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Evolution of Microcomputer-Based Medical Instrumentation

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Abstract—**This paper provides a historical review of the evolution of the technologies that led to modern microcomputer-based medical instrumentation. I review the history of the microprocessor-based system because of the importance of the microprocessor in the design of modern medical instruments. I then give some examples of medical instruments in which the microprocessor has played a key role and in some cases has even empowered us to develop new instruments that were not possible before. I include a discussion of the role of the microprocessor-based personal computer in development of medical instruments.**

I. INTRODUCTION

THE history of the development of the computer extends from the first mechanical computers such as those built by Charles Babbage in the 1800s to modern personal computers. The only computers prior to the twentieth century were mechanical, based on gears and mechanical linkages.

In 1941, a researcher named Atanasoff together with a graduate student named Berry demonstrated the first U.S. example of an electronic digital computer that they called ABC (Atanasoff-Berry Computer). This device was primitive even compared to today's four-function pocket calculator. The first serious digital computer called ENIAC (**E**lectronic **N**umerical **I**ntegrator **A**nd **C**alculator) was developed in 1946 at the Moore School of Electrical Engineering of the University of Pennsylvania. Quite simple compared to the modern PC, this device occupied most of the basement of the Moore School and required a substantial air conditioning system to cool the thousands of vacuum tubes in its electronic brain.

The invention of the transistor at Bell Labs in 1948 led to the Univac I, the first commercial digital computer. Several other companies including IBM subsequently put transistorized computers into the marketplace. In 1961, researchers working at Massachusetts Institute of Technology and Lincoln Labs used the technology of the time to build a novel minicomputer quite unlike the commercial machines of the day. This discrete-component, transistorized minicomputer with magnetic core memory called the LINC (**L**aboratory **IN**strument **C**omputer) was the most significant historical development in the evolution of the PC.

The basic design goal was to transform a general-purpose computer into a laboratory instrument. Such a computer, as its designers envisioned, would have tremendous versatility because its function as an instrument could be completely revised simply by changing the program stored in its memory. Thus this computer would perform not only in the classical computer sense as an equation solving device, but also by reprogramming (software), it would be able to mimic many other laboratory instruments.

The LINC was the most successful minicomputer used for biomedical applications. In addition, its design included features that we have come to expect in modern PCs. In particular, it was the world's first interactive computer. Instead of using punched cards like the other computers of the day, the LINC had a keyboard and a display so that the user could sit down and program it directly. This was the first digital computer that had an interactive graphics display and that incorporated knobs that were functionally equivalent to the modern joystick or mouse. It also had built-in signal conversion and instrument interfacing hardware, with a compact, reliable digital tape recorder, and with sound generation capability. You could capture an ECG directly from a patient, digitize it, save it on magnetic tape, and show the waveform on the graphics display.

The LINC would have been the first personal computer if it had been smaller (it was about the size of a large refrigerator) and less expensive (it cost about $50,000 in kit form). It was the first game computer. Programmers wrote software for a two-player game called Spacewar. Each player controlled the velocity and direction of a spaceship by turning two knobs. Raising a switch fired a missile at the opposing ship. There were many other games such as pong and music that included an organ part from Bach as well as popular tunes.

The LINC was followed by the world's first commercial minicomputer, which was also made of discrete components, the Digital Equipment Corporation PDP-8. Subsequently Digital made a commercial version of the LINC by combining the LINC architecture with the PDP-8 to make the dual-processor LINC-8. Digital later introduced a more modern version of the LINC-8 called the PDP-12. These computers were phased out of Digital's product line some time in the early 1970s. I have a special fondness for the LINC machines since a LINC-8 was the first computer that I programmed that was interactive, could display graphics, and did not require the use of awkward media like punched cards or punched paper tape to program it. One of the programs that I wrote on the LINC-8 in the late 1960s computed and displayed the vectorcardiogram (VCG) loops of patients. Such a program is relatively easy to implement today on the modern PC using a high-level computing language such as C.

Although invented in 1971, the first microprocessors were relatively-expensive, poor central processing units. It was not until the mid-1970s when useful 8-bit microprocessors

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such as the Intel 8080 were readily available. The first advertised microcomputer for the home appeared on the cover of *Popular Electronics Magazine* in January 1975. Called the Altair 8800, it was based on the Intel 8080 microprocessor and could be purchased as a kit. The end of the decade was full of experimentation and new product development leading to the introduction of PCs like the Apple II and microcomputers from many other companies.

II. EVOLUTION OF MICROPROCESSOR-BASED SYSTEMS

The microcomputer has made a significant impact on the design of biomedical instrumentation. The natural evolution of the microcomputer-based instrument is toward more *intelligent* devices. More and more computing power and memory are being squeezed into smaller and smaller spaces. The commercialization of laptop PCs with significant computing power has accelerated the technology of the battery-powered, patient-worn portable instrument. Such an instrument can be truly a *personal* computer looking for problems specific to a given patient during the patient's daily routines. The ubiquitous PC itself evolved from minicomputers that were developed for the biomedical instrumentation laboratory, and the PC has become a powerful tool in biomedical computing applications. As we look to the future, we see the possibility of developing instruments to address problems that could not be previously approached because of considerations of size, cost, or power consumption.

The evolution of the microcomputer-based medical instrument has followed the evolution of the microprocessor itself. The microprocessor is now more than three decades old. It evolved from modest beginnings as an integrated circuit with 2,000 transistors (Intel 4004) in 1971 to the powerful multi-core central processing units of today having on the order of one billion transistors (e.g., Intel Core 2 Duo). Gordon Moore, one of the founders of Intel, observed that the number of functional transistors that can be put on a single piece of silicon doubles about every one-and-one-half to two years, and this observation has become known as Moore's Law. Intel's introduction of microprocessors to date has followed Moore's Law exceptionally well. The company has continuously demonstrated an ability to produce microprocessors with this exponential growth in the number of transistors per microprocessor chip. Both very powerful desktop computers and battery-powered laptops have evolved with technologies that can support development of portable medical devices.

The evolution of the microprocessor from its early beginnings in 1971 as a primitive central processing unit to the powerful component of today has made a significant impact on the design of medical instrumentation. More computing power and memory are being squeezed into fewer integrated circuits to provide increasingly more powerful instruments. The PC itself has become a powerful tool in biomedical computing applications. In the future, we will be able to develop new medical instruments to address problems that were previously not solvable. This possibility exists because microprocessor-based systems continuously increase in computing power and memory while decreasing in size, cost, and power consumption.

III. THE UBIQUITOUS PC

A significant historical landmark was the introduction of the IBM PC in 1981. On the strength of its name alone, IBM standardized the personal desktop computer. Prior to the IBM PC, some of the most popular computers used the 8-bit Zilog Z80 microprocessor (an enhancement of the Intel 8080) with an operating system called CP/M (Control Program for Microprocessors) or a company-specific operating system. At the time, the largest-selling personal computer was the Apple II which was the core computer for many biomedical applications. But there was no generally accepted way to format a floppy disk among the personal computer companies at that time, so it was difficult to transfer data from one company's PC to another. IBM singlehandedly standardized the world almost overnight on the 16-bit Intel 8088 microprocessor, Microsoft DOS (Disk Operating System), and a uniform floppy disk format that could be used to carry data from machine to machine. They also stimulated worldwide production of IBM PC compatibles by many international companies. This provided a standard computing platform for which software developers could write programs. Since so many similar computers were built, inexpensive, powerful application programs became plentiful. This contrasted to the minicomputer marketplace where there were relatively few similar computers in the field, so a typical program was very expensive and the development of new software was relatively slow.

The evolution of the microprocessor has dramatically improved the performance of computers. The cost per million instructions per second (MIPS) has decreased exponentially with the introduction of each new microprocessor. This exponential decrease in cost-per-MIPS will likely continue as long as microprocessor manufacturers can continue to follow Moore's Law.

An important PC landmark was the introduction of the Apple Macintosh in 1984. This computer popularized a simple, intuitive user-to-machine interface driven by a mouse. Subsequently, this graphical user interface (GUI) approach was implemented on all PCs.

Almost 30 years have elapsed since the introduction of the IBM PC, and most of the changes in the industry have been evolutionary. PCs have continued to evolve and improve with the evolution of the technology, particularly the microprocessor, but also the memory chips as well as input-output integrated circuits. We now have laptop PCs and compact, microprocessor-based devices like smart cell phones that are portable and battery powered. We can carry around a significant amount of computing power wherever we go.

In the 1970's, the principal microprocessors used in desktop computers as well as other systems including medical instruments were 8-bit microprocessors. The 1980's were dominated by the 16-bit microprocessors. The 1990's were launched with the 32-bit processor. The technology's exponential growth in the 2000's has led to new 64-bit architectures like multi-core processors on single integrated circuit chips.

IV. ECG INTERPRETATION BY COMPUTER

One example of the impact of the microprocessor-based instrument is in the field of electrocardiography. ECG interpretation techniques were initially developed and used on mainframe computers in the early 1960s [1]. In those days, mainframe computers centrally located in computing centers performed ECG analysis and interpretation. The ECGs were transmitted to the computer from remote hospital sites using a specially designed ECG acquisition cart that could be rolled to the patient's bedside. The cart had three ECG amplifiers, so three leads were acquired simultaneously and transmitted over the voice-grade telephone network using a three-channel analog FM modem. The interpretation program running in the mainframe computer eventually consisted of several hundred thousand lines of FORTRAN code.

As technology evolved, minicomputers located within hospitals took over the role of the remote mainframes. The ECG acquisition carts began to include embedded microprocessors in order to facilitate ECG capture. Also, since the interpretation algorithms had increased failure rates if the ECG was noisy, the microprocessors increased the signal-to-noise ratio by performing digital signal preprocessing algorithms to remove baseline drift and to attenuate power line interference.

Ultimately the ECG interpretation programs were incorporated within the bedside carts themselves, so that the complete process of acquisition, processing, and interpretation could be done at the patient's bedside without transmitting any data to a remote computer. This technology has now evolved into stand-alone microprocessor-based interpretive ECG machines that can be battery powered and small enough to fit in a briefcase.

The early ECG carts had three built-in ECG amplifiers and transmitted 2.5-second epochs of three simultaneous channels. In order to acquire all 12 leads, they sequenced through four groups of three leads each, requiring 10 seconds to send a complete record. Thus, the four acquired three-lead sets represented four different time segments of the patient's cardiac activity. Since a 2.5-second interval only includes two or three heartbeats, the early algorithms had difficulty in deducing abnormalities called arrhythmias in which several heartbeats may be involved in a rhythm disturbance. In order to improve arrhythmia analysis, three additional leads, typically the VCG leads, were recorded for a longer period of six seconds and added to the acquired data set [2]. The modern microprocessor-based interpretive machines include eight ECG amplifiers so that they can simultaneously sample and store eight leads—I, II, and V1–V6. They then synthesize the four redundant leads—III, aVR, aVL, and aVF. These machines include enough memory to store all the leads for a 10-second interval at a clinical sampling rate of 500 samples per second.

V. THE MICROCOMPUTER-BASED MEDICAL INSTRUMENT

The progress in desktop and portable computing in the past two decades has provided the means with the PC or customized microcomputer-based instrumentation to develop solutions to biomedical problems that could not be approached before. One of my personal interests has been the design of portable instruments that are light, compact, and battery powered [3]. A typical instrument of this type is truly a personal computer since it is programmed to monitor signals from transducers or electrodes mounted on the person who is carrying it around.

One example of such a portable device is the portable arrhythmia monitor which monitors a patient's electrocardiogram from chest electrodes and analyzes it in real time to determine if there are any heart rhythm abnormalities. We designed a prototype of such a device more than four decades ago [4]. Because of the technology available at that time, this device was primitive compared with modern commercially-available portable computers.

The evolution of the technology also permits us to think of even more extensions that we can make in portable ECG monitoring. Instead of just assigning a heart monitoring device to follow a patient after discharge from the hospital, we can now think of designing a device that would help diagnose the heart abnormality when the patient arrives in the emergency room. With a careful design, the same device might go with the patient to monitor the cardiac problem during surgery in the operating room, continuously learning the unique characteristics of that patient's heart rhythms. The device could follow the patient throughout the hospital stay, alerting the hospital staff to possible problems in the intensive care unit, in the regular hospital room, and even in the hallways as the patient walks to the cafeteria. The device could then accompany the patient home, providing continuous monitoring that is not now practical to do, during the critical times following open heart surgery [5].

There are many other examples of portable biomedical instruments in the marketplace. A microcomputer-based device that we contributed to developing was a calculator-size product called the CALTRAC™ that used a miniature accelerometer to monitor the motion of the body. It then converted this activity measurement to the equivalent number of calories and displayed the cumulative result on an LCD display [6]. The idea of using accelerometry in a device is now manifested in implanted pacemakers that use accelerometers to measure the level of a patient's activity in order to adjust the pacing rate.

We also developed a portable device that monitored several pressure channels from transducers on a catheter placed in the esophagus. It analyzed the signals for pressure changes characteristic of swallowing, then recorded these signals in its semiconductor memory for later transfer to a PC where the data were further analyzed [7].

Another portable device that we designed monitored pressure sensors placed in the shoes to determine the dynamic changes in pressure distribution under the foot for patients such as diabetics who had insensate feet [8].

VI. PC-BASED MEDICAL INSTRUMENTS

The economy of mass production has led to the use of the desktop PC as the central computer for many types of medical instruments and applications. Many companies use PCs for such applications as sampling and analyzing physiological signals, maintaining equipment databases in the clinical engineering department of hospitals, and simulation and modeling of physiological systems.

The modern PC has user-friendly, interactive characteristics much like those pioneered by the LINC. This is an important aspect of computing in the medical laboratory or clinic. The difference is that the PC is a much more powerful computer in a smaller, less expensive box. Compared to the LINC of more than five decades ago, the PC has orders of magnitude more computing power and memory in about one-twentieth the space for one-twentieth the cost. However, the LINC gave us tremendous insight into what the PC should be like long before it was possible to build a personal computer.

We use the PC as a general-purpose laboratory tool to facilitate research on many biomedical computing problems and many clinical applications. We can program it to execute an infinite variety of programs and adapt it for many applications by using custom hardware interfaces.

VII. A LOOK TO THE FUTURE

As the microprocessor and its parent semiconductor technologies continue to evolve, the resulting devices will stimulate the development of many new types of medical instruments. We cannot even conceive of some of the possible applications now, because we cannot easily anticipate and start designing for the significant advances that will be made in computing in the next decade. With the multi-billion-transistor, multi-core microprocessor will come true personal supercomputing. Only futurists can contemplate ways that we will be able to exploit such computing power in the health care system. Even the nature of the microprocessor as we now know it might change more toward the architecture of the artificial neural network, which would lead to a whole new set of pattern recognition applications that may be more readily solvable than with today's microprocessors. Indeed, there are now computer architects working on reverse engineering the brain in order to design biomimetic computer architectures.

The hardware/software flexibility of the PC is permitting us to make instrumentation in areas that were previously too difficult, too expensive, or simply impossible. We have come a long way in biomedical computing since those innovators put together that first PC-like LINC almost five decades ago. Expect the PC and its descendants to stimulate truly amazing accomplishments in clinical medicine in the next decade.

REFERENCES

[1] Pordy, L., Jaffe,H., Chesky, K. et al. 1968. Computer diagnosis of electrocardiograms, IV, a computer program for contour analysis with clinical results of rhythm and contour interpretation. *Comp. Biomed. Res.*, **1**: 408–33.

[2] Bonner, R. E. and Schwetman, H. D. 1968. Computer diagnosis of the electrocardiogram II. *Comp. Biomed. Res.*, **1**: 366.

[3] Tompkins, W. J. and Webster, J. G. (eds.) 1981. *Design of Microcomputer-based Medical Instrumentation.* Prentice Hall.

[4] Tompkins, W. J. 1978. A portable microcomputer-based system for biomedical applications. *Biomed. Sci. Instrum.*, **14**: 61–66.

[5] Tompkins, W. J. 1988. Ambulatory monitoring. In J. G. Webster (ed.) *Encyclopedia of Medical Devices and Instrumentation*. New York: John Wiley, **1**:20–28.

[6] Doumas, T. A., Tompkins, W. J., and Webster, J. G. 1982. An automatic calorie measuring device. *IEEE Frontiers of Eng. in Health Care*, **4**: 149–51.

[7] Pfister, C., Harrison, M. A., Hamilton, J. W., Tompkins, W. J., and Webster, J. G. 1989. Development of a 3-channel, 24-h ambulatory esophageal pressure monitor. *IEEE Trans. Biomed. Eng.*, **BME-36**(4): 487–90.

[8] Mehta, D., Tompkins, W. J., Webster, J. G., and Wertsch, J. J. 1989. Analysis of foot pressure waveforms. *Proc. Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 1487–88.