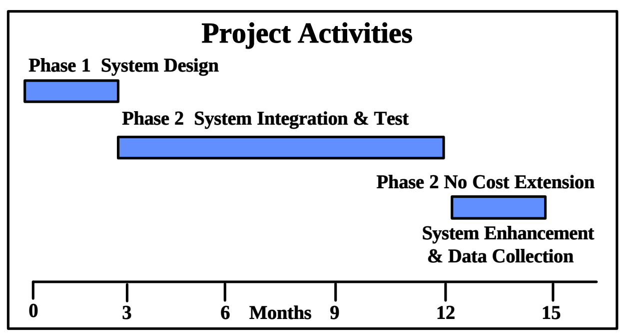
Background: maximum 3 hour “window” from symptom onset for administration of t-Pa

Protocol: neurologist at hospital views patient vital signs and the administration of the NIH Stroke Scale in ambulance by a trained EMT

Measure: time from arrival at hospital to definitive diagnosis of stroke - compare to time to diagnosis prior to use of Mobile Telemedicine System (MTS)

Systems Integration & Test

The project team designed, integrated, and installed in three ambulances a mobile telemedicine system (MTS) using commercial-off-the-shelf (COTS) equipment with data management and physician interface software developed in JAVA. The team conducted a series of tests including a dozen patient transports. Resolving stability issues caused by the COTS equipment delayed the data collection.



Technology Proven

This groundbreaking project demonstrated the technical feasibility of the MTS and obtained preliminary data suggesting that the system indeed provided clinical value.

Key Project Results

- MTS Technical Feasibility Demonstrated
  - = Cellular communications integration accomplished
    - Macroplexing multiple phones possible
    - Frame rates of 1 image / 3 seconds sufficient
  - = Real-time vital sign data transmitted with video
  - = Information automatically presented to physician via intuitive, easy to use browser interface
- Clinical Effectiveness Suggested
  - = Insufficient data collected to date for definitive analysis
  - = Preliminary data suggests benefits will be achieved
  - = Physician participants enthusiastic about potential
  - = EMT participants excited about assistance MTS provides

Recommended Next Steps

Additional data collection is needed for the brain attack model as well as for other acute care clinical models such as myocardial infraction (heart attack). Additional investigation is needed to assess alternative communications modes such as multiple cellular providers in parallel and use of connectionless IP services to expand MTS usability to rural areas. Alternative video compression algorithms need to be assessed for improving video transmission frame rates. Other recommended infrastructure enhancement activities include integration of more patient data, such as heart and lung sounds and blood chemistry.

2. Introduction

The project Team of BDM [now owned by TRW, Inc.], the University of Maryland at Baltimore (UMAB) and HCI Technologies has been investigating the feasibility of transmitting real-time vital signs data and video images from en-route ambulances back to the receiving trauma center via digital cellular communications. Each member of the Team brought unique yet complementary features to the project - TRW supplying project management, systems integration, programming, and technical expertise; HCI supplying their network communications expertise, and UMAB supplying clinical perspective, requirements definition, and testing of the system. The project has also been generously supported by Maryland ExpressCare, the primary critical patient transport company for the University of Maryland Hospital.

The goal of the project has been to improve the quality and timeliness of care provided during the "golden window" immediately following injury and to provide better information to the emergency department (ED) staff prior to the arrival of patients at the hospital. The Team originally proposed the following objectives for meeting this goal:

Technical Feasibility (Does it work?)

- Demonstrate that a mobile telemedicine system can be implemented via cellular communications between ambulances and correspondent trauma centers,
- Demonstrate that both real-time vital sign data and video image data can be transmitted and used effectively in such a mobile system, and
- Demonstrate that the electronic patient record can be implemented effectively at the initial point of care.

Process Improvement (Does it make a difference?)

- Enhance the diagnosis and management of trauma care and other medical emergencies,
  - Leverage trauma center and hospital resources (i.e. Physicians and other caregivers),
  - Provide audit trail of care provided,
- Better prepare trauma centers for incoming patients,

Experiments performed by the Team prior to the start of the project had successfully demonstrated the wireless transmission of images and data from a mobile ambulance, proving the feasibility of the project and providing a test-bed foundation for meeting the project objectives. A phased implementation approach was used, leveraging the initial proof-of-principle work accomplished by the

Team in Phase 0 as a starting point. The two subsequent implementation phases were defined as follows:

Phase I: System Design, encompassing

- the analysis of the results of the UMB proof-of-principle demonstration,
- the identification of additional emerging technologies which can support video transmission via digital cellular,
- the upgrade of the system architecture described below based on the emerging technologies identified,
- the development of a detailed work plan and schedule for a Phase II testbed demonstrating the feasibility and practicality of such a mobile telemedicine application, and
- the refinement of the collection plan and evaluation criteria for assessing the clinical contribution of the mobile telemedicine application.

Phase II: System Integration and Test, encompassing

- the establishment of the mobile telemedicine testbed,
- the collection of performance and clinical effectiveness data, usability assessment, and
- the evaluation and publishing of results.

Based upon insightful feedback from the NLM review of the Phase I Plan, the Team sharpened the clinical evaluation model to focus upon speeding the treatment of brain attack (acute ischemic stroke) patients. Treatment of brain attack is time-critical; the available treatment options are constrained by the delay between symptom onset and definitive diagnosis. The FDA-approved treatment protocol requires that recombinant human tissue plasminogen activator (t-PA) must be administered within three (3) hours of symptom onset[6]. Delays in receiving treatment result in only around 3% of the patients that could potentially benefit from receiving t-PA.

The revised model was chosen with the collaboration of the Maryland Brain Attack Center (MBAC), a specialist team formed in August 1996 to speed the treatment of brain attack patients. Using the mobile telemedicine system to transmit diagnostic information en-route allows shortening the delays to therapeutic treatment, increasing the available treatment options and potentially improving patient outcomes. This redirection of the project provided a much clearer clinical model for the evaluation of the system efficacy than the somewhat imprecise 'process improvement' objective originally planned.

The clinical effectiveness of the mobile telemedicine system was to be measured by the saved time to definitive diagnosis of stroke by the MBAC neurologist following admission to the University of Maryland Hospital. Patients with stroke transported prior to the study were used as controls and compared to those transported during the study. The time from the moment of arrival at the University of Maryland Hospital to completion of the diagnosis was the metric for comparison (ref. Fig 1). Analysis of over 300 historical controls showed the shortest time to definitive diagnosis as 7 minutes, the longest as 82 minutes, with the average time as 35 minutes.

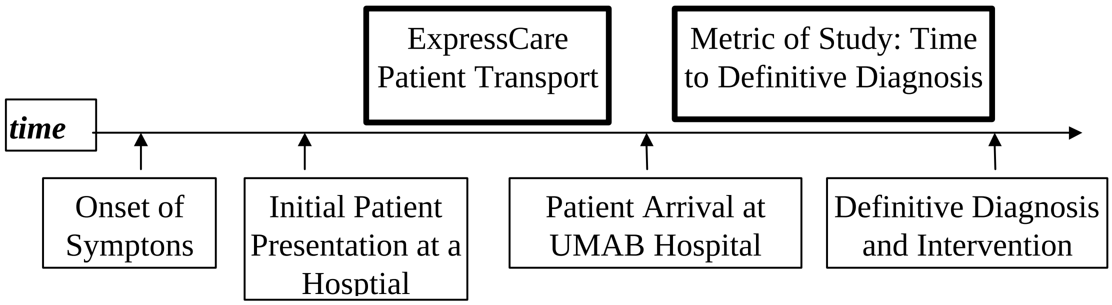


Figure 1: Time to Definitive Diagnosis

Phase II activities took significantly longer to accomplish than had originally been planned, delays due primarily to failures of the commercial system components to perform in a stable and reliable manner when integrated within the mobile telemedicine system. Each of these failures resulted from conditions unexpected by the component vendors, and only encountered by this Team's aggressive use of cutting-edge technology. While the project successfully addressed each problem, the problem solving activities delayed achieving a stable and reliable system. Hence, a no-cost extension was granted to address remaining stability issues and to continue the data collection.

3. Summary of Work Performed

Since the project's inception in October 1996, the Team has developed, installed, and field-tested an ambulance data transmission system, a hospital reception/information delivery system, and a protocol for the remote neurological evaluation of brain attack patients.

The system has been deployed on three ambulances, one of which has subsequently been retired from service. The system is currently in use on two ambulances for remote evaluation of brain-attack patients.

Figure 2 represents the overall design of the system information flow of the mobile telemedicine system. Data containing video images and patient biosignals are transmitted separately from voice. Individual video images are captured sequentially over time and stored in individual files. Each of the images are tagged with a time stamp for proper sequencing during replay.

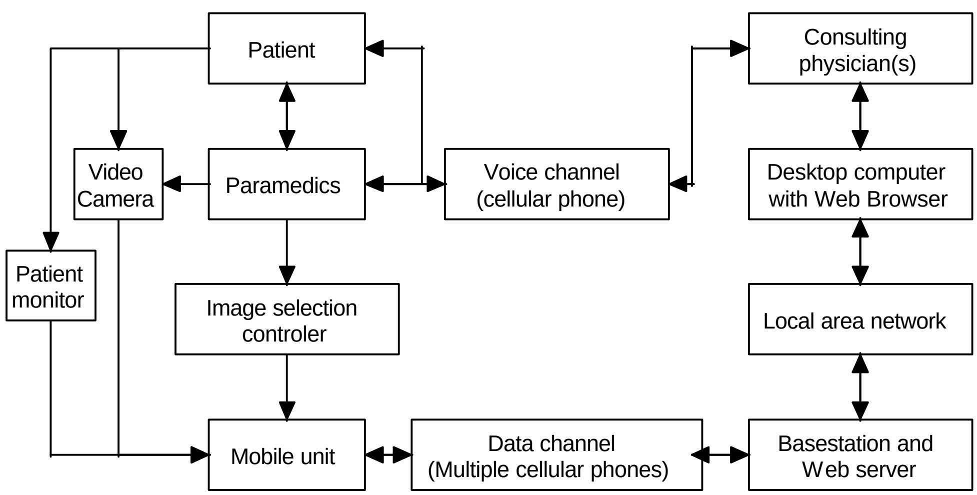


Figure 2 Information Flow within the System

The design approach taken was to use existing, open-systems, commercial components wherever possible in order to keep costs low and to best leverage external technology development. In canvassing the marketplace, the project identified the following vendor technologies as key components for the mobile transmission system:

1) FoNet (www.firstlook.com)
FoNet is an award-winning manufacturer of mobile video transmission systems for the broadcast television market. Early

(Phase 0) testing with a FoNet ResQCam™ system (developed by FoNet in support of the Oklahoma bombing rescue efforts) led to the selection of the FoNet AmbuCam™ system as a core project technology. The FoNet system is responsible for capturing, digitizing, and compressing the video data stream, and for managing the wireless communications. A unique, patent-protected feature of the FoNet system is the ability to manage the transmission of data over multiple cellular lines in parallel, required by the project to achieve the desired aggregate transmission bandwidth.

2) Protocol Systems, Inc. (www.protocol.com)
Protocol Systems designs, manufactures and markets vital signs monitoring instruments and systems. Their portable monitoring unit, the Propaq Encore™, is the standard patient vital signs monitor used within the Maryland ExpressCare ambulances.

3) WESTECH Mobile Solutions (www.westechmobile.com)
WESTECH is a leading manufacturer of software programs for the pre-hospital environment. WESTECH had developed a digital interface to an earlier version of the patient vital signs monitor, and was recommended by Protocol Systems as the firm of choice for developing the interface software required by the project to load data from the patient monitors.

4) Sprint/American Personal Communications (Sprint/APC) (www.sprintsectrum-apc.com)
Sprint/APC was selected as the wireless communications carrier because of their digital PCS network and data transmission services in the Washington/Baltimore area. The Sprint PCS network offered both an encrypted signal for patient data protection and the promise of high-bandwidth speed improvements throughout the project.

The identified commercial components were integrated within the remote mobile ambulances as shown in Figure 3. Patient vital signs data are captured from the standard Propaq monitoring equipment by the commercial interface software (WESTECH) executing upon the video and communications computer (FoNet). The patient data are transmitted to the FoNet video and communications processing computer. The FoNet software's queuing mechanism integrates the patient data with the input video data for communication back to the hospital. The VCR is used to record ambulance audio and video data, allowing perform post-transit data comparisons against the transmitted information. The data transmission uses multiple Nokia cellular phones in parallel (i.e. simultaneous transmission over multiple lines) to increase the system throughput.

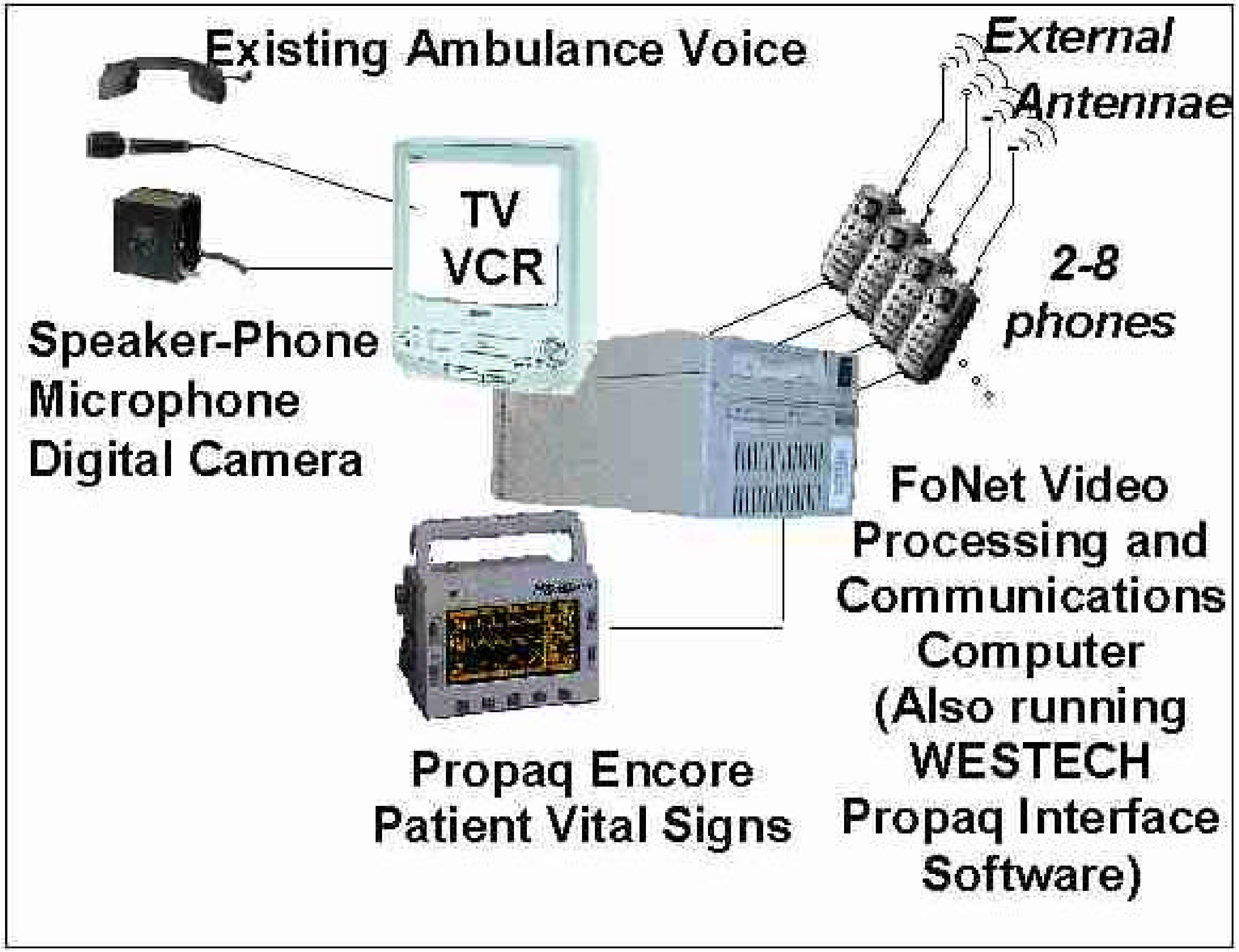


Figure 3 Ambulance Configuration

Two design objectives for the mobile unit were: minimal need for user interaction during usage on ambulance, and pre-transmission editing capability for selecting images or a series of images to be transferred. The mobile unit was designed to be installed in a cabinet on the ambulance, with no keyboard or monitor. The paramedics simply press a single ON/OFF switch to activate all parts of the unit. Video images are sampled automatically at rates determined by the transmission capacity available (on the order of 1 image every 12 seconds). For certain diagnostic procedures, a higher sampling rate may be required (e.g. to approximate live video) and images may need to be sampled at specific times (e.g., to capture at the moment when the patient closes his eyes). An image selection controller is provided to the paramedics; by pressing the button on the controller, the paramedics can select which images are captured at any given time. By holding down the button, a stream of images are captured at a sampling rate higher than transmission capacity. The buffered images are then transmitted as the system capacity allows.

Two queues were used in image capturing and transfer. Other data, such as patient biosignals, are injected directly into the priority queue. Figure 4 summarizes the logic design used in capturing and transferring video images.

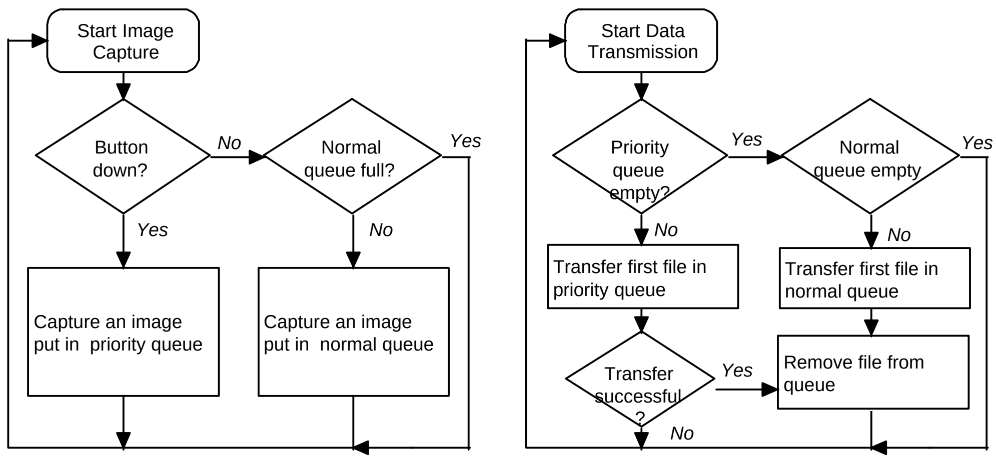


Figure 4 System Logic for Image Capture and Transmission

Upon the hospital side, data is received over regular land-line modems and stored on a secure Microsoft NT server (see Figure 5). The data are served with the Microsoft Internet Information Server (a web server) to make the data available over the hospital Intranet. Physicians use a simple web-browser client (e.g. Netscape or Internet Explorer) to access ambulance data in real-time over the hospital LAN from their desktops.

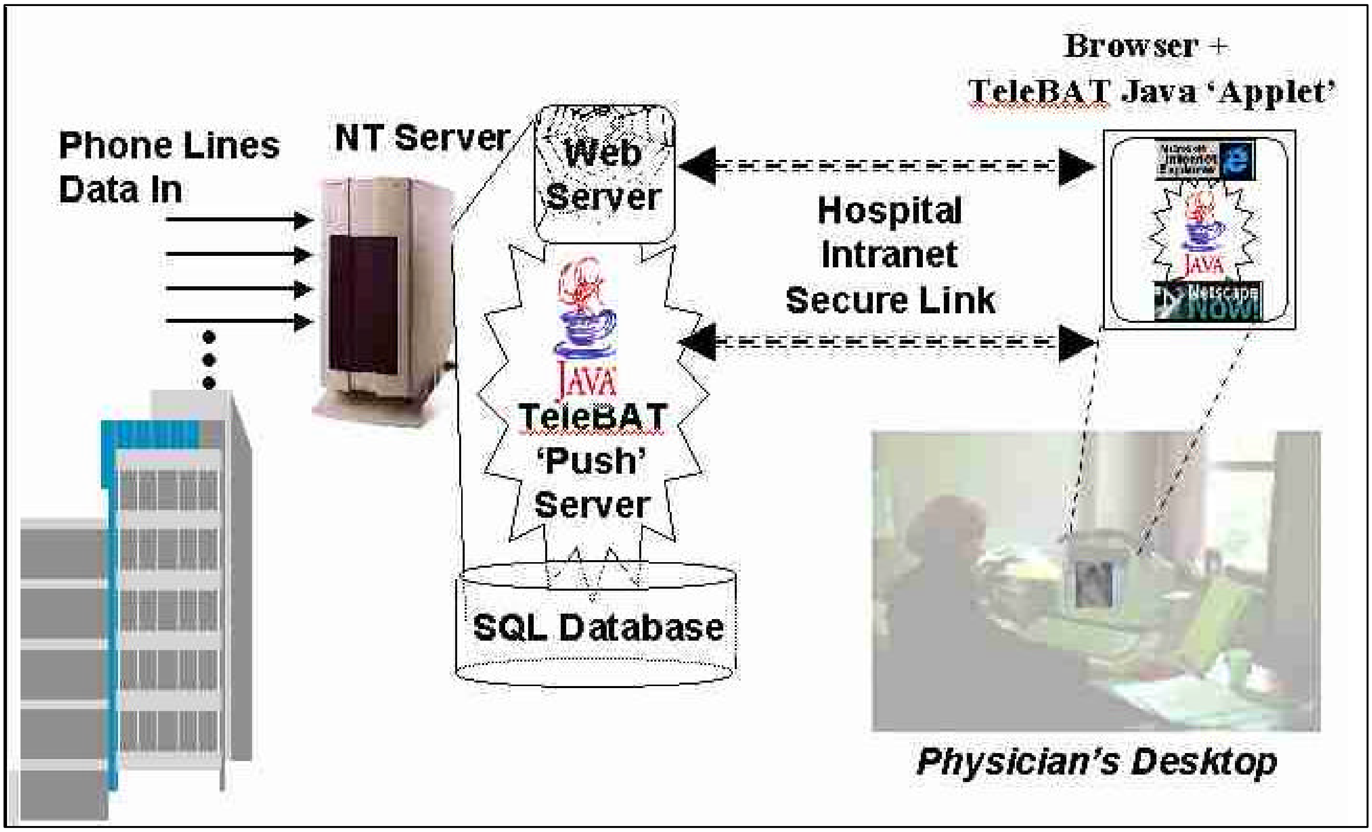


Figure 5 Hospital Configuration

The software architecture leverages the latest "Server-Push" technology to update the desktop display. A secure HTTP connection is established from the desktop client to the Intranet server that is kept open by the client. As new data arrives from the ambulance into the server, project software on the server generates dynamic updates that are automatically transferred to the client. This approach continually presents the viewer with the latest data received (see Figure 6), without requiring the user to initiate frequent requests for data updates.

This approach has several advantages over a more traditional client/server approach. All project software is 'hidden' from the users, running upon the backend web server. No custom client software is needed (beyond a current web browser), minimizing the costs associated with adding additional users. All components within the architecture remain based upon open Internet standards, allowing the rapid adoption of technology improvements.

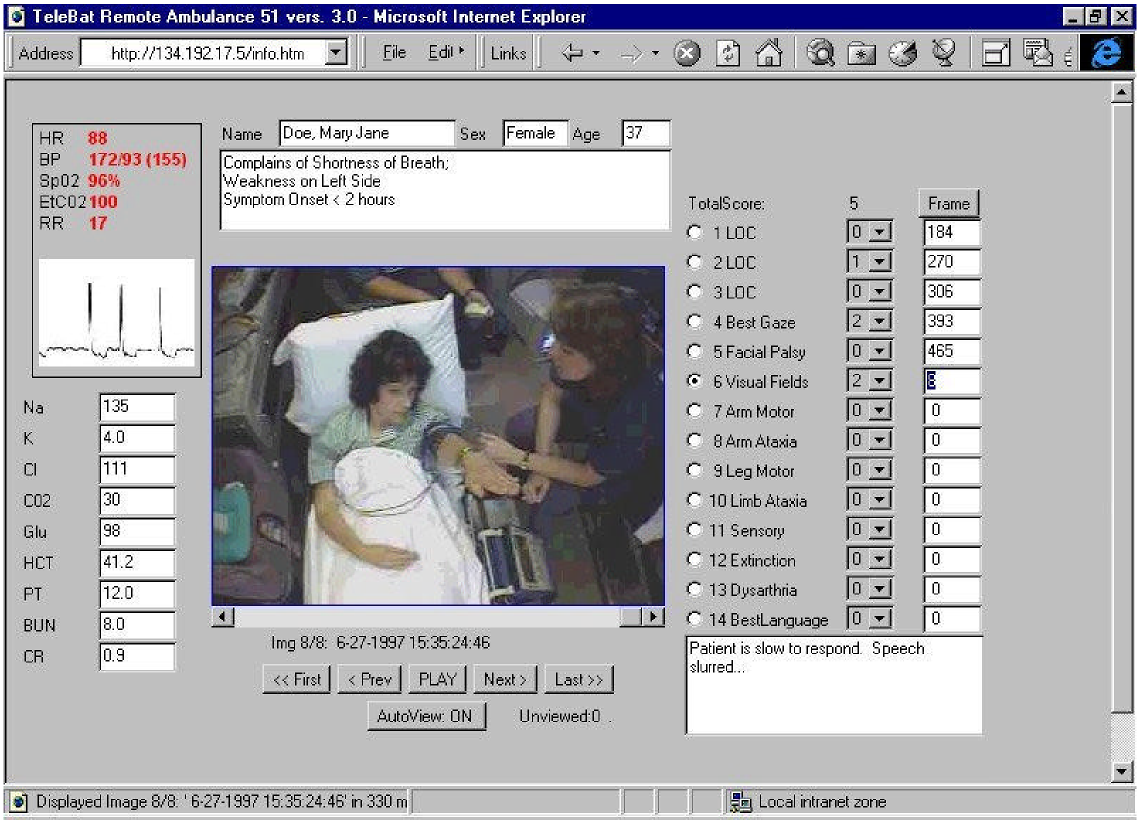


Figure 6 Physician's Desktop User Interface

4. Results Achieved

The key objectives of the mobile telemedicine testbed can best be summarized in the following questions:

- Is the approach feasible? (Does it work?), and
- Is it clinically effective? (Does it make a difference?).

Each of these objectives and their respective components are discussed below.

4.1 Technical Feasibility Objective: Demonstrated

The feasibility objective required the successful integration of the core technological components necessary for the system to function. Each of these was demonstrated within the integrated system, as described below:

4.1.1 Cellular Communications: Demonstrated

The project successfully demonstrated that a mobile telemedicine system could be implemented via cellular communications between ambulances and correspondent trauma center. However, two issues were identified:

1. *Published digital cellular bandwidth improvements have yet to materialize.*
   Each cellular phone channel has a theoretical speed of 9.6Kbps, but the connectivity testing measured realized throughputs of around 5Kbps. Throughputs of the Sprint Spectrum network were expected to increase during 1997 by a factor of between 2 and 4 through improvement of the underlying network protocols, but standardization of the revised GSM protocols has taken longer than Sprint anticipated. Nevertheless, the future growth potential for this wireless transmission technology remains strong, with technology 'prototypes' demonstrating data throughputs of up to 100Mbps.

2. *Stability of the transmission link remains an issue.*
   The team worked closely with the Ambucam™ system vendor FoNet to enable their system to automatically reconnect the cellular data connection whenever a line disconnected ('drops'). However, three scenarios continue to cause transmission link stability problems:
   a) all connected phones dropping simultaneously when traveling through 'holes' in network coverage,
   b) connected phones dropping when traveling from one network cell into another (if the newly entered cell has insufficient circuits available to support both all of the connected ambulance lines and regular calls being handled by that cell), and

c) reconnection occurring only when circuits were available within the newly entered cell, and

In practice this meant that we could not rely upon having more than two phones connected at any time, and that the connectivity of those two lines was *intermittent*.

These issues could be resolved by introducing a hybrid communications architecture with overlapping network coverage. Such a system would still drop and reconnect lines, but overall system connectivity would remain stable. Cellular competition throughout the US is resulting in multiple digital cellular providers in most areas; for example, Sprint Spectrum has now been joined in offering digital cellular service to the Washington/Baltimore area by Bell Atlantic and AT&T. It should also be noted that the latest of cellular phones are now dual-mode, combining analog and digital network connectivity. These dual mode phones provide hybrid network connectivity at the phone itself, switching to the analog network when the digital network is unavailable in order to provide more stable connectivity. The Team has entered into discussions with Bell Atlantic to examine introducing their recently announced data transmission services into the system, but exploring this approach was beyond the project resources.

4.1.2 Real-Time Patient Data Transmission: Demonstrated

The project successfully demonstrated that both real-time vital sign data and video image data can be transmitted and used effectively in such a mobile system. The original project goals included the transmission of the following three categories of real-time patient information:

1. *Vital signs information*
   - Numerical Vital Signs information
     - Heart Rate
     - Blood Pressure
     - Pulse oximeter
     - End tidal CO2
     - Temperature
   - Real-time vital signs information
     - Digitized waveform data from pulse oximeter
     - End tidal CO2
     - Electrocardiogram

Vendor delays in supplying all the needed components delayed the implementation and testing of the vital-signs data transmission until the last few months. The Team successfully demonstrated the end-to-end transfer of both the numeric and waveform vital-signs data, yet did not have the opportunity to test this with a real patient. Furthermore, although the waveform data is included in the transmission, the software to decode and properly display the waveform data has not yet been completed.

2. *Blood test analysis information*
   - blood gas
   - blood chemistry
   - blood coagulation

   Maryland ExpressCare is piloting the use of the iSTAT™ portable electronic blood chemistry analysis device. The results of the blood analysis are currently being communicated verbally over the audio-communications link. Integration of the iSTAT™ results directly into the system's data-stream remains possible (transmitted via an on-board infrared printer-interface port), but requires the development of interface software.

3. *Real-time or near real-time video transmission*

   The Team's early system testing determined that the optimal image size and rate would vary depending upon the task model being evaluated; the Team worked with the vendor FoNet to modify their video and communications processing software to allow us to specify the frame size and compression ratios used by the remote unit.

   For the brain attack task model, we found that medium compression of 320x240 size image provided sufficient information to distinguish the subtle asymmetries in facial expressions needed for the conduct of the remote neurological exam.

   At this size and compression, an individual image requires approximately 7Kbytes of storage, and takes roughly 10 seconds to transmit over a single phone line. The rate of the image transfer may be improved depending upon how many phone lines are connected; we are realizing an average of 2 images every 10 seconds.

   The project has examined switching from a JPEG image compression scheme to a wavelet/fractal compression scheme, and found that a factor of two improvement in the compression of the image data would be possible (but would require the introduction of slightly faster processors on the ambulance). Taken together with a hybrid communications architecture, these improvements would likely quadruple the data transmission rate. However, implementation of these improvements were beyond the project resources.

4.1.3 Initiation of Electronic Patient Record: Partially Demonstrated

The project attempted to demonstrate that the electronic patient record can be implemented effectively at the initial point of care. We found that the entry and transmission of patient records was possible, but that the implementation was too difficult to use in practice for the following reasons:

1. Poor display screen on the records entry computer

The project purchased the Westech EMS™ system that had been deployed extensively in police vehicles and had been tested in Vancouver ambulances. The systems we received were based upon the Fujitsu Stylistic 1000 tablet computer, which uses a 'transflective' display. This type of display is more expensive than traditional LCD panels, with the screen's legibility improving in direct sunlight (traditional LCD screens become 'washed-out' and hard to read in sunlight).

Unfortunately, the 'transflective' display performed poorly under the florescent ambulance lighting, making the system difficult to use. Using an alternative screen technology may produce better results.

2. Poor performance of the handwriting recognition system

The handwriting recognition system was found to be too inaccurate to be useful, requiring excessive user training and user care to produce acceptable data entry.

Using a keyboard and mouse for data-entry would address this problem.

3. Unique records requirements not addressed

Maryland ExpressCare's record requirements were not fully met by the Westech EMS™ system. Although some customization of the Westech screens is possible, resolution of this issue was deemed less important than the data input and screen display issues discussed above.

Each of these issues could be resolved by using customized run sheets hosted upon a different patient record computer (i.e. one with a better display and keyboard).

4.2 Reduction of the Time to Definitive Diagnosis Objective: Partially Demonstrated

Unfortunately, technical problems in the system implementation have delayed sufficient data collection to completely assess this objective. A total of 37 testing sessions were conducted, in which 18 were lab tests, 7 were ambulance tests, and 12 of which were during patients transports (of which 6 were non-stroke patients, 3 were cardiac catheterization patients, and 3 of which were stroke patients). The tests were conducted in Baltimore-Washington area using Sprint-Spectrum digital PCS networks, transmitting over 32,000 images over a cumulative duration of 64 hours (averaging 8.3 images per minute).

The images captured were optimally set (as determined through experimentation) at 320x240 24-bit pixels, with JPEG compression of 30% quality (lossy compression). The size of image files is dependent on image content and lighting, and varied between 2~12 Kbytes (Figure). Four phones with digital data service were used for the system setup, each with a nominal data rate of 9.6 kbps. The actual throughput rate fluctuated considerably, as shown in the Figure 7 for two lab tests and Figure 8 for two patient transfers.

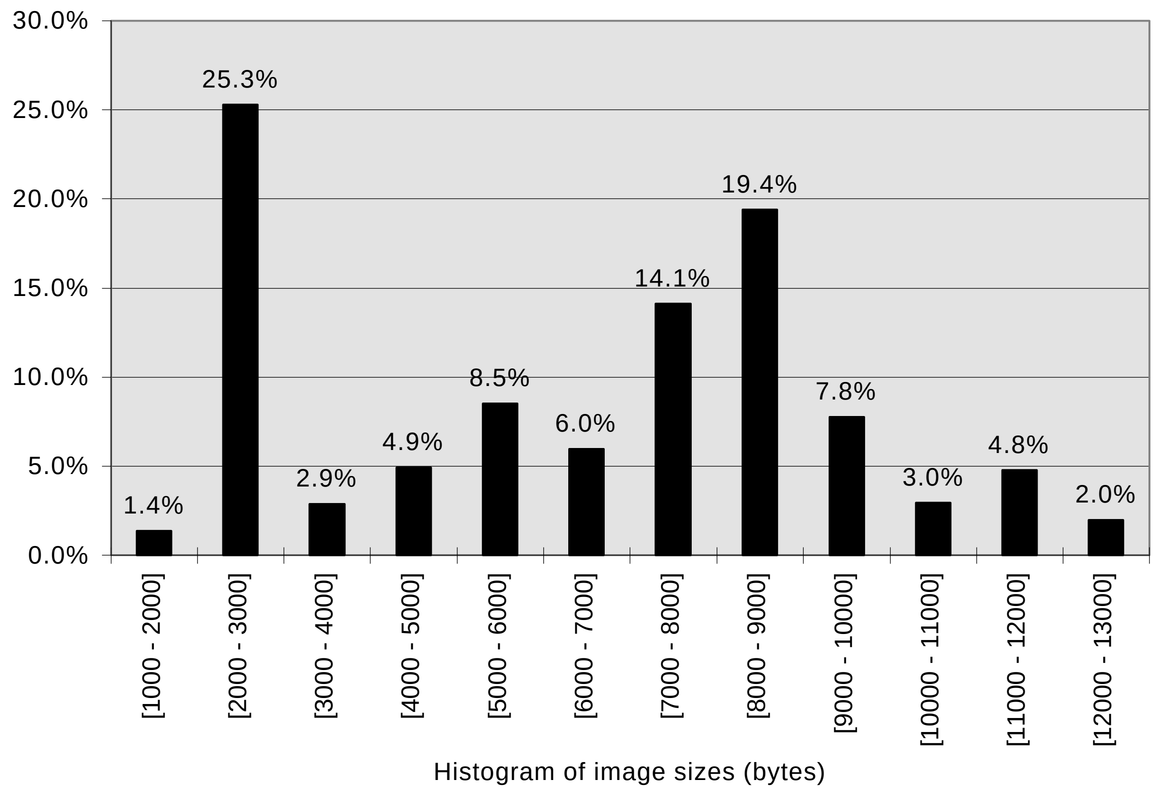


Figure 7 Transmitted Image sizes

The first mode at 2kB was for highly compressed 'dark' images during ambulance tests when lights were out; the second mode at 8kB was for images under normal lighting conditions.

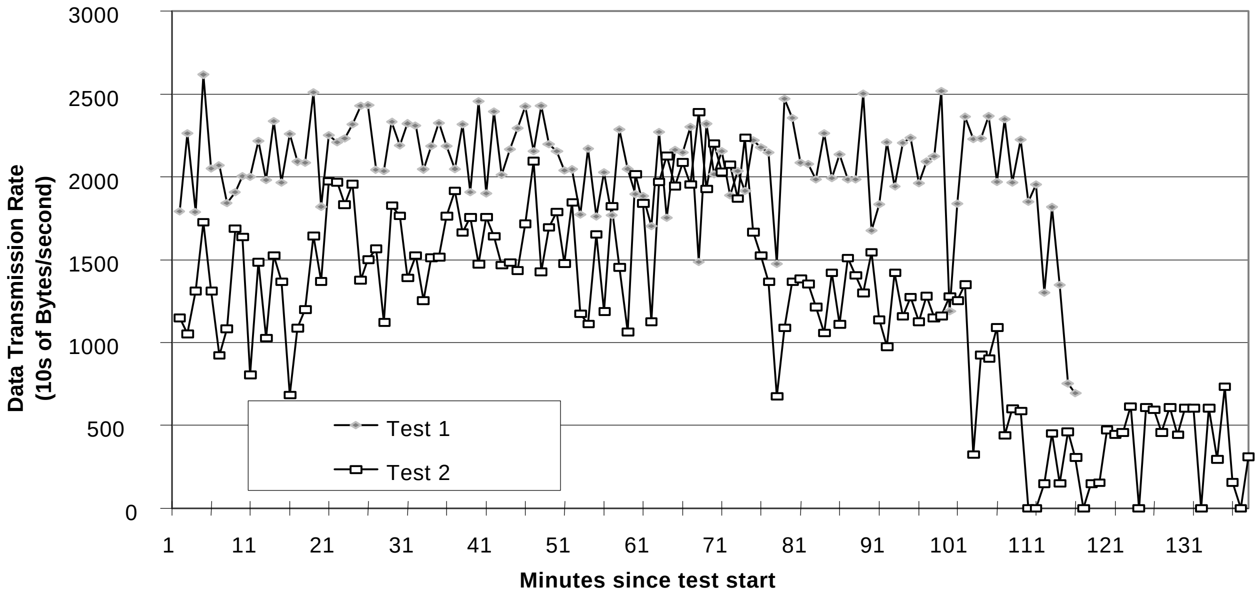


Figure 8 Data Transfer Rates During 2 Lab Tests

Data rate for two lab tests in bytes/second. Trend analysis reveals the number and connectivity of phones transmitting in parallel, ranging from a single phone providing roughly 6Kb/s to four phones providing roughly 22.5Kb/s connectivity.

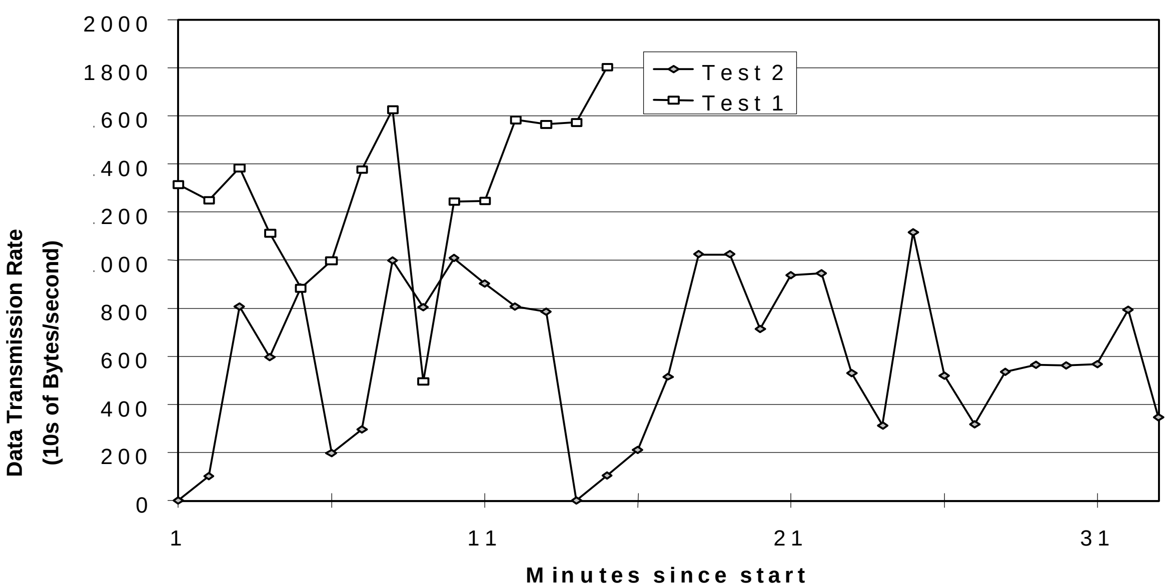


Figure 9 Data Transfer Rates During 2 Patient Transfers

Data rate for two patient transfers in bytes/second. The deep trough in the second patient transport represents a loss of connectivity by all phones, followed by the automatic reconnection.

The average rate of image transfer was 8.3 images/minute (see Figure 10). Due to the variability in file size per image, a more meaningful indicator of data transfer speed was bytes per second. An average of 882 bytes/seconds was achieved (Figure 11). There was a signal latency (lagtime) of 10~15 seconds between when an image was captured and when it was displayed on the receiving computer in the hospital.

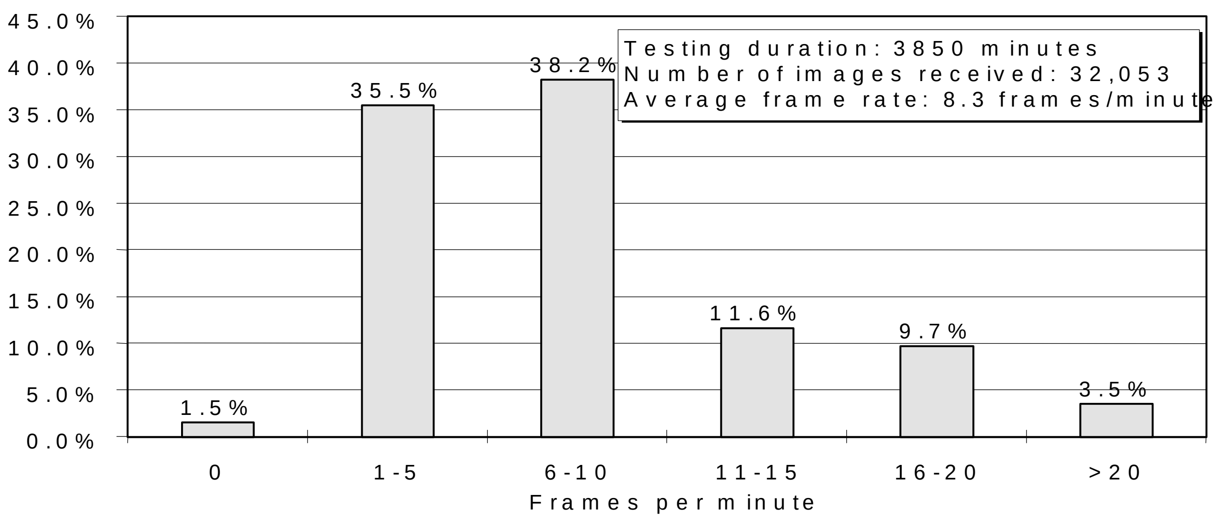


Figure 10 Histogram of Frame Rates

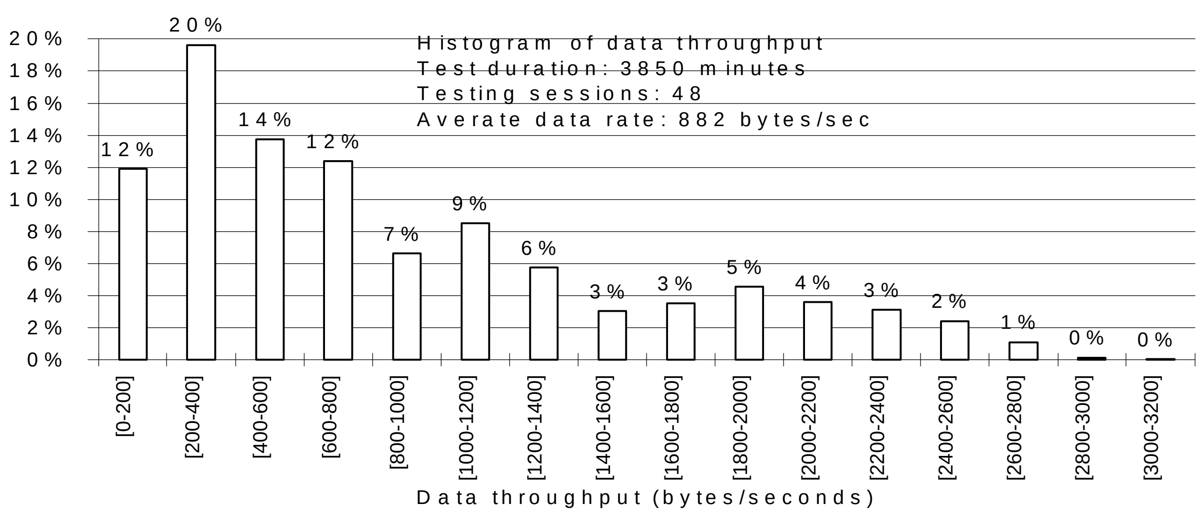


Figure 11 Histogram of Data Throughput Rate

Feedback received from these initial patient runs suggests that the system can provide significant useful clinical information. This was demonstrated during a cardiac patient transport of August 27th 1997, wherein 260 images were transmitted over the course of 21 minutes - a new image roughly every 5 seconds. The transmitted images provided enough diagnostic information to complete the initial portion of the NIH Stroke Scale, sufficient information was transmitted to assess the patient’s Level of Consciousness.

This was again demonstrated for the stroke patient transport of January 12th 1998, wherein the NIH stroke scale examination was completed. Towards the end of the exam, however, the paramedic recognized a change in the patient's status for the worse. The paramedic repeated the exam, and the physician was able to observe the dramatic change in the patient's abilities since the initial exam (see Figure series 12a..12i). [Note: The patient's consent was obtained to use the data for presenting the project results.]

Patient is asked to raise his arms (Note 12 seconds interval)

Figure 12a Time: 18:34:59.79

Figure 12b Time: 18:35:05.89

Figure 12c Time: 18:35:11.38

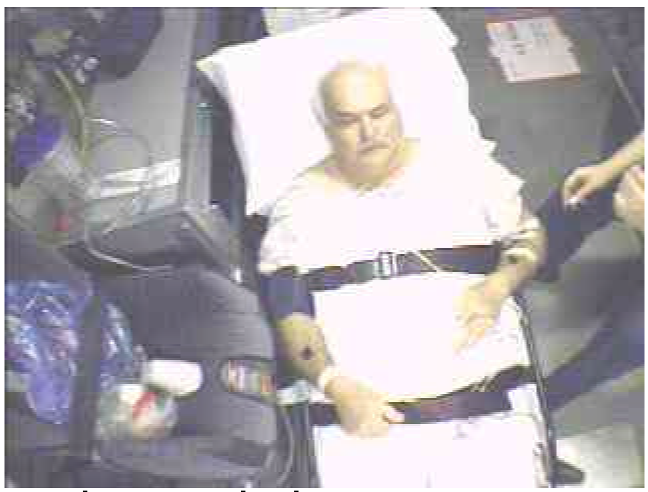


Figure 12d Time: 18:42:11.89

Toward the end of the transport, note the patient's left arm drops from his lap indicating possible weakness

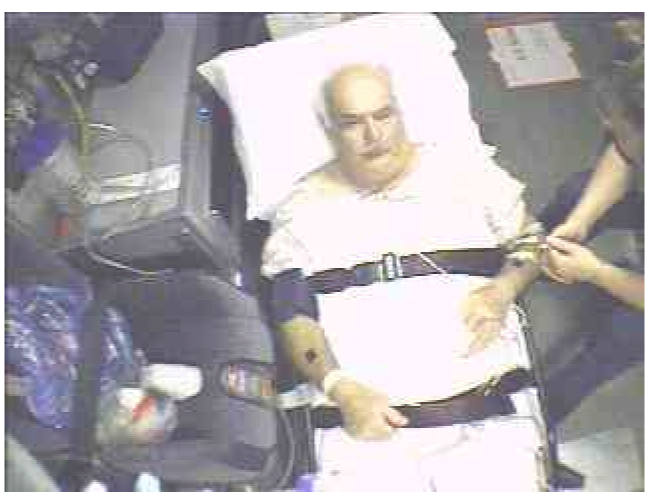


Figure 12e Time: 18:42:31.01

Figure 12f Time: 18:42:42.32

Figure 12g Time: 18:42:51.67

Paramedics recognizes decline in status and repeats exam, but patient's left arm is paretic

Figure 12h Time: 18:43:03.58

Figure 12i Time: 18:43:09.24

Figure 12 series a..i:

Visible change in patient's status

5. Lessons Learned

Key lessons learned on the project are that:

- Leveraging commercial components requires a trade-off of internal control versus lower costs and a faster external development cycle.

- Achieving reliable, high-bandwidth wireless data communications is difficult today but possible; it should get easier over the next few years as the underlying networking infrastructures and products mature.

- The transmission of patient data from enroute ambulances is feasible and can make significant difference in patient outcomes.

More detail is provided below about the specific problems encountered on the project and their resolutions.

5.1 Remote Diagnosis May Be Difficult

Shortly after the first ambulance installation of the FoNet equipment, the Team was presented with the first Brain Attack transport. Although the complete software and hardware infrastructure was not yet in place, we seized the opportunity to ‘try-out’ the image transmission capabilities of the system (using a single phone line). The following Figure 13 is taken from that first patient transport.

Figure 13 First Patient Transport

Although the system performed well, the patient was never a candidate for t-PA because the onset of symptoms occurred over two weeks prior to the transport (the patient had presented four times at two separate hospitals within the previous two weeks). Interestingly, this transport did reveal a valuable lesson - *a patient that is difficult to diagnose in person is also difficult to diagnose remotely*. The patient was later diagnosed with spinal meningitis that had diminished his neurological function in such a way as to mirror the symptoms of stroke.

5.2 Unreliable Commercial Components

The project deliberately chose to heavily leverage cutting-edge commercial component technologies. While this decision allowed the project to incorporate externally developed, inexpensive components, it also exposed the project to additional risk. None of the component technologies performed reliably when integrated within the system, exposing problems unanticipated by the component vendors.

Despite vendor assurances that their equipment was ready for integration, repeated partial deliveries delayed the system integration and testing. In hindsight, these vendor delays were caused by the inability of the vendor software platforms - FoNet’s system originally ran under Windows 3.1 and WESTECH’s system originally ran under DOS - to meet the project’s rigorous timing and interfacing constraints. Satisfying the project requirements has forced both vendors to migrate their systems to the multi-tasking

Windows 95 operating system. While this architectural modification provided significant advantages (e.g. the ability to integrate all ambulance software upon a single computer), it has also introduced unexpected errors.

These problems are often encountered on complex system integration projects such as this, and can be exceedingly difficult to resolve. Because one is tying together multiple commercial products, each of the vendors presumes the problem must lie in the other vendor’s component. The situation is exacerbated when the problem is “one-of-a-kind”, has been reported by no other customers, and the vendor is unable to replicate the error.

As with any new system, there are unknown variables influencing the success of the system operation. Identification of these variables is difficult due to the turnkey nature of the system design, e.g. the ambulance equipment was intentionally designed with only an on/off switch. Most frustrating to the end-user was the sparse notification when problems do occur, e.g. the client browser software has no method of knowing that the cellular phones are out of range of the network, or that the hospital server has crashed. The Team's approach was to isolate each problem and either correct it or develop a work-around. The main issues encountered are described in more detail below.

5.2.1 Cellular Connectivity Issues

The Team struggled early in the project with problems interfacing with the cellular network. The computer interface to the cellular phone network is made using a Type II PCMCIA card that emulates a Hayes AT-compatible modem. The transmitting computer’s interface software expects to use AT commands to initiate and manage the remote connection and data transfer.

Although the interface was expected to be seamless, testing identified problems with the automatic detection and reconnection of dropped lines. This problem was believed to be caused by network timing issues unique to the digital cellular network that result in a ‘race’ condition for the software drivers. Because the cellular network coverage is not perfect, resolution of this problem was critical for ‘turn-key’ hands-off operation of the system.

Detailed testing was performed to isolate and remove this problem, with exceptional support provided by both FoNet (provider of the video/communications computer) and Sprint/American Personal Communications (provider of the digital cellular phone service). Sprint/APC hosted multiple rounds of laboratory testing at their engineering facilities in Bethesda to isolate this problem, bringing in both their network engineering staff and Motorola GSM experts. Initial suspicions were that this problem was a minor timing issue that could be corrected by altering the FoNet software drivers, but this was proven not to be the case.

Testing finally tracked the cause to firmware within the Motorola cellular phone PCMCIA interface cards. Initial testing made using the cellular phone equipment from Nokia - the only alternative equipment provider - confirmed that the problem lay within the Motorola cards.

Working with Motorola to identify and correct their software was deemed beyond the project scope, and the decision was made to abandon the Motorola equipment in favor of Nokia. This change meant that the slightly higher throughput of the Motorola equipment (achieved through deactivation of the wireless RLP network protocol) had to be sacrificed for the superior connectivity of the Nokia. Further, the Nokia equipment did not support the attachment of an external antenna, which earlier testing proved desirable for a stronger network connection. A vigorous market search identified a European firm (Algon) which makes an inductive coupling for the Nokia phone. The Algon connector provides a inductive ‘sleeve’ that slides over the small phone antenna, which is then connected to the larger external antenna.

The frequent dropping and automatic reconnecting of calls exposed two additional unanticipated problems: the stability of the Microsoft Win95 Telephone Application Programmatic Interface (TAPI) layer, and the stability of the Nokia phone’s internal computers.

The FoNet Ambucam software communicates with the phones through the Win95 TAPI software interface. A lockout problem was encountered within the Win95 TAPI layer that is preventing the Ambucam software from reconnecting lines. As lines are repeatedly dropped and reconnected, Win95 is locking up the interface to individual lines, blocking the Ambucam software’s ability to use that line. The FoNet vendor is investigating a software workaround, but moving to an NT platform is expected to resolve this issue.

Each of Nokia phones is actually an embedded a computer system running its own operating environment. The project encountered random crashes of the Nokia phone computer during the automatic redial process. Resetting the phone requires disconnecting the phone cabling and removing the battery – a process too cumbersome for the ambulance personnel. This problem has been reported to Nokia and should be resolved in a subsequent release of the firmware, but to date no workaround has been identified.

5.2.2 Maturing Internet Software Model

Key to project's software architecture is to provide ambulance data to the physician's desktop over the hospital’s existing LAN, using standard web browser technology (i.e. Netscape or Explorer) to view the dta. As data arrives at the server, the data viewed by the client workstations must be dynamically updated. Because web pages are normally static in their content, we had planned to accomplish this using a combination of the Internet 'Server-Push' and 'Client-Pull' techniques. This was to have been accomplished via a mixture of the straightforward HyperText Transfer Protocol (HTTP), HyperText Markup Language (HTML), and the simple browser scripting language, JavaScript.

In theory, these techniques allow the Server to push new data to the client that updates the screen, and allows the client to automatically request data updates without requiring the user to push any buttons. In practice, the initial 'Push/Pull' prototypes found the underlying open-standard techniques to be poorly supported by both Microsoft and Netscape's browsers. Techniques that worked for one would crash the other; neither were robust and would fail after running properly for 10-20 minutes.

The decision was made to move the software development to Java, requiring a significant redesign of what had been anticipated as relatively simple web software. Moving to Java required accepting a tradeoff of additional software complexity in exchange for greater algorithmic control and operational stability.

The revised architecture embeds a Java 'applet' (a small browser-based application) within an HTML web page. The applet establishes connectivity from the client to a Java application running on the Web Server. The Java 'push' server application can accept connections from multiple clients, and pushes data as it is received at the server out to each of the clients. The client's Java applet updates the display with the new data as it is received from the server.

Operational testing revealed that the write-once/run-anywhere promise of Java remains an elusive goal. Furthermore, the Team found that the Microsoft Java run-time environment - on both the Win96 client and the WinNT server - would become unstable after long periods of operation (e.g. on the order of an hour for the client, on the order of days for the server). These problems are due to cumulative implementation errors (such as memory leakage) within the Microsoft and Netscape Java Virtual Machines (JVM). The Team has remained vigilant in testing and installing the latest Microsoft JVM patches, and plans to migrate to Sun Microsystem's JVM, which can be embedded to run under both browsers for more consistent performance.

We found that the Java client software was extremely sensitive to differences in the browser within which the software runs – and between different versions of the same browser. For example, the software would crash when run under different versions of Internet Explorer and Netscape. Furthermore, the operation of the user interface elements (pull-down choice boxes, sliders) would function differently between the browsers. Software work-around solutions have been found for each of these issues, gradually improving the stability of the client software.

Crashes of the Java Push Server software were traced to a failure in the underlying Microsoft NT Java Virtual Machine (JVM) run-time environment (i.e. the Java program itself was fine, but the operating system was crashing). This problem was resolved by running the Push Server within a loop from an alternative runtime environment. A simple Perl script was developed that runs the Push Server in an infinite loop:

Loop
Run the Java Push Server
End Loop

When the Microsoft Java environment crashes, control is returned to the Perl environment. The Perl Loop ends and the software is automatically restarted with the environment reinitialized.

The loop modification of the server software allowed the Team to implement a browser-based remote server administration feature. Server logs were added that allow the remote administrator to monitor the status of the server, the software execution, and the client-to-server connections. The server software itself was modified to accept a control message that aborts the Java Push Server. Whenever the Server software is updated, a remote termination message can be sent from the Administrative Interface. The Java Push Server will exit, but the loop within the Perl script will restart the execution using the latest version of the software.

5.2.3 Microsoft Software Issues

The overwhelming majority of software issues were traced to problems within the Microsoft Windows 95 (Win95) and Windows NT (WinNT) environments. In addition to the Java, Browser, and TAPI issues described above, problems were encountered with both the configuration and the stability of the runtime environments.

Once the cellular network connectivity issues described above were resolved, the Team worked to achieve parallel communications over multiple cellular phone lines. These efforts were slowed by an error eventually tracked to a Win95 bug in the internal handling of the modem's 'friendly' name. Having multiple modem's of the same type (i.e. 'Nokia PCMCIA Data Card 1', 'Nokia PCMCIA Data Card 2', etc.) created a system resource error in mapping the modem name to the physical modem line. Once the source of this problem was identified, the modems were renamed through manual editing of the Win95 resource registry. The Team successfully achieved parallel video transmission over four digital cellular phone lines on June 24th of 1997. To our knowledge, this has never before been accomplished - the best previous parallel connectivity had been made (by FoNet) using two analog cellular phones.

It was discovered that the ambulance systems would occasionally activate a low-level Win95 system diagnostic (a lengthy surface scan of the hard disk) when the unit was powered-on. There is no means of determining when Win95 will run the diagnostic – which can easily take over 30-minutes to complete – leading to inconsistent and unpredictable performance. Because any system malfunction would require transferring the unit to a maintenance facility, these diagnostics provide no value within the ambulance environment. The Team disabled the system diagnostics of the ambulance units in order to resolve this problem.

The system architecture originally used a separate Win95 computer as the FoNet receiving basestation, which would transfer data received from the ambulances to the NT Intranet server. Stability error within the FoNet basestation (manifested as crashes of the FoNet Ambucam software) was traced to a runtime error within the Win95 memory management routines. These routines were completely rewritten by Microsoft for Windows NT, giving the WinNT runtime greater stability than the Win95 runtime environment. Integrating the Ambucam software within the NT web server resolved this problem while simplifying the system architecture by removing the need for the basestation.

5.3 Desirable System Enhancements

As a direct result of the project experimentation, the following system enhancements were identified and should be implemented:

- Create a hybrid connectivity architecture using overlapping wireless infrastructures. By taking advantage of the overlapping network coverage, higher data throughput and improved cell-to-cell connectivity can be achieved. The resulting hybrid communications subsystem architecture will allow dynamically optimizing the selected communication channels for bandwidth, stability, and cost.

- Incorporate a commercial real-time wavelet-base image compression algorithm. Preliminary investigations suggest that moving from a JPEG to a wavelet/fractal image compression scheme will produce a factor of 2 improvement in the data throughput without noticeably changing the quality of the transmitted images. As part of the compression upgrade, the store-and-forward of compressed video-streams should be modified to use the superior compression. The current system is able to capture video streams at a rate of approximately 1.6 frames per second. This limitation is due to the frame-by-frame nature of the image capture; achieving a higher frame rate requires redesigning the system's internal data flow for streaming video to an interim memory cache rather than directly to disk.

- Upgrade the ambulance system to a more powerful Windows NT-based computer that has a sleep/power-save mode. This upgrade will resolve outstanding instability issues caused by Windows95, and the sleep/power-save mode will prevent the system from improper shutdown. Supporting real-time wavelet/fractal compression requires more powerful processors than the current 166 MHz Pentium systems. Moving to faster (i.e. 300MHz or better) Pentium II MMX processors will better support moving from the current Windows 95 environment to Windows NT.

- Add a permanent flat-panel LCD display, keyboard, and mouse to the EMT work area. Connected directly to the transmission system, this display would allow the EMT to better monitor the system and could also be used support the entry of patient record information.

- Develop an infrared interface to automate the introduction of the iSTAT™ blood chemistry data into the system data stream. The iSTAT™ data is currently sent over the audio link by the EMT.

6. Current Status and Recommendations

The described mobile telemedicine system is in use today at the University of Maryland, installed within two ambulances. The system has been running for roughly four months of test operation, which has included multiple runs with true trauma patients. System performance has been mixed due to a combination of stability issues. When the system is up and running the hospital staff are ecstatic, and have responded with such enthusiastic expressions as "This is amazing, absolutely fantastic." Unfortunately, they are equally expressive when the system is not running.

Feedback received from our initial patient runs suggests that the system can provide significant useful clinical information *when it is performing properly*. Questionnaires completed by four users (two paramedics and two stroke specialists) of the mobile telemedicine system indicated that:

(1) the system did not impose intrusion to the privacy of the patient or the paramedics,
(2) it was easy to use,
(3) it was adequate for conducting clinical examinations, and
(4) it conveyed critical clinical information.

Through informal communications with Marian LaMonte, M.D., Director of the Brain Attack Team and assistant professor of Neurology at the University of Maryland School of Medicine, the importance of the system becomes increasingly clear. Although the results have not yet published, the clinical trials of the efficacy of t-PA therapy in the 3-5 hour and 3-6 hour windows following symptom onset have been halted, showing no difference against the control group. This means that the current 3-hour window remains the only opportunity for intervention known to improve patient outcomes, and highlights the importance of the telemedicine system in saving time to patient treatment.

The continued use of the system is in currently in question due to the communications stability issues described above. Unfortunately, the resources to implement the needed system enhancements have to date been unavailable. The project Team strongly recommends that the system enhancements identified by the project be implemented, and that the revised system be used to speed the treatment of Brain Attack patients. Our Team is continuing efforts to identify the resources necessary to meet these goals.

7. Project Publicity

There has been a strong interest in the press about this project, and the feedback received from presentations has been extremely positive. A web site of information about the project is available at http://hfrp.ummc.umaryland.edu/telebat.html, and the project has been described in multiple publications, including the proceedings of the 1997 AMIA conference (and has been submitted for the 1998 AMIA proceedings). Included in the project publicity are the following:

Presentations

- "Telemedicine at the University of Maryland", Colin Mackenzie, Greater Baltimore Council's TechNite'97 featured presentation, September 23, Baltimore Convention Center, Baltimore MD
- "Evaluating Mobile Telemedicine", Yan Xiao presentation to the Association for the Advancement of Medical Instrumentation (AAMI) June 10, 1997, Washington, DC
- "TeleBAT: Telemedicine for The Brain Attack Team", LaMonte, Xiao, Mackenzie, Hu, Gaasch, Cullen, and Gagliano, featured Poster Presentation at the 23rd International Conference on Stroke and Cerebral Circulation
- "Mobile Telemedicine at the University of Maryland", Peter Hu presentation to the University of Shanghai Medical Department, 1997, Shanghai China
- "Telemedicine: Past, Present & Promise", Colin Mackenzie presentation to the Medical & Chirugical Faculty of Maryland Symposium, Sept 27th 1997, BWI Airport Marriott,Baltimore
- "TeleBATSM: Mobile Telemedicine for the Brain Attack Team", Health Information Infrastructure 1998 (HII'98),Feature Presentation at the 3rd Annual Conference of the Friends of the NLM, April,98, Washington, DC
- HIMSS'98 Symposium - Healthcare Information Management System Society (handouts/brochure at booth on exposition floor)

Publications

- D. M. Gagliano and Y. Xiao (1997): "Mobile Telemedicine Testbed" Proceedings of 1997 the American Medical Informatics Association (AMIA) Annual Fall Symposium, 383-387

- D.M. Gagliano and A. Allen: Wireless ambulance telemedicine may lessen stroke morbidity", Telemedicine Today, Cover article Feb 1998 issue

Articles and Videos

"Taking telemedicine to the streets" By Tracie Thompson
- Telemedicine and Telehealth Networks Magazine vol 3, no 5, p.30, 1997

"Stroke Maryland Brain Attack Center"
- Health Week, Maryland Public Television First aired on July 27, 1997

"Mobile Telemedicine and BAT"
- Maryland State of Mind, Maryland Public Television First aired on Jan 29, 1998

- Baltimore Local News, Channel 13 on Mobile Telemedicine for Stroke Patients, Feb 6, 1998

- Baltimore Local News, Channel 11 on Mobile Telemedicine for Stroke Patients, Feb 9, 1998

- Ivanhoe Broadcast News, Life Saving Computer / Medical Breakthroughs, July 1998 (also viewable at the web site: http://www.ivanhoe.com/stream/lifesavingcomputer.html)

Press Interviews

- Self Magazine (Dr. Marian LaMonte)
- Better Housekeeping Magazine (Dr. Marian LaMonte)
- BBC (Dr. Marian LaMonte)
- Nurse Week Magazine (Dr. Marian LaMonte)
- The African American (Dr. Marian LaMonte)
- New York Physicians Weekly (Dr. Marian LaMonte)
- The Stroke Connection (Dr. Marian LaMonte)