The computerization of patient care is one of the biggest success stories of modern medicine. Mayo Clinic has long been noted as a leader in clinical informatics and its use of computers in the clinical setting coincides with the earliest uses described anywhere in the world. This review highlights some of the earliest achievements and contributions by Mayo Clinic in this field and describes how they helped lay the groundwork for current informatics initiatives. Early successes were rooted in the automation of patient monitoring which ultimately led to the computerization of cardiac and intensive care. Mayo Clinic was also a leader in using computers to provide consultative and evaluation services to remote locations in some of the earliest descriptions of telemedicine. Finally, Mayo was a pioneer in computerized advanced imaging technology which paved the way for improved and more available diagnostic and even interventional techniques. This brief history is a small chapter in a story that continues to unfold.

Clinical informatics describes the use of information, together with systems and processes, to improve patient care. Informatics has played an important role in the history and success of Mayo Clinic and began long before the introduction of computers to clinical medicine. Mayo Clinic’s rich informatics history can be traced to the medical record system created by Dr Henry Plummer and Mable Root in 1907. This system allowed for cross-referencing records on the basis of disease, surgeon, surgical technique, and diagnosis. The organizational structure this system provided served the clinic well during the initial growth years and provided the basis for important epidemiological research that could not have been possible in other settings. Although the history and research successes of the medical record system at Mayo Clinic have been previously reported, little has been written about the effect of computer informatics on patient care.

Mayo Clinic has long sought to be a leader in clinical informatics, and its use of computers in the clinical setting coincides with the earliest uses described anywhere in the world. Globally, the 1950s and 1960s were a time of significant advancement in introducing computers into biomedical research and patient care. By the early 1960s there were multiple instances of successful computerization of medical diagnosis and record processing. During this time, the National Institutes of Health created an Advisory Committee on Computers in Research to promote this agenda. Simultaneously, individual groups and institutions such as the Massachusetts Institute of Technology and Stanford University were successful in designing and implementing interactive computing machines for use in both the clinical and research domains. Mayo Clinic was one of many institutions heavily involved in this technological revolution and contributed substantially to this effort.

In this article, we review some of those specific efforts and achievements that ultimately laid the groundwork for the current computer informatics initiatives at Mayo Clinic. This review will specifically detail the era of first- and second-generation computing systems before the introduction of personal computer hardware, operating systems, development tools, and relational databases.

1960s

One of the first practical applications of computers in medicine arose from the 1961 efforts of Dr Howard P. Rome from the Section of Psychiatry to automate both the administration and the scoring of the 550-question Minnesota Multiphasic Personality Inventory (MMPI). He theorized that the use of
Some of Mayo Clinic’s earliest successes in computerizing direct patient care occurred in the field of neurology. In the early 1960s, Dr Reginald G. Bickford from the Section of Physiology introduced computers of average transients that could analyze electroencephalographic (EEG) recordings and simultaneously process evoked EEG responses. More advanced was the ability to use a Control Data Corporation 3200 computer for EEG analysis and parameter computation of epileptic spikes. This ability led to a collaboration with the Bell Labs telephone company to use telephone lines to transmit EEG recordings from a patient’s residence (natural environment) to the clinic in what was described at the time as telemedicine.

Beyond these early advancements in neurology, the bulk of patient care computerization in this decade occurred in the field of cardiology. In the early part of the decade, Mayo Clinic was recording approximately 200 electrocardiograms (ECGs) per day, with that number increasing rapidly. Collaboration with Medtronic Inc. allowed for simultaneous multilead recordings that reduced the time of ECG acquisition from 15-20 minutes to 30 seconds. A pilot study of this new technology recorded and classified (normal, borderline, and abnormal) 300 ECGs with 1 console in an 8-hour period with readings that agreed with cardiologists more than 85% of the time. In addition, patients’ ECGs obtained at the bedside were then able to be transmitted, via telephone lines, to a computerized ECG laboratory in the Plummer Building that matched the ECG tracing pattern to one of the stored, previously generated algorithms to produce a narrative interpretation.

This ability to perform real-time analysis of ECG tracings provided a framework for introducing bedside monitoring of patients in the intensive care unit (ICU). In 1965 new monitors, almost exclusively designed and assembled by Mayo Clinic engineers, were installed in the medical ICU that could detect heart rate and alert nurses when either tachycardia or bradycardia was detected. Just 3 years later, an International Business Machines (IBM) 1800 computer was installed in the same ICU that was able to record and store multiple physiological parameters (blood pressure, heart rate, temperature, urine flow, blood
draining from the chest, and cardiac output) in individuals recovering from open heart surgery (Figure 1).\textsuperscript{30,31} Data stored on these monitors could be retrieved and printed out for review or become part of the patient’s record. In addition, these monitoring computers were programmed to initiate action for abnormally low blood pressures or urine output by either giving a blood transfusion or starting an infusion of mannitol.\textsuperscript{32} These processes were accomplished by continuous monitoring of pressures (both arterial and atrial) and urine output with automated infusions triggered when values fell outside a range entered manually by the surgeon after surgery. An early efficacy and cost analysis of this technology (<$100 per patient per day)\textsuperscript{32} justified its continued use and laid a foundation for computerized ICU care in place today.

1970s

Advancements in ICU and cardiac care computerization surged forward in the 1970s and became a primary focus of the decade. Collaboration with IBM led to the computerization of the cardiac postoperative recovery, coronary intensive care, and cardiac catheterization units.\textsuperscript{33,34} The capability of these units to monitor multiple patients simultaneously using a central computer (System/7) (Figure 2) was a novel concept that furthered the use of computers in patient care.\textsuperscript{35} This eventually led to Mayo opening of one of the first cardiac surgical ICUs in the world, fully equipped with the automated monitoring and reflexive medication administration (eg, blood and mannitol) systems described earlier.\textsuperscript{36}

The work of ECG computerization begun in the previous decade saw even further success in the 1970s. Refinement of ECG recording and interpretation algorithms continued as acquisition time decreased to 10 seconds, with computer interpretations improving in sensitivity and specificity.\textsuperscript{37,38} Early transmission of ECG recordings between Mayo Clinic buildings laid the groundwork for large-scale use of this technology. In 1971, Dr Ralph Smith sent an ECG obtained from a patient in Sydney, Australia, to a Mayo Clinic computer laboratory in Rochester, Minnesota, for automated interpretation and return to Sydney within 3 minutes.\textsuperscript{39} This new technology had clinical relevance, as it allowed regional hospitals without reliable cardiology coverage to transmit ECG recordings to a Mayo Clinic laboratory for real-time computer interpretation and physician overread.\textsuperscript{40}

Improved computer capabilities combined with wireless transmission eventually expanded cardiac care outside the hospital setting. With the help of Congressmen Hubert Humphrey and Walter Mondale, Mayo Clinic was granted dedicated frequencies on a national basis for the transmission of real-time cardiac....
telemetry. This allowed ambulance personnel at the scene, most effective within a 15- to 20-mile radius, to attach a small portable unit to the patient that transmitted a signal to a tower atop the Mayo Clinic building. This information was then sent via a dedicated landline to Saint Marys Hospital where a computer terminal allowed a cardiology fellow to interpret findings and radio back instructions to the ambulance regarding medication administration or defibrillation in an attempt to stabilize the patient before transport.41 Although an early 7-month review (June through December 1973) of the experience with this new technology yielded modest survival statistics (3 of 17 patients with cardiopulmonary arrest successfully resuscitated at the scene), these metrics were on par with other centers with similar technology.32,43 Despite not dramatically affecting on-the-scene resuscitation mortality figures, this system was thought to be effective in continuous monitoring during transport those with dysrhythmias, chest pain, or syncope.43

During the 1970s, the efforts of introducing computers to improve the quality of care at Mayo Clinic directly affected those afflicted with cancer. In 1973 the Programmed Console-12 Radiotherapy Planning System was installed that dramatically decreased the time to measure and verify radiation beam profiles. In addition to a computerized tumor registry, this allowed clinicians and researchers speedy access to various information pertaining to tumors tailored to Mayo equipment, needs, and treatment philosophy.44,45 These additions, along with advancing administrative and tracking capabilities, allowed the Mayo Clinic Cancer Center to become a world leader in clinical trials with an average of 100 simultaneous cancer research trials conducted at any one time by the end of the decade.46

Some of the biggest achievements during this decade involved the computerization, automation, and standardization of laboratory medicine. In 1973, Mayo Clinic acquired a Vickers M-300 Multichannel system that automatically performed 5 tests (glucose, sodium, potassium, bilirubin, and creatinine) at once, with analytics digitally reported and printed as a computer-generated results page (Figure 3). This machine was the fastest known to date (300 samples/h) and was the first of its kind to be used clinically in the United States.47 Later that decade, Mayo Clinic purchased a gas chromatograph–mass spectrometer that quickly compiled one of the largest computer libraries of nearly 8000 compounds.48 Further advancements in the automation of clerical and reporting tasks led Mayo Clinic to become a leader in laboratory medicine and culminated in Mayo Medical Laboratories (MML) becoming the largest and fastest growing of the Mayo Clinic outreach programs.49-51

This outreach began as MML performed laboratory tests that were too complex or costly for many clinical or hospital laboratories. IBM computer-printer terminals were used to receive and print laboratory results.
automatically. In 1977, Mayo Clinic purchased 25 terminals and placed them in multiple locations throughout the United States. Laboratory tests sent to Mayo Clinic were run in Rochester, with results collected and transmitted over telephone lines during the night for each location with a computer-printer terminal. Within a few years, MML were serving more than 2000 hospitals and clinics in every state and performed more than 20,000 tests every month.52 These efforts allowed MML to become a tertiary reference laboratory and offer true medical consultation services throughout the world.53,54

The end of the decade ushered in an era of significant progress in the combination of computers and imaging. One area that Mayo Clinic had a primary role in and became a worldwide leader was the development of 3-dimensional imaging.55 After securing substantial National Institutes of Health grant funding, the Biodynamics Research Unit at Mayo Clinic collaborated with Raytheon Company to design and construct the dynamic spatial reconstructor.55–57 The dynamic spatial reconstructor prototype was one of the earliest imaging modalities with the ability to connect the structural-to-functional relationships of vital organs such as the heart and lungs.58 Initial feasibility studies found the efficacy of this technology in detailing complex pathological states by using less x-ray and contrast exposure than did previously applied methods.59

1980s

Even though Mayo Clinic introduced some of the first computerized advanced imaging equipment at the end of the last decade,55,60–63 it was during the 1980s that this technology evolved and laid the foundation for the sophisticated modalities in use today. The addition of newer and faster computed tomography (CT) scanners resulted in scans completed in less than 5 seconds and allowed Mayo Clinic to perform more scans (>80,000 scans in half a decade) than any other medical center in the world.54 During this decade, the introduction of CT ultrasound allowed for the detection of smaller breast cancers and decreased time to initiation of treatment.65,66 First described by Dr James F. Greenleaf from the Department of Physiology and Biophysics, this technology was then used in other centers to detect cancers with near-perfect sensitivity and specificity.66,67

This evolution of CT imaging coincided with the addition of Mayo Clinic’s first magnetic resonance imaging (MRI) machine in 1982 (Figure 4).68 At the first introduction, MRI was described as providing a biochemical blueprint of the body; however, its role in clinical medicine was unclear.68 Mayo Clinic immediately began using MRI for rigorous clinical evaluation of the brain, spinal cord, and soft tissues to determine its role in the diagnostic evaluation of patients. By 1984, Mayo Clinic had performed more than 2500 scans and had purchased its second scanner that was 10 times more powerful at a cost of $2.5 million.69

The use of computers also penetrated other imaging techniques such as angiography and cardiac catheterization. In 1982, digital subtraction angiography was used to provide

**FIGURE 4.** A, Demonstration of how a patient is scanned by the magnetic resonance imaging (MRI) scanner. The cylinder in which the patient lies is 10 ft long. B, A paper clip is drawn to the magnet in the center of the scanner. C, An image from an MRI scanner shows a sagittal view of a tumor in the posterior fossa. Used with permission of Mayo Foundation for Medical Education and Research.
a computerized radiographic method of imaging the vascular system.\textsuperscript{70} This became one of the earliest ways to screen at-risk patients for carotid, renovascular, and aortic vascular disease.\textsuperscript{71} Computer algorithms were also used to convert the interpretative text of cardiac catheterization reports to generalized picture models available for computer printout. These images provided graphical representation of coronary blockage, which could be used for patient education and interventional planning and could easily be placed in the medical record.\textsuperscript{72}

Computer applications combined with imaging sophistication during the 1980s perhaps saw its greatest achievement in the field of interactive surgical technique. Mayo Clinic became the first hospital in the United States to use computer-assisted stereotactic technology for brain tumor removal.\textsuperscript{73} By mid-decade, stereotactic technologies were used for biopsies, epilepsy treatment, implanted radiation, and hydrocephalus interventions with more than 100 operations performed successfully.\textsuperscript{74,75} In addition, the ability to create 3-dimensional CT images allowed for computer-interactive surgical procedures for such conditions as orbital tumors and related reconstructions.\textsuperscript{76}

Even though 1980s are recalled mainly for computerized imaging advancements, there were other important developments broadly affecting clinical practice. In 1982, Mayo Clinic introduced telephone and computer pacemaker testing for patients located all over the world.\textsuperscript{77,78} In 1987 a computerized drug distribution system was launched that automatically controlled preparation and medication delivery, with drugs being dispensed in computer-generated envelopes containing critical information for both the pharmacist and the nurse.\textsuperscript{79} In just a short period of time, this new system decreased waste from chemotherapies and total parenteral nutrition to less than 1%, with unmeasurable improvements in wasted labor and overhead costs.\textsuperscript{80} And finally, the Department of Anesthesiology used the abundant information processing system support at Mayo Clinic to computerize the surgical schedule and data acquisition systems, to design effective information management systems, and to introduce a novel computer-based video paging system.\textsuperscript{81-84}

Discussion

“To err is human; to really foul things up requires a computer!”\textsuperscript{85} This phrase tacked to the wall (Figure 5) by a Mayo Clinic employee shortly after the introduction of computers could have been an ominous sign for this technological transition. However, the understanding of leadership that “current practices were being outpaced by the growth of the clinic” prevailed and the use of computers in clinical care at Mayo Clinic remains one of the biggest achievements in its rich history.\textsuperscript{86}

The brief and early history of computerization of Mayo Clinic described in this article is just 1 small chapter of a story that is still being told. Our focus for this review was to highlight events in the era of mainframe computing before the explosion in personal computer technology.\textsuperscript{87} The advent of personal computers and the electronic medical record has brought unprecedented opportunity to advance
applied clinical informatics like never before, with Mayo Clinic at the forefront of this effort as well. It can be said that Mayo Clinic was one of the first to realize that “if all of us are not familiar with the many remarkable things that computers have made possible, we are at least aware that they have made possible many remarkable things” in the care of patients.⁹¹,p313

Although this review describes individual advancements and implementations at a granular level, a more broad discussion of the processes and systems undertaken is important to identify lessons learned that can ultimately maximize the success of future endeavors. In almost all the endeavors described in this article, there was a symbiotic relationship between clinical domain experts and engineering or informatics personnel. Even though Mayo Clinic collaborated closely with some of the largest technology companies in the world, it also invested significant time and money in supporting institutional research and building its own departments and informatics staff. This was a key component ensuring alignment of technological advancement with the core value of Mayo Clinic that “the needs of the patient come first.”⁹⁰,⁹⁹

During this time of significant computerization, we were able to provide many evidences of descriptive literature exquisitely detailing technology development, implementation, and user response. However, we were able to identify only rare examples of actual outcomes in patient care affected by the technological advances. As we move forward and continue this technological revolution, the need for outcome validation is greater than ever. If earlier implementations needed only evidence of novelty or meaningful use, future endeavors may ultimately require meaningful outcome effect for institutional or even governmental support.⁹⁰

Conclusion
The 3 decades of the 1960s through 1980s were a time of great excitement and success in computerizing medical care in almost all domains. There were a myriad of institutions and organizations leading the way, with Mayo Clinic being one of the most active participants. The contributions described in this article have added to those of others to help create the foundation for a technological sophisticated world in which we care for patients today.

Abbreviations and Acronyms. AMH = automated medical history; CT = computed tomography; ECG = electrocardiogram; EEG = electroencephalographic; ICU = intensive care unit; MML = Mayo Medical Laboratories; MMPI = Minnesota Multiphasic Personality Inventory; MRI = magnetic resonance imaging

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