ORIGINAL RESEARCH PAPER
Volume-8 | Issue-9 | September - 2019 | PRINT ISSN No. 2277 - 8179 | DOI : 10.36106/ijsr
INTERNATIONAL JOURNAL OF SCIENTIFIC RESEARCH

DEVELOPMENT OF ULTRASONIC PULSER-RECEIVER FOR BONE DENSITY ASSESSMENT

Engineering

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ABSTRACT

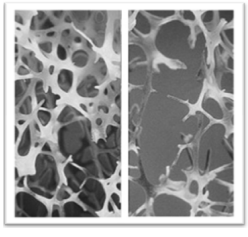
Osteoporosis is a major health problem affecting millions of people every year, significantly in women after menopause and men over the age of 50 years. It is a deteriorated condition of the bone becoming weak and fragile due to decrease in mineral content such as calcium, resulting into high risk of bone fracture. There are traditional methods for bone mineral density measurement using X-rays. In many recent studies ultrasound method has emerged as a non-invasive method for bone density assessment and has been found to be helpful in mass screening high risk group of subjects.
In view of above, a low cost Ultrasonic Pulser-Receiver has been developed comprising four integrated circuit devices and a high voltage MOSFET to be used in transmission mode. Rate generator chip (LM555) followed with a mono-stable chip (LM74121) generates trigger pulses of 2 microsecond duration with a pulse repetition frequency of 200 Hertz. These pulses are used to fire a MOSFET (5N120BND) through a Schmitt trigger chip (MC33151) to generate 600Volt pulses of short duration to excite the ultrasonic transducer.
The transmitted ultrasound through the heel of the subject is received by another ultrasonic transducer and amplified using a quad operational amplifier chip (OPA4354). The output signal is captured on a pen-drive through a digital storage oscilloscope for final processing on a personal computer. Hardware development is reported in this paper.

KEYWORDS

Bone mineral, osteoporosis, ultrasonic transducer, pulser-receiver.

1. INTRODUCTION

Osteoporosis, which means porous bone, is a disease in which the density and quality of bone are reduced with a consequent increase in bone fragility and susceptibility to fracture[1]. It is usually a painless disease until a bone breaks or fractures. Fractures are the most common result of osteoporosis. Figure 1 shows[2] the appearance of a normal and a porous bone.



(a) (b)

Fig.1: Microscopic appearance of (a): normal bone (b): osteoporotic bone
(Courtesy Report of International Osteoporosis Foundation; 2009)

It is estimated about 75 million people in Europe and United States, of which about 75% are women are affected by osteoporosis; while in India, accurate data is not available at present, but the count is increasing due to increasing population of elderly men and women, and a significant increase in patients suffering from fractures, thereby implying an urgent need for early detection, diagnosis and preventive strategies[3]. Osteoporosis is not usually diagnosed at initial stage and shows no symptoms; hence it is not clinically evident until fractures occur. Age factor is the major cause for increasing risk of fracture, giving rise to significant unhealthy state of bone condition[4]. Other risk factors are body size, race and family history. However, woman stands to a higher risk of osteoporosis in comparison to men. One-third of women aged 60–70 years and 2/3 of women aged 80 years and above have osteoporosis. Approximately one in five men over the age of 50 will have an osteoporosis-related fracture in their remaining lifetime and one of two women has an osteoporosis-related fracture in her lifetime (International Osteoporosis Foundation, 2005).

Measurement of bone density is a very important factor for the diagnosis and clinical management of osteoporosis, because low bone density is associated with fracture risk. Bone density shows a high correlation with bone strength. As much as 25-30% of the observed variation in bone strength may be due to other factors, such as bone microstructure, architecture, and state of bone metabolism[5-6]. Through last three decade several techniques have been developed for the measurement of bone density. Most of these techniques use some form of ionizing radiation (x-rays), and the measurement obtained is based on the attenuation of a beam of energy as it passes through bone and soft tissues. Dual-energy x-ray absorptiometry (DEXA) is the most commonly used method to diagnose osteoporosis, however it is relatively expensive and not widely available. Nevertheless DEXA scan is considered to be gold standard technique for diagnosis of osteoporosis. For mass screening it is inadvisable due to its invasive character and reasonably high-price, therefore use of DEXA is confined to high risk osteoporosis subjects as indicated by clinical risk factors[7-9]. Other methods used are conventional radiography, ultrasound densitometry and Quantitative Computed Tomography (QCT). The conventional radiography shows thinning bone; however, by the time it reveals osteoporosis, the bone is already too weak and the disease is in its advanced stage. QCT is expensive and requires high radiation dose. There is a need for development of low-cost non-invasive devices which can measure bone health in a given subject Next to X-rays, Ultrasound has revolutionized the field of medicine. It started with the measurement of foetal bi-parietal parameter and detection of mid line shift in the brain as far back as 1969[10] and subsequently invaded into all fields of medicine like Cardiology, Obstetrics and Gynaecology, Internal Medicine, Nephrology etc. It started with a simple A-scan displaying only transmitted pulse and reflected echo on the oscilloscope screen followed with B-Scan, TM-Mode Echocardiography, Linear Array Real Time Scan, Phased Array Sector Scan etc. Today it's the first choice of investigation in all kinds

of ailments after pathological testing. Computerized Tomography, Magnetic Resonance Imaging or Positron Emission Tomography are always thought of after Ultrasound Scanning. Actually speaking, ultrasonic imaging has been the first tomographic imaging in the field of medicine, prior to ultrasound it was only the planer imaging be it X-ray or nuclear imaging.

Though initially ultrasound was avoided for study of bony areas due to heavy attenuation, it is now recommended as feasible choice for estimation of bone quality and it's response to mechanical loads to predict fracture risk[11]. Ultrasound, being a mechanical wave, interacts with bone in a basically different way compared with ionizing electromagnetic radiation. Ionizing radiation attenuates at the atomic level, whereas ultrasound attenuates at the macroscopic level[12]. Also the fact that ultrasound requires non-ionizing radiation and is comparatively simple to implement and process, accounts for the widespread interest it has received recently. Another advantage of ultrasound is the potential for sound to be modified by bone's structure, composition, and mass in a way to provide additional information related to the mechanical competence of the skeletal condition[13]. Quantitative Ultrasound (QUS) method has been initiated since 1984 and for first two decades the major goal has been of refining and promoting risk assessment for osteoporotic fractures[14]. Commercial devices are speedily introduced based on assorted technical concepts leading to adequately prevalent use of the technology.

For ultrasound measurements there are two modes, reflection mode and transmission mode. Reflection mode uses single transducer, which acts as transmitter as well as receiver. The transducer transmits the wave and receives back the reflected wave from the measuring site. This mode is significantly used in medical imaging techniques and is simple to implement since it uses single transducer. In transmission mode two transducers are used, one as transmitter and other as receiver. In this approach, the acoustic properties of the tissue can be obtained by comparing the received signal with a standard or reference waveform. The received signal detects the altered wave and provides the information about the medium through which it travels. This mode has been used for assessment of bone strength and bone quality.

Several pulse generator circuits are available for generation of high voltage short-pulses high power signal, however they are expensive[15-16]. A remarkable evolution of semiconductor technology, particularly metal-oxide-semiconductor field-effect-transistor (MOSFET) switching technology, has made the implementation of fast and high voltage pulse generation simple and inexpensive. In this paper, development of a low-cost ultrasonic pulser-receiver is reported for estimation of bone health at heel as a measurement site.

2. MATERIALS AND METHOD

In the present work an ultrasonic pulser-receiver has been developed for making the system to be used in transmission mode as shown in Figure 2. It comprises two ultrasonic transducers used as transmitter and receiver placed on either side of the heel and a pulser-receiver circuit. The generation of ultrasonic wave is possible by triggering the transducer with the help of a high voltage narrow pulse compatible with resonance frequency of the transducer. This ensures a broadband and high frequency signal. Both the ultrasonic transducer used for this system are having a center frequency of 0.5MHz and 1 inch diameter with input output BNC connectors.

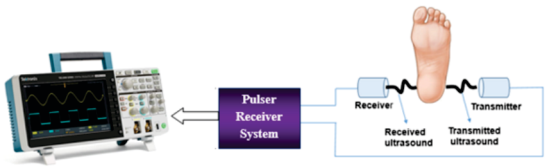


Figure 2: *schematic diagram of low-cost ultrasonic pulser-receiver system. Output of the pulser-receiver is seen on digital storage oscilloscope and the same is processed on a desktop for derivation of sensitive parameters for osteoporosis.*

Pulser-receiver system comprises a power supply unit, a transmitter unit and a receiver unit shown as (a), (b) and (c) respectively in Figure 3. Mains transformer has two secondary windings of 12V and 500V respectively. The secondary voltages are rectified using bridge rectifiers and capacitive filters to obtain near DC voltages of 17V and 750V. 17V DC is given to the three terminal regulators 7805 and 7812 for obtaining regulated 5V and 12V respectively designated as V1 and V2 in Figure 3(a). 750V unregulated DC, designated as V3, is connected to the drain of the switching MOSFET through a load resistance of 10KΩ.

Pulser circuit comprises an astable multivibrator, a monostable multivibrator, inverting Schmitt trigger, high voltage switching MOSFET and pulse shaping circuits, similar to that of reported by Hidayat et al[17]. Astable multivibrator uses Timer IC (NE555) to generate pulses at a pulse repetition frequency of 200Hz, which serves as a trigger for the monostable multivibrator (Sn74121). The monostable returns pulses of shorter duration (2µsec) to serve as input to Schmitt trigger (MC33151), which eventually converts the output of monostable multivibrator into 12 Volt rectangular pulse of 2µsec duration. Chosen Schmitt trigger IC has two high current

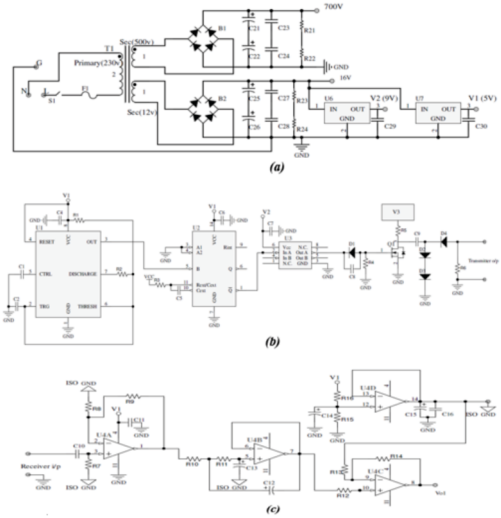


Figure 3: *shows circuit diagram of the low-cost ultrasonic pulser-receiver system with (a) power supply unit, (b) pulser circuit and (c) receiver circuit.*

totem pole at the output with rise and fall time of 15 ns with 1000 pf load, considered essential to drive the MOSFET. An N-channel MOSFET(5N120BND) having 4.5A continuous source drain current, 18.8A pulsed source drain current and 1200V drain source voltage; has been used for switching the high voltage supply for generating the desired excitation pulse. The positive pulses coming from the Schmitt trigger are connected to gate of the MOSFET. The voltage at the drain pin of the MOSFET is V3, when the gate voltage is zero. When the gate voltage becomes 12V for 2 µsec, synchronous with monostable output, MOSFET conducts from drain to source, offering a very low resistance. This results in falling of the drain voltage from 700V to nearly zero. Thus, a negative output pulse gets generated at the drain pin of the MOSFET with a pulse repetition frequency of 200Hz. This rectangular pulse is differentiated with the help of a high voltage polycarbonate capacitor. Diodes D2-D4 remove the positive part from the differentiator output and pass on negative part to the load resistor and the ultrasonic transducer used as transmitter. For driving the high voltage and resulting positive high voltage short pulses at the drain pin. Further, the pulses are converted into the negative high voltage spike pulses removing DC offset voltage by circuit network of C4, D1, D2, D3 and RL. This high voltage pulses are adequate to excite the ultrasonic transducer in transmission mode.

Receiver Circuit shown in Figure 3© senses the transmitted ultrasound through the body tissue with the help of another ultrasonic transducer similar to that used for transmission. The receiver part comprises a first order high pass filter, a second order low pass filter, a balancing ground circuit and a wide band amplifier. A high frequency quad operational amplifier (OPA4354) having low supply voltage of 2.5 to 5.5V is used for the receiver circuit. This op-amp features unity-gain bandwidth of 250 MHz and wide band width of 100MHz which is suitable for the selected ultrasonic transducer. In receiver part balancing ground circuit (U4D) is implemented to maintain a steady reference potential for the remaining op-amps of the device (U4A, U4B, and U4C). The received signal is band limited (50 KHz to 0.7 MHz) with the help of a

first order high-pass filter (U4A) and a second order low-pass filter (U4B) with a nominal gain of 6. The filter output is further amplified (X11) with the help of U4C. This processed and amplified signal is finally displayed on digital storage oscilloscope (DSO; model no. TBS1102B-EDU).

3. RESULTS AND DISCUSSIONS

Figure 4 shows transmitter output in (a). The lower end of the pulse is not discernible as it is beyond the range of DSO. On x-axis one square represents 25µsec and on y-axis one square represents 50 Volts. Though 350 Volt pulse is seen in the figure with transducer connected, in reality, it is approximately 450 Volt. Figure 4(b) shows receiver output signal from a young subject. On x-axis one square represents 25µsec and on y-axis one square represents 0.5 Volts. The initial transients are due to pick up from transmitter circuit followed with transmitted ultrasound energy through the body, nearly co-incident with the center of the screen. Figure 4(c) depicts signal similar to that of 4(b) from an elderly subject suspected with bone mineral deficiency. A comparison of 4(b) and 4(c) indicates that attenuation of ultrasound energy is much more in young person as compared to that in old person.

Digital data of Figure 4(b) and 4(c) is transferred to desktop with the help of a pen-drive. The frequency spectrum of the received ultrasound energy is shown in Figure 5(a) and (b). Absence of high frequency components in the elderly subject is obvious from the figure. Even the low frequency peak gets split in the elderly subject. These observations need clinical correlation. Further work in this regard is in progress.

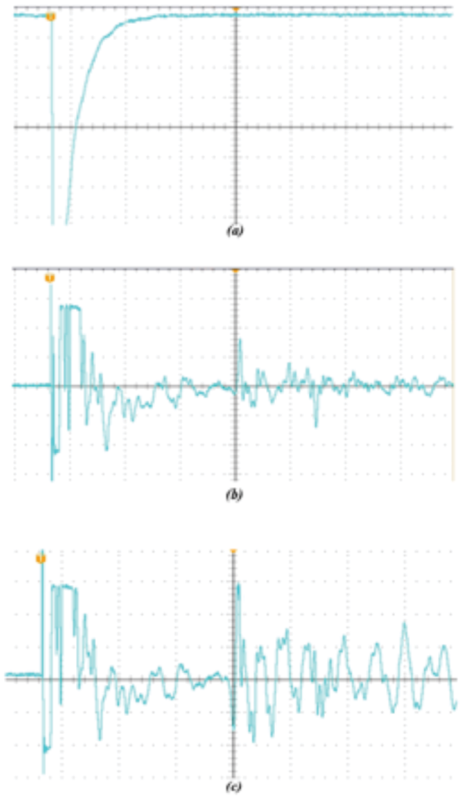
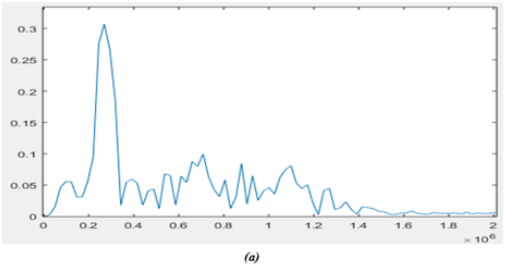


Figure 4: *shows output waveforms (a) Transmitted pulse, (b) output waveform from a young subject, ©: output waveform from an elderly person.*



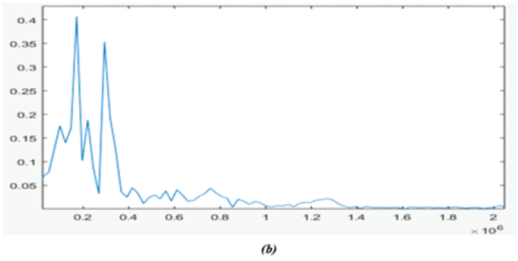


Figure 5 *shows frequency spectrum of transmitted ultrasound in a young subject (a) and an elder subject (b); difference in the spectrum can evidently be seen.*

4. CONCLUSION

High voltage, low-cost ultrasonic pulse generator and receiver system has been developed and tested on subjects from different age groups. It has been observed that ultrasonic energy is largely attenuated in subjects of lower age (<30 years) and is attenuated less in subjects of higher age (>50 years). The frequency spectrum also is observed to be significantly different. These observations need be validated with dual energy X-ray absorptiometry for its use in screening patients for osteopenia and osteoporosis. Further work is in progress.

Acknowledgement

The authors are grateful to Dr. S K. Narayankhedkar, principal, MGM College of Engineering and Technology, Kamothe, Navi Mumbai, for his guidance and encouragement throughout this research work; to Shri S.K. Lalwani, scientific officer (H) and Shri Rajesh Kumar Jain, scientific officer (G) from Electronic Division, Bhabha Atomic Research Centre for their valuable guidance from time to time. The authors are also thankful to Ms. Manasi S Sawant, Mr. Suryapal Prajapati, Mr. Nazim Mommin, Mr B.V. Gaikwad and Shri Vilas Ukarande for their continuous help and support in carrying out this work.

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