A Portable Monitor for Fetal Heart Rate and Uterine Contraction

Long-Term Ambulatory Monitoring for High-Risk Pregnancies with a Low-Power, Lightweight Device

Chih-Lung Lin[1], Han-Chang Wu[1], Tz-Yi Liu[1], Maw-Huei Lee[1], Te-Son Kuo[1,2] Shuenn-Tsong Young[3]

[1]Department of Electrical Engineering, National Taiwan University

[2]Research Center for Medical Engineering, National Taiwan University

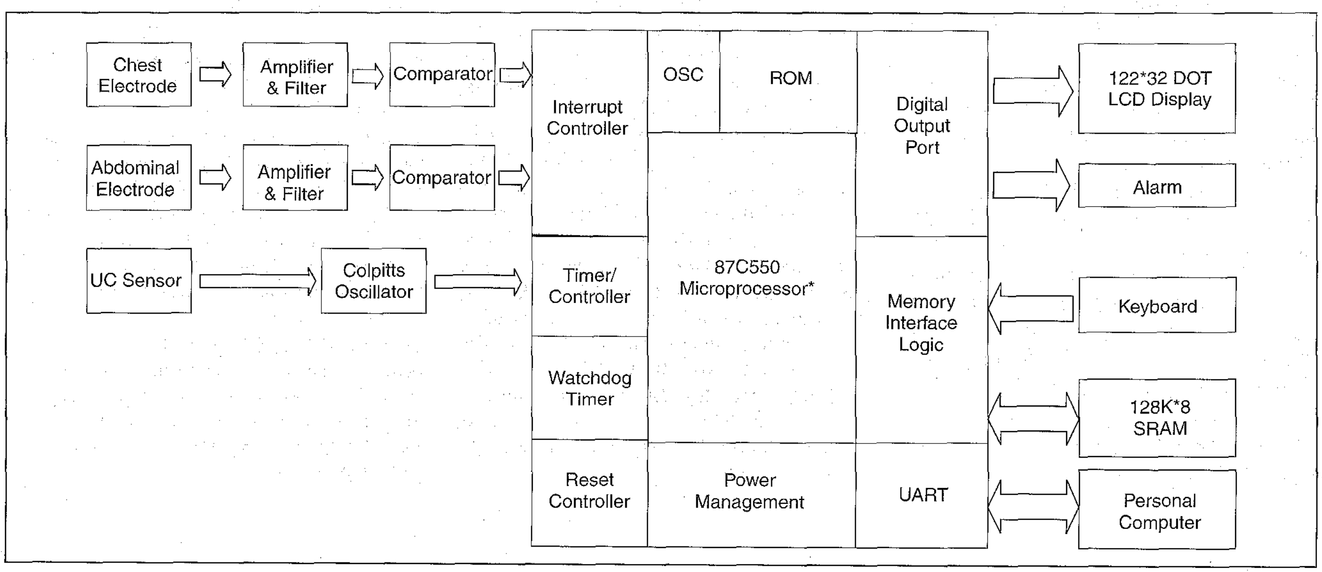
[3]Institute of Biomedical Engineering, National Yang-Ming University

Abnormalities of fetal heart rate (FHR) and uterine contraction (UC) are the harbingers of prematurity and miscarriage. It is very important to monitor for such abnormalities in pregnant women at high risk for prematurity and miscarriage. These abnormalities are unpredictable and may occur at any time, especially in the case of preterm labor. The pathogenesis of preterm labor is still poorly understood. However, the occurrence of prematurity and miscarriage can be largely prevented by the timely diagnosis of preterm labor and its arrest with tocolytic medication.

To diagnose preterm labor, ambulatory monitoring for abnormal FHR and UC has proven to be a useful method [3]. FHR and UC are usually normal most of the time, even for pregnant women with high risk of prematurity and miscarriage. These women can maintain normal daily activities and work, and avoid unnecessary hospital stays, with the use of long-term monitoring of FHR and UC—up to several weeks or months. Many studies have shown that a home monitor combined with more patient awareness and more intensive nursing contact will reduce the incidence of prematurity and miscarriage [1-3].

Some precise and multifunctional systems [4] have been designed to monitor FHR and UC in the hospital. These monitors are complex and expensive and are inconvenient to use in the normal living and working environment. Portable FHR monitors have also been developed, some using Doppler ultrasound [5], but are unsuitable for long-term ambulatory monitoring [6]. Some monitors record the fetal heart wave [7] but require too much power and become too heavy to be truly portable. Some miniature heart-rate telemeters with microcontrollers are low power, small size, and portable, but they cannot store abnormal data when outside of the hospital.

In this article we present a portable instrument we developed to monitor FHR and UC continuously. It can record the abnormal FHR and UC, and it alerts pregnant women when to go to the hospital to see a physician. The abnormal FHR and UC recorded by the monitor can be analyzed by the associate system, which provides valuable data for the physician as an aid to diagnosis and treatment. The monitor is miniaturized for ambulatory monitoring and is powered by a commercial alkaline 9V battery.



1. A block diagram of the monitor hardware.

Methods

Implementation of Hardware

The hardware block diagram of the monitor is shown in Fig. 1. It is composed of electrode pairs, a UC sensor, a main circuit board, and user interfaces.

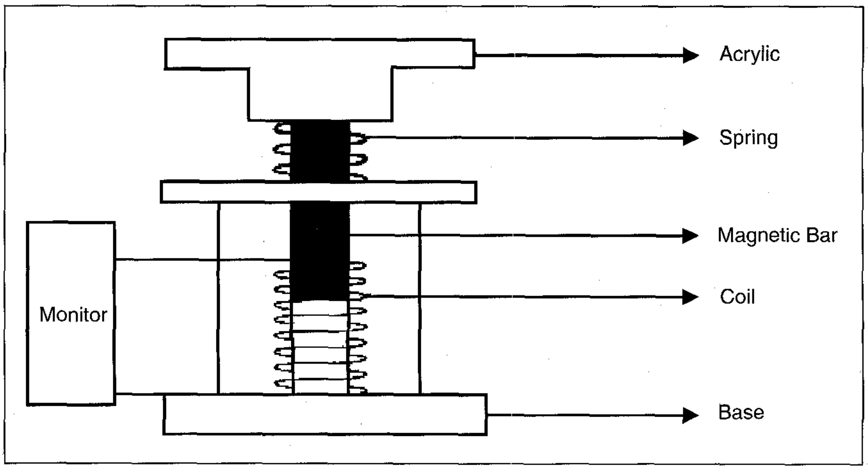
Two pairs of electrodes are applied on the chest and on the abdomen of a pregnant woman to sense the maternal and the fetal electrocardiograms (ECGs), respectively. The ECGs are amplified with gains of 1000 and filtered by a fourth-order Butterworth lowpass filter to remove high-frequency noise, and by a second-order highpass filter to remove motion and muscle activity noise artifacts. The filtered signals pass into comparators to generate clock trains associated with the R-waves of the maternal and the fetal ECGs, which then enter into the microprocessor through interrupt lines. The maternal heart rate (MHR) and the FHR are obtained by the microprocessor from the clock rates.

The UC sensor detects abdominal pressure variations. This sensor, as shown in Fig. 2, consists of a magnetic bar, coil, spring, and an acrylic base. It is attached to the patient's abdomen by a belt. Tightness of the belt is adjusted to a preloaded condition so that the sensor detects a very small variation of abdominal pressure. Any variation of abdominal pressure changes the length of the magnetic bar within the coil. This, in turn, varies the inductance of the coil, which is part of a Colpitts oscillator. Thus, intensity of UCs are converted to frequency variations.

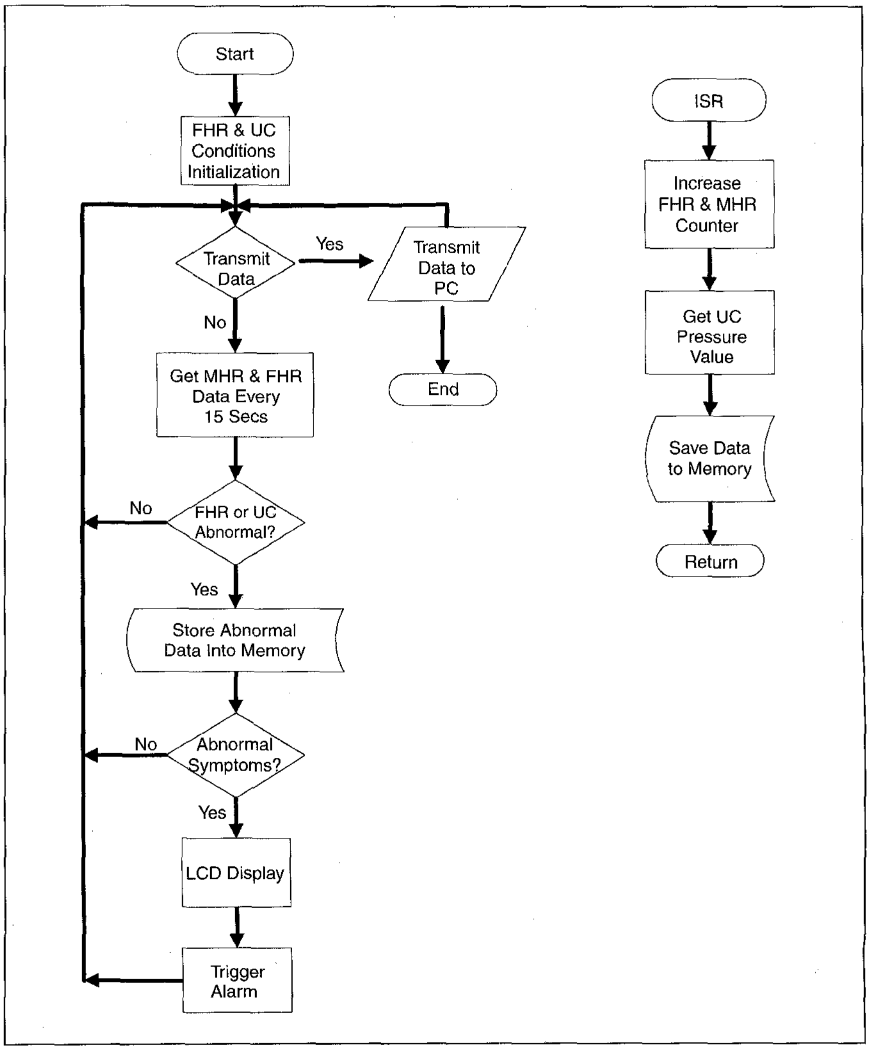
The main circuit board includes an 87C550 microprocessor, 128 Kbytes of static random access memory (SRAM), and peripheral circuits. The 87C550 microprocessor is an 8-bit CMOS chip that provides both high performance and low power consumption. It incorporates many on-chip system functions, including power management, two external interrupts, two timer interrupts, one RS232 interrupt and a programmable watch timer.

The microprocessor captures the FHR and the UC from the peripheral circuits, makes primary medical decisions, and alerts the pregnant woman to go to hospital if necessary. The SRAM stores all abnormal FHR and UC signals.

The user interfaces allow communication between the monitor with the patient. Included here are function keys, a liquid crystal display (LCD), and an alarm. The keys are used to initialize the monitor, to modify the preset thresholds of abnormal FHR and UC, and to transmit data to a PC. The black-and-white LCD of 122 by 32 dots is used to display the SRAM contents and other relevant information. The alarm is used to alert the pregnant woman when preliminary medical decisions detect an abnormal symptom. When the monitor alarms, the pregnant woman can transmit the abnormal data stored in the SRAM via a modem to the hospital. She can also go



2. The uterine contraction sensor structure.



3. Program flow chart of the portable monitor.

directly to the hospital with the monitor for physician intervention.

Implementation of Software

The monitor software is divided into foreground and background tasks. The foreground tasks initiate the system, capture the FHR and the UC, store the abnormal data, and make preliminary medical decisions. The background task is an interrupt service routine that transmits abnormal data from the monitor to a hospital computer. The software flow chart is shown in Fig. 3.

When the system is first turned on, the pregnant woman must set the abnormal thresholds for FHR and UC according to her body condition. She also needs to calibrate the offset of the UC sensor with the keypad, according to her posture. The microprocessor then initiates the timer and enables its interrupts every 15 seconds for data acquisition. The acquired data are used to decide whether the FHR or the UC is abnormal; that is, either higher or lower than the preset thresholds. When an abnormality is detected, an 8-byte record is stored in the SRAM, including occurrence time of year, month, date, minute, and second; MHR, FHR, and UC pressure. If the abnormality is prolonged over a preset period, the monitor triggers the alarm and displays a warning on the LCD.

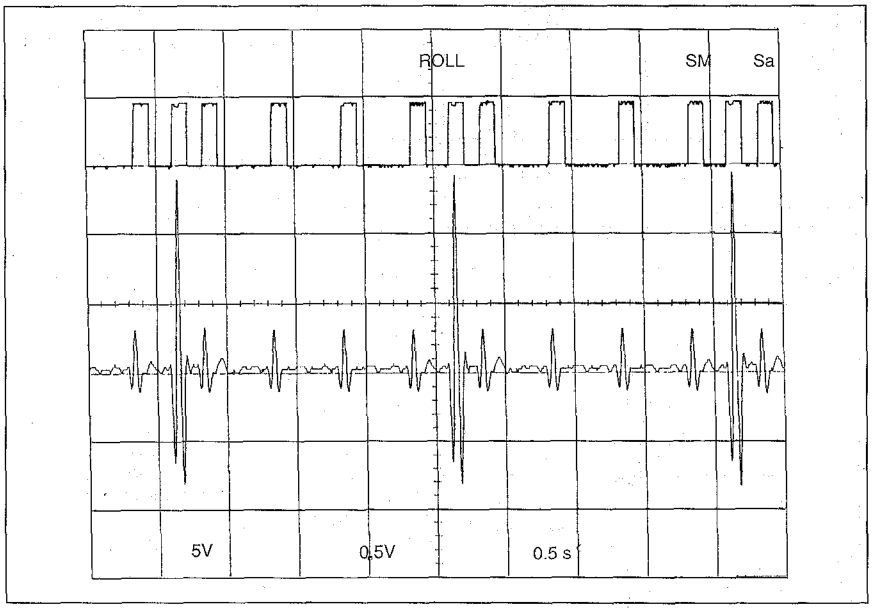
Generally, there are three abnormality symptoms that will trigger the alarm:

(a). The abnormality is continuous and prolonged for more than two hours.

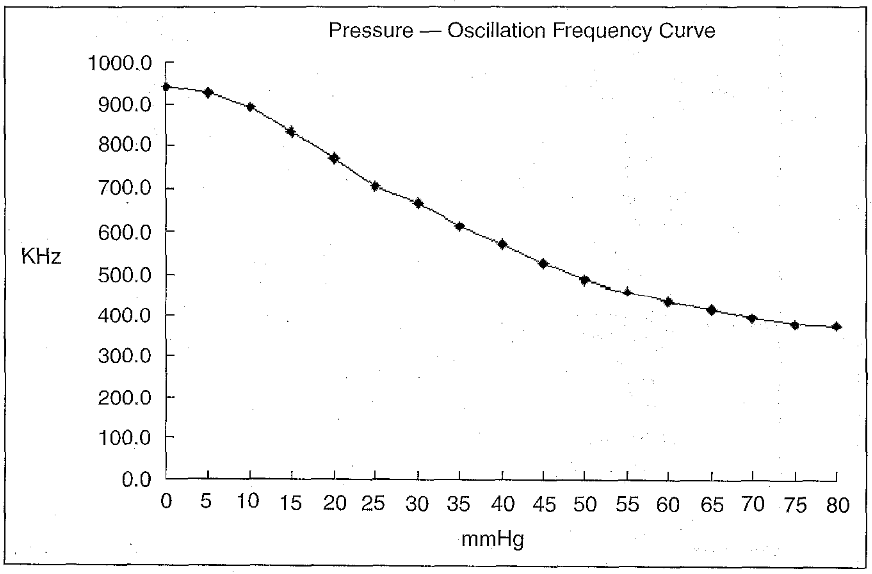
(b). The abnormality happens by fits and starts, but accumulates more than 30 minutes every hour and continues for several hours.

(c). The abnormality is present for a few minutes, but continues for several days.

However, the preset conditions for alarm can be modified by the physician for the individual patient.



4. The filtered electrocardiograph from abdominal electrode and its associated clock train.



5. The uterine contraction sensor characteristics showing the relation of the pressure variation caused by the contractions versus the frequency of the Colpitts oscillator.

Implementation of Associated System

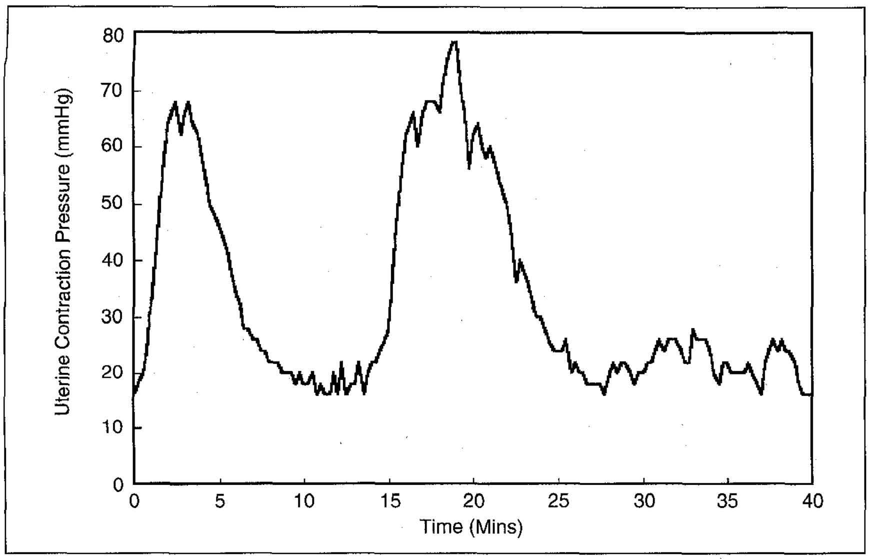
When an abnormality triggers the alarm, the pregnant woman may go to hospital with her monitor, where the abnormal data within the SRAM can be downloaded to a PC. A receiving program and a window graph program are included in the PC software. The receiving program accepts the abnormal data from the monitor through an RS232 port. The window graph program displays the abnormal data for the physician's inspection. There are four display windows: the abnormal UC, the abnormal FHR and MHR, the data list of occurrence time, and a window used for physician comments.

Results

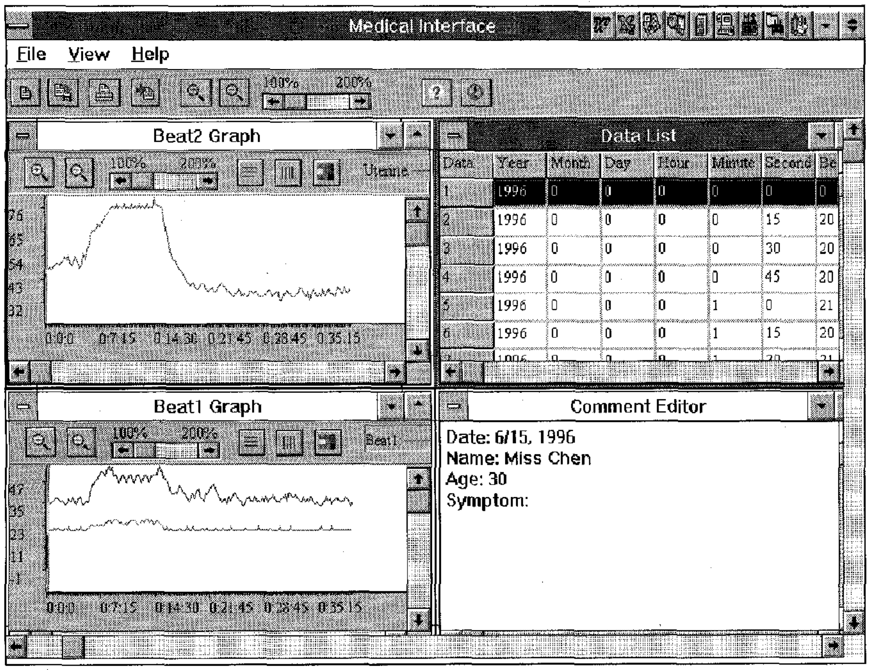
An example a filtered abdominal ECG is shown in Fig. 4. The R-waves of the ECG are used to generate clock trains. The clock train from the abdominal ECG includes the fetal and the maternal heart beats, and that from the chest ECG only includes the maternal heart beats. Subtracting the two clock trains gives the FHR.

Figure 5 shows the frequency response of the Colpitts oscillator relative to the pressure applied to the UC sensor. Increasing pressure results in decreasing frequency. Fig. 6 shows an example of abdominal pressure variation detected by the UC sensor.

The monitor stores abnormal data as 8 bytes every 15 seconds. With 128 Kbytes of SRAM, the monitor can store 16K records of abnormal data. In the worst case, when the abnormality is continuous, the monitor can operate for at least 66 hours.



6. An example record of sensed uterine contractions.



7. A utility screen of the associated system for the data display and physician application.

The associated system of the monitor has a graphical control panel and a data-management screen: a utility screen is shown in Fig. 7. There are four different data integrated in the screen: the data list transferred from the monitor, a graph of the FHR and MHR, a graph of pressure variation caused by UCs, and patient information and physician comments. A scroll bar allows display of different sections of FHR and UC on the graphs. The windows can zoom out and in for comparative inspection. Using these graphs, the physician can easily follow the progress of the patient while she is outside of the hospital. Diagnosis and the treatment commands can be entered from subwindows. The screens can be printed out and kept as part of the formal patient record.

Discussion

This study presents a miniature portable monitor for fetal heart rate and uterine contraction. Its size is 9 x 8 x 4.4 cm and its weight is 205 g with a 9-V alkaline battery. The monitor checks the FHR and the UC of the pregnant woman every 15 seconds, and abnormal FHR and UC are recorded by the monitor. Each abnormal datum occupies only 8 bytes of SRAM, so that the progress of a high-risk pregnant woman can be monitored for a substantial period of time outside of the hospital. Long-term monitoring is important to maintain normal living and working conditions for the patient.

Doppler ultrasound and fetal electrocardiogram (FECG) are two commercial methods used to measure FHR. The Doppler ultrasound requires skill to operate and position the transducer so as to acquire the fetal heart sound, making it unsuitable for long-term ambulatory monitoring. FECG, as used by some monitors, is usually concerned with the waveform. These monitors are equipped with massive memory, but record only a short period of FECG. Recently, high-capacity removable disks and flash memory have become available to record the FECG and prolong the operating period of the monitors. However, the complex control circuit and weight factor still prevent the commercial FECG monitors from being portable. Since the FHR and the UC are valuable for long-term monitoring, our monitor is much more practical for long-term ambulatory use.

Furthermore, the UC sensor developed in our study is also much better than traditional sensors, which are implemented with strain gauge or linear variable differential transformers (LVDT). The strain gauge is sensitive to temperature, and its nonlinearity makes the compensation circuit complex. Operation of LVDT requires an AC source, which makes it inconvenient as a portable monitor. The new UC sensor uses inductance changes to detect the pressure variation caused by UC. The inductance changes are transferred into frequency changes of a Colpitts oscillator. The sensor is not sensitive to temperature, and it just needs a DC source. These characteristics make the sensor superior to traditional UC sensors in the sense of being more accurate and simpler to use.

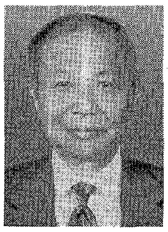
The monitor can make some primary medical decisions based on the FHR and UC. The abnormal data stored in the monitor can be transmitted to the hospital computer by a modem or can be brought to the hospital directly for physician inspection. An associated system based on a personal computer analyzes and presents the abnormal data in graphic form to aid the physician in diagnosis and treatment. The diagnosis and treatment are then integrated with the abnormal data to form the patient record.

The most important aspect of the monitor is its detection of the preset abnormalities and its ability to alert the pregnant woman to visit the hospital for more detailed medical care. This feature lessens the burden on the hospital and keeps the pregnant woman living and working under normal conditions for as long as possible.

Chih-Lung Lin was born in Tainan, Taiwan, the Republic of China, in 1965. He received the M.S. degree in electrical engineering in 1993 from National Taiwan University, where he currently is a Ph.D. candidate. His research interest are medical instrumentation, medical electronics, and neuron modeling.

Han-Chang Wu was born in Taipei, Taiwan, in 1974. He received the B.S. degree and is working toward the M.S. degree in electrical engineering from National Taiwan University. His research interest are biomedical signal processing and biomedical hardware design.

Tz-Yi Liu was born in Taipei, Taiwan, in 1972. He received the B.S. degree in electrical engineering from National Taiwan University. Currently, he is working toward a Ph.D. degree from Stanford University, CA. His research interest are signal processing and biomedical hardware design.



Maw-Huei Lee was born in Taiwan, the Republic of China, in 1969. He received the B.S. degree in electrical engineering from National Taiwan University, Taipei, Taiwan, in 1962, and the M.S. and the Ph.D. degrees in electrical engineering from Georgia Institute of Technology, Atlanta, Georgia, in 1969 and 1975, respectively.

In the United States, he has held various positions in Fortune 500 and fast growing startup companies. The positions include research engineer, research and development manager, director, general manager, vice president, executive vice president, research advisor, etc. He is currently a professor in the Department of Electrical Engineering at National Taiwan University.

One of Dr. Lee's interests is creativity and innovation. He holds 20 United States patents. He has over 100 other inventions that the patents are not applied for due to proprietary or trade-secret reasons. The spectrum of his inventions and innovations include the electrical, electronics, mechanical, chemical, and manufacturing processes areas. He has also synthesized systematic creativity and innovation approaches used by many world famous inventors and innovators. He has been invited to give lectures on "How To Be More Creative" in the United States for various organizations in the past few years. Many attendees have become first-time inventors after listening to his speeches. His fields of interest are circuits and systems, power electronics, and invention & innovation engineering.

Te-Son Kuo was born in Taiwan, Republic of China, on January 8, 1938. He received the B.S. degree in electrical engineering from National Taiwan University, Taipei, Taiwan, in 1960, and the M.S. and the Ph.D. degrees in electrical engineering from Georgia Institute of Technology, Atlanta, Georgia, in 1967 and 1970, respectively.

From 1963 to 1964, he had one year of study on digital computers in the Philips International Institute of Technological Studies, Eindhoven, Netherlands. He was a visiting assistant professor of the Electrical Engineering Dept. at Texas A&M University, College Station, Texas, in 1970. From 1970 to 1973 he was an associate professor and became a full professor in 1973. He then served as the department head from 1975 to 1981, all in the Department of Electrical Engineering at National Taiwan University, Taipei, Taiwan, where he is now a full professor. He has been also holding a joint appointment with the center for biomedical engineering, National Taiwan University, since February 1993. His fields of interest are computer-aided design, control systems, and biomedical engineering.

Shuenn T. Young was born in Taiwan, the Republic of China, in 1959. He received his M.S. and Ph.D. degrees from Department of Electrical Engineering, National Taiwan University, in 1989. Since 1994, he has been a professor at the Institute of Biomedical Engineering, National Yang-Ming University. He has also been the Chief of Experimental Surgery, Surgery Department, Veterans General Hospital-Taipei, since 1989. His research interest are medical instrumentation, medical imaging, and medical electronics.

Address for Correspondence: Shuenn-Tsong Young, Institute of Biomedical Engineering, National Yang-Ming University, No.155, 2 Sec, Li -Nung St., Shih-Pai, Taipei, Taiwan, R.O.C. 11221. Tel: 886-2-8267022. Fax: 886-2-8210847. E-mail:young@bme.ym.edu.tw

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