UWB Radar for Patient Monitoring

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ABSTRACT

During the last few years the Moscow Aviation Institute (Russia) and the Industrial Technology Research Institute (Taiwan) have worked jointly on the development of ultrawideband (UWB) medical radars for remote and contactless monitoring of patients in hospitals. Preliminary results of these works were published in [1]. As of the present, several radars have been produced and tested in real conditions in hospitals in Russia and Taiwan. Some results of these tests are given.

MEDICAL UWB RADAR – SHORT DESCRIPTION

The specific feature of medical UWB radars is that they are capable of registering the movement of the thorax and the heart beat at a low amplitude (up to 0.1 mm) of a motionless person at a distance up to 3 to 3.5 m.

Figure 1 demonstrates the hardware of the radar out of its casing. As a probing signal, a short radio pulse is used (Figure 2). Such a signal provides the capability for the processing system based on a highly sensitive phase detector. Short signal duration makes possible protection against passive interference and re-reflections using a strobe receiver. This enables measurements to be carried out in rooms where many static and moving objects are located. The radar measures heart rhythm and respiration rate in the frequency range from 0.05 Hz to 5 Hz (from 3 to 300 beats or breaths per minute).

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The radar used for medical measurements has the following parameters:

- operation range: 0.6m – 3.5m;
- signal spectrum: 6.2 to 6.6 GHz (level –3dB);
  5.75 to 7.35 GHz (level –10dB);
- pulse power: 9 mW;
- average power: 0.05 mW;
- pulse repetition frequency: 2 MHz;
- antenna pattern width: 31.5°;

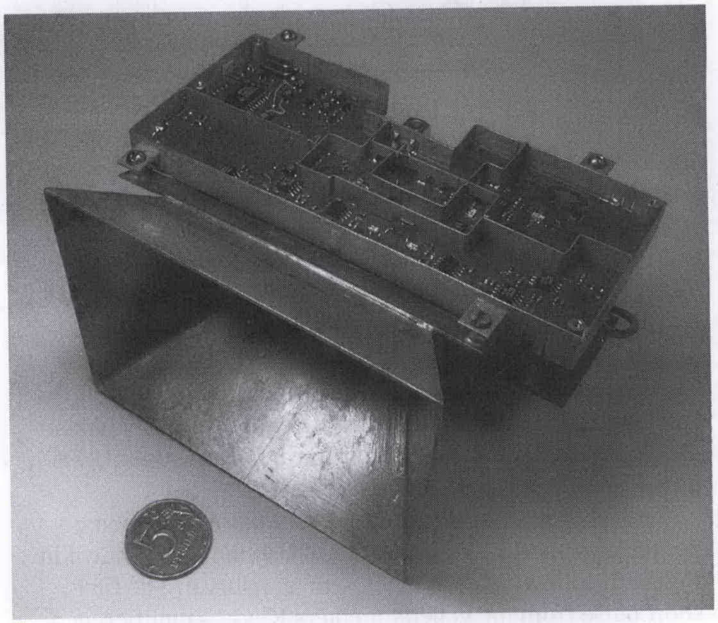

Fig. 1. Hardware of the radar without outside casing

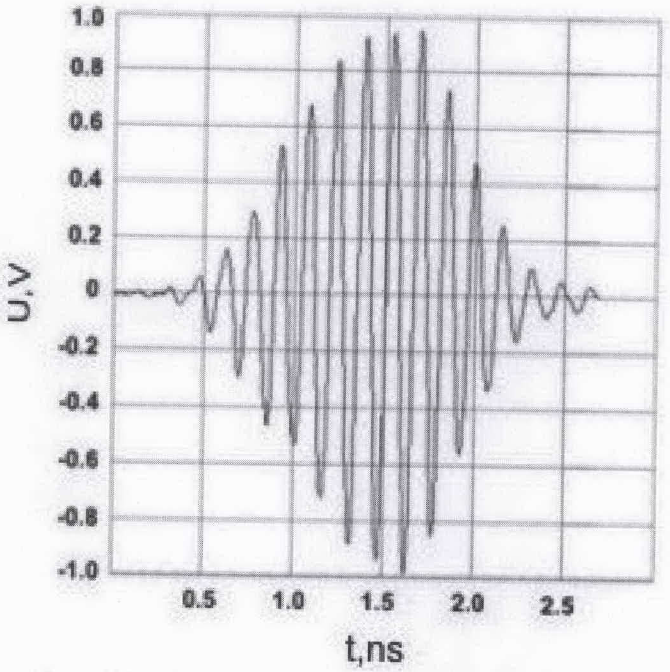

Fig. 2. Radar Signal

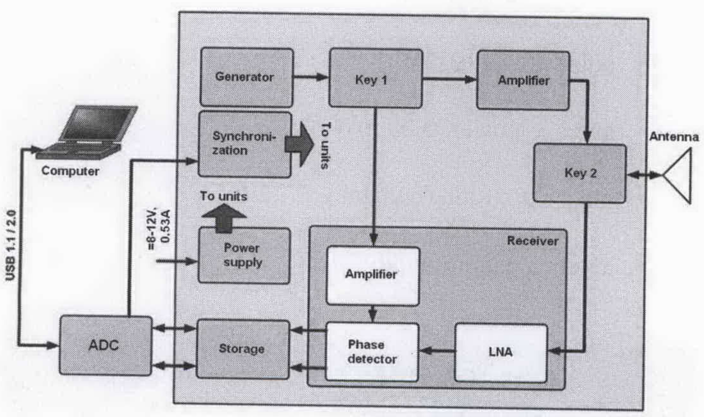

Fig. 3. Functional scheme of the radar

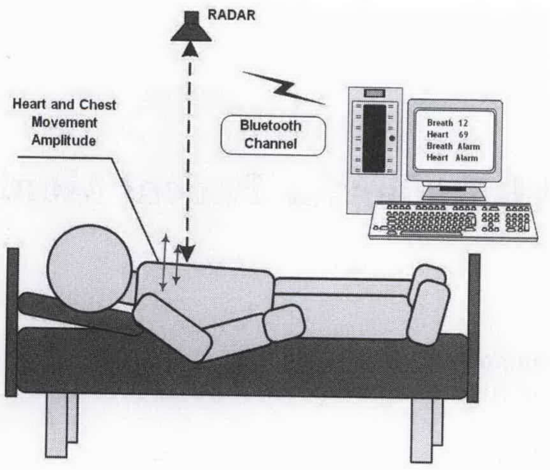

Fig. 4. Scheme of Monitoring

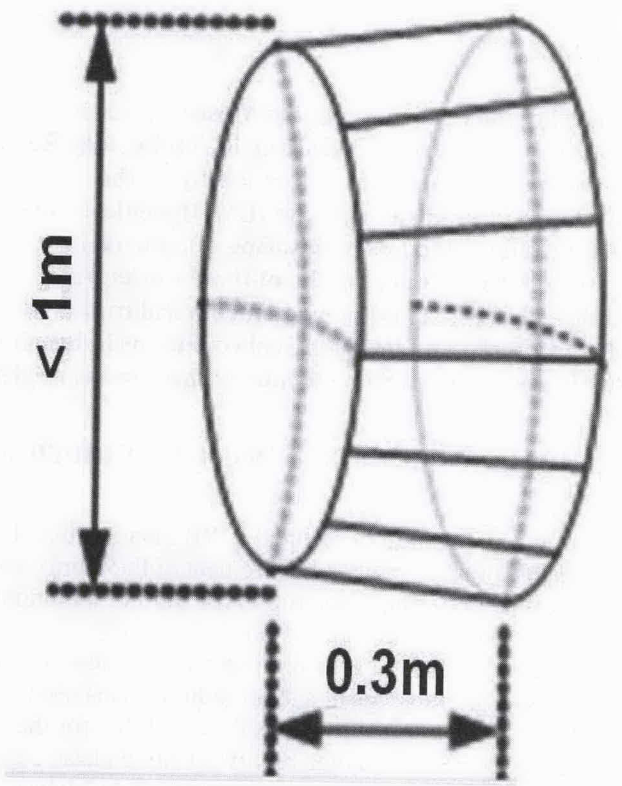

Fig. 5. Working Strobe

- power consumption: 1 W; and
- radiated power meets FCC requirements [2, 3].

The radar functional block diagram is given in Figure 3.

UWB radar equipment incorporates the following units: antenna, pulse generator, analog-to-digital converter (ADC), power supply unit, and personal computer.

The pulse generator forms, in every pulse repetition period, two short UWB pulses similar to the pulse shown in Figure 2, following each other with an interval. The first short pulse from the generator enters Key1, Amplifier, and Key 2, and then it is fed to Antenna and radiated into space. After that, both keys change their states. As a result, the second short pulse from the generator goes via the amplifier into a reference channel of the phase detector. The pulse reflected by the object goes via the antenna and low noise amplifier (LNA) into the receiving channel of the phase detector.

The phase detector has two separate channels (two quadratures). The signals from the receiver are fed into the channels of the phase detector in phase; signals from the reference channel are phase-shifted by 90°. This eliminates the probability that an object-reflected signal will appear in

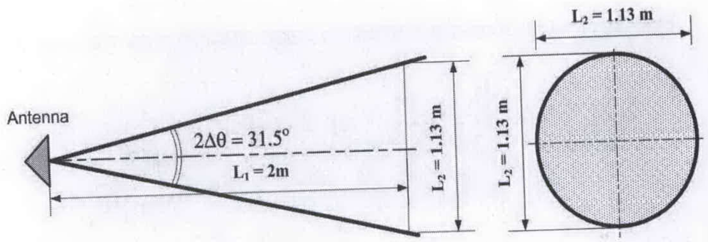

Fig. 6. Diameter of a working strobe formed by the antenna on a bed

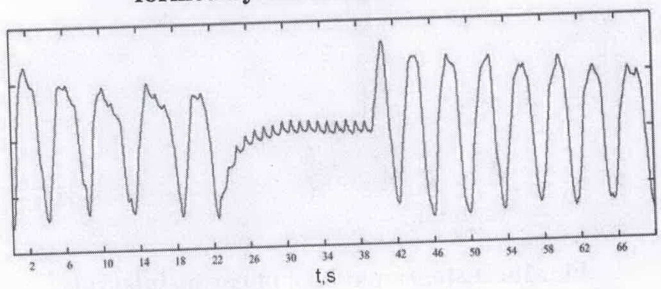

Fig. 7. Movement of Patient's Thorax and Heart

Fig. 8. The test radar in the Moscow hospital (left) the radar by the close-up

the low phase sensitivity area of the phase detector. Output signals from each channel of the phase detector enter two channels of storage, which perform signal amplification and storing. Stored quadrature signals are then digitized in the ADC and transferred to the personal computer, which provides further processing.

Figure 4 demonstrates the patient monitoring scheme. The time interval between the first and the second generated pulses determines the range from which the object-reflected signal is received. This range is equal to the distance between the radar and the patient. At this distance, the radar forms a working strobe (Figure 5) on the patient's bed. The working strobe's diameter approximately corresponds to the cross-section of the patient's bed in order to eliminate signals reflected from objects outside the bed. At the distance of about 2 m from the radar, the strobe diameter, which is determined by antenna directivity (Figure 6), is equal to approximately 1 m. The working strobe depth, which is determined by the range resolution of the radiated signal, is equal to about 30 cm. The short depth of the working strobe makes it possible to eliminate signals re-reflected by other objects located in the chamber. This is the basic advantage of UWB radar over systems operating with another signal.

The personal computer restores the true form of back-and-forth motion of the patient's thorax and heart using the quadrature channel signals. In case of small amplitudes of the object's movement, signal processing to restore the form requires a large volume of mathematical operations. Figure 7 demonstrates the fragment of the restored signal before it was divided by frequency between the heart beat signal and the respiration signal.

Large oscillations are caused by the patient's thorax movement. The patient stopped breathing in the time interval from 22 to 38 seconds; in this interval, only the signal caused by heart beats was registered.

USE OF MEDICAL RADAR IN RUSSIA

Background

The medical radar was tested in post-operative chambers in two Moscow hospitals. It was used for long-term monitoring of respiratory, cardiac, and motion activity of patients who had cardiac and blood vessel operations.

Method

The radar was placed at a distance about 2 m higher than the patient's thorax (Figure 8). Verification of the radar data was made periodically in 3 to 5 minute intervals by comparing the patient's heart rhythm (HR) and variability of heart rhythm (VHR) measured by the radar and as indicated by the electrocardiograph.

The personal computer provided processing and analysis of quadrature signals which contain the information on the patient's heart rhythm, respiration rate, and motion activity. The curves corresponds to heart systoles and thorax motion were indicated separately in different program windows in real-time (Figure 9). The data on heart rhythms and respiration rate were shown in the same windows below the curves. If required, the signal from the control electrocardiograph (ECG) was indicated in the supplementary program window (not shown in the figure).

The radar signal processing program automatically issues an alarm signal if the patient's systole or respiratory rates are out of the upper or lower threshold levels given.

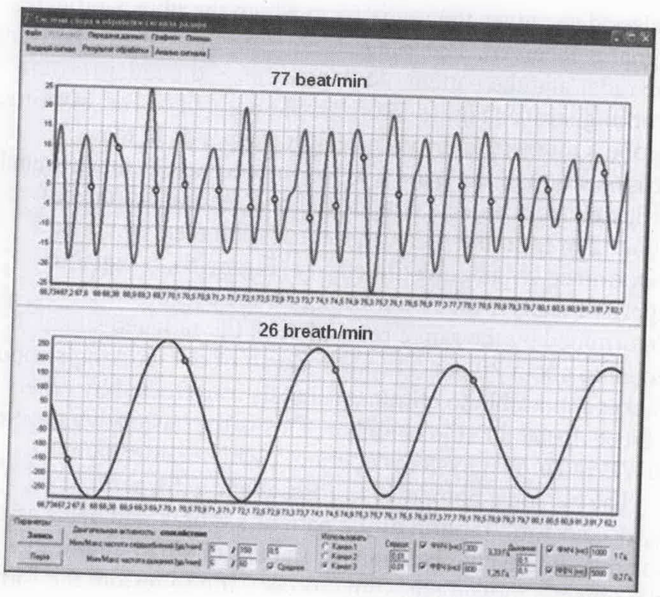

Fig. 9. Heart systoles (upper curve) and thorax movement (lower curve)

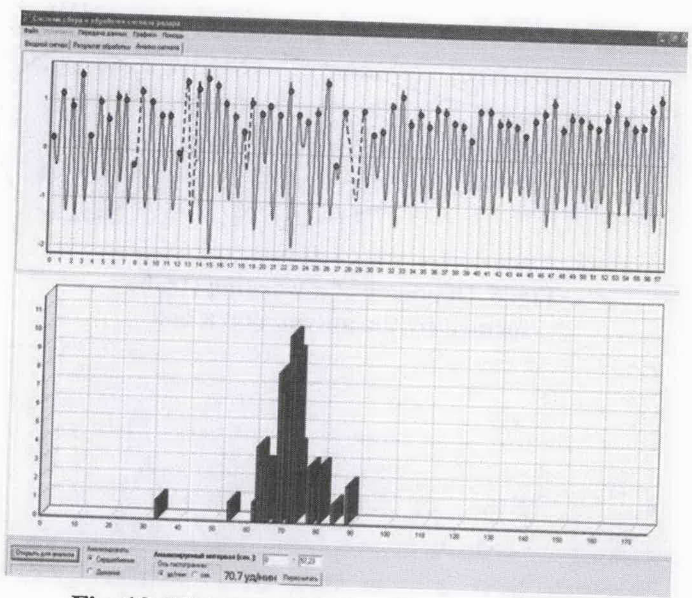

Fig. 10. Histogram design of cardio intervals (lower curve) by the heart beat curve (upper curve)

In addition, the radar signal processing program is able to perform radar signal analysis in «stop-frame» mode with manual selection of the time interval to be analyzed. In this case, histograms of selected characteristics of the signal registered are produced (Figure 10). On the heart systole curve shown in this figure, the fragments "rejected" by the program as unproved are marked by a dotted line. In these fragments, the patient's motion activity that resulted in an increase of interference was registered, and hence, measurement errors.

Results

During hospital monitoring, patients' HR and VHR, measured with the radar and the ECG were compared repeatedly (Figure 11).

With synchronized recording of radar and ECG signals, their maximums do not coincide. Different positions of the maximums are resulted from the different nature of parameters measured. ECG maximums appear when changes in heart electrical potential take place while radar signal maximums are related to heart mechanical motion. The time shift between these maximums is caused by the delay of a systole relative to the moment when an electrical potential initiated this systole is applied. This delay was taken into consideration when comparing VHR curves.

The values of heart beat maximums make it possible to plot the dependence of the time intervals between heart beats from the beat number both for radar signal and ECG, and then, provide for the comparison of the readings from both devices to determine the error of radar remote monitoring of heart activity, taken as a reference the electrocardiograph data. An example of patient's HR records obtained by using the radar and ECG during time interval of 96 seconds is shown in Figure 12. The radar data is plotted as a black line;

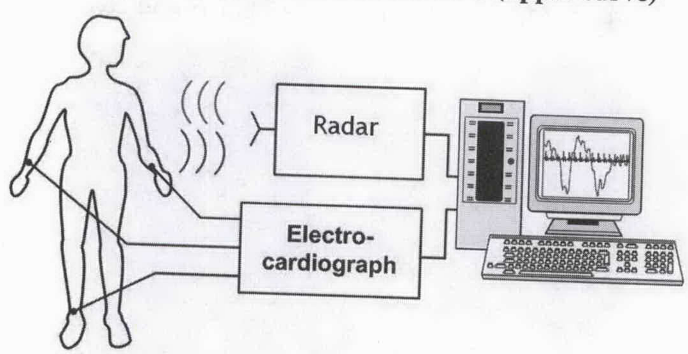

Fig. 11. Scheme for comparing the radar and ECG data

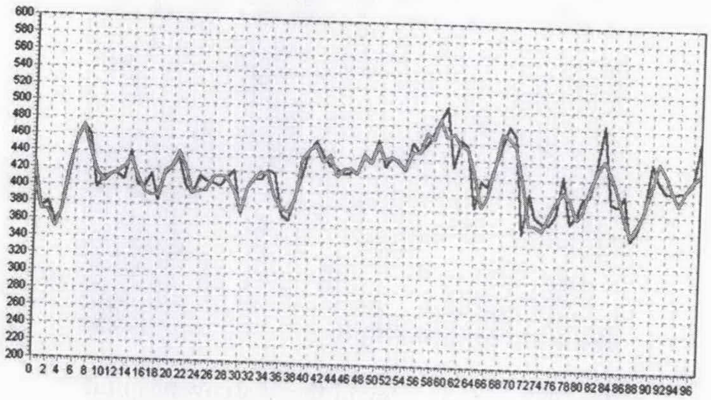

Fig. 12. VHR (radar and ECG) for every heart beat

ECG data are plotted as a grey line. Using these data, the averaged error and the correlation coefficient between VHR data measured by the radar and ECG were calculated. For the signals given in Figure 12, an average deviation of the radar data from ECG data is $\Delta = 2, 8\%$, the correlation coefficient is 0.86.

Some noncorrect instrumentation indications (artifacts) appearing during the measurement process can influence the

Table 1.

Subject	Time (day)	Level of Agreement
A (born preterm, male)	1	96.8
A	2	96.8
A	3	97.6
B (born preterm, female)	1	95.3
B	2	97.0
B	3	96.8
C (one month-old, female, congenital heart problem)	1	95.0
C	2	95.9
C	3	97.7
D (two month-old, male, Nager Syndrome)	1	98.2
D	2	95.6
D	3	97.1

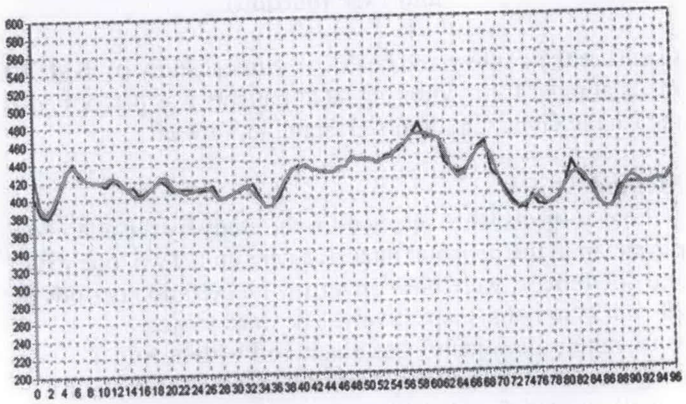

Fig. 13. VHR from Figure 12 averaged by two heart beats

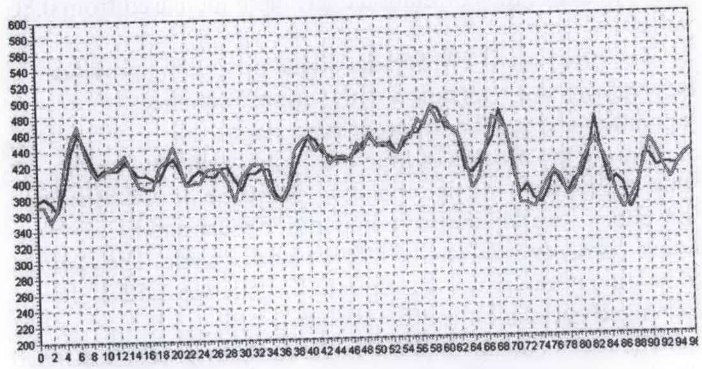

Fig. 14. VHR from Figure 12 after correlation processing

value of the correlation coefficient. To reduce their influence, the program for radar signal processing provides data averaging. Data averaging can be performed by several heart beats, the number of which is determined by an operator. It reduces an artifacts influence with no distortion of the general picture of the function's regularity. Figure 13 gives VHR records of radar and ECG signals from Figure 12, averaged over two heart beats. In this case, an average deviation in the radar data from ECG data is 0.86%, the correlation coefficient is 0.97.

The shape of the radar signal cannot be clearly defined as it is dependant on the patient's body shape and the measurement conditions. Radar processing of a signal allows correlation processing of radar signals, and thus, in improvement in their quality. To perform that, an interval

Fig. 15A.

Fig. 15B.

Fig. 15. The test set-up in the NICU

with relatively high signal quality with duration of n samples is selected from the heart beat signal and is used as a reference signal. The correlation processing is performed for the whole fragment of the input signal in "sliding window" with a reference signal shifted by one sample.

The analysis of VHR plots reveals that these plots have some periodical features. So, it is advisable to take the duration of the reference signal interval approximately equal to an average period shown in the VHR plot.

Correlation processing provides improvements in output signal parameters. Figure 14 demonstrates the correlation processing of VHR signal shown in Figure 12. The average deviation of the radar data from ECG data was reduced from 2.8% to 2.5%, the correlation coefficient increased from 0.86 to 0.9.

The program of UWB radar signal processing provides several ways of realization with various sequences of operation and number of processing stages.

During the process of long-term monitoring over more than ten patients in post-operative chambers of two Moscow hospitals, several hundred comparative radar and ECG measurements of HR and VHR have been made. The average deviation of the radar data from ECG data was 1.52%; the averaged correlation coefficient was 0.915.

The results obtained allow UWB radar to be recommended for long-term contactless monitoring of patients in hospitals and at home.

USE OF MEDICAL RADAR IN TAIWAN

Background

Apnea of Prematurity (AOP), which is a common symptom in the preterm-born infant population, can result in brain damage due to lack of oxygen and lead to permanent injury. As a result, the respiratory function of preterm-born infants must be monitored for a lengthy period of time, whether they remain in the hospital or are at home, in order to ensure their safety and health. A clinical study of the UWB medical radar for monitoring AOP patients was performed at the Chang Gung Children's Hospital in Taiwan.

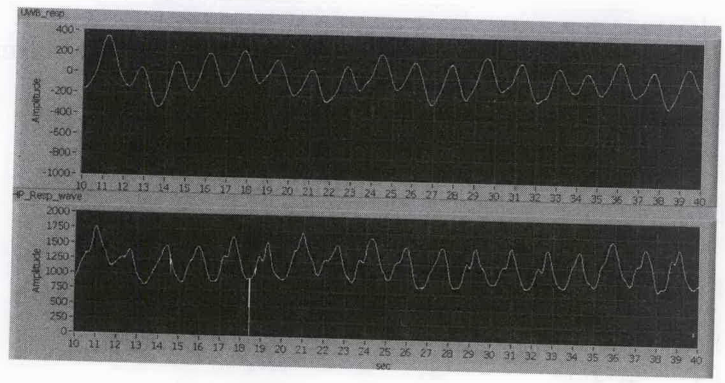

Fig. 16. Breathing signals acquired from UWB (top) and IMP (bottom)

Method

Four subjects were selected for the study by the attending physician in the neonatal intensive care unit. Two, one male and one female, were born preterm with gestation periods of 29 and 33 months, respectively. The third subject (one-month-old female) was diagnosed with having a congenital heart problem (complete endocardial cushion defect), and the fourth subject (two-month-old male) diagnosed as having Nager syndrome. Parental consents were obtained before the study. During the study, the respiration rate of each subject was monitored for three separate days and the monitoring time for each day was eight hours. An UWB non-contact monitor was installed about 20 cm on top of the chest area while the subject was lying supinely as shown in Figures 15A and 15B. To verify the performance of the UWB non-contact monitor, a bedside patient monitor was employed to acquire an impedance pneumography (IMP) breathing signal from the subject simultaneously. The

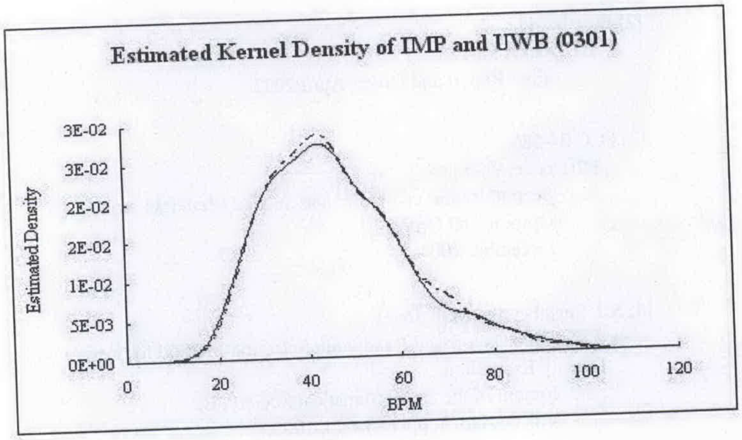

Fig. 17A.

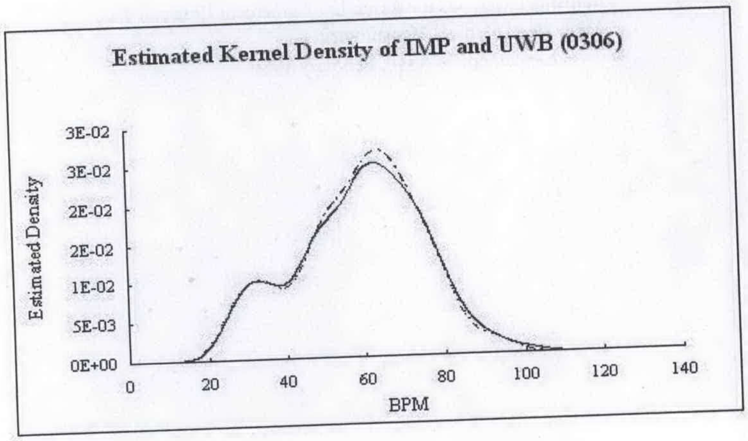

Fig. 17B.

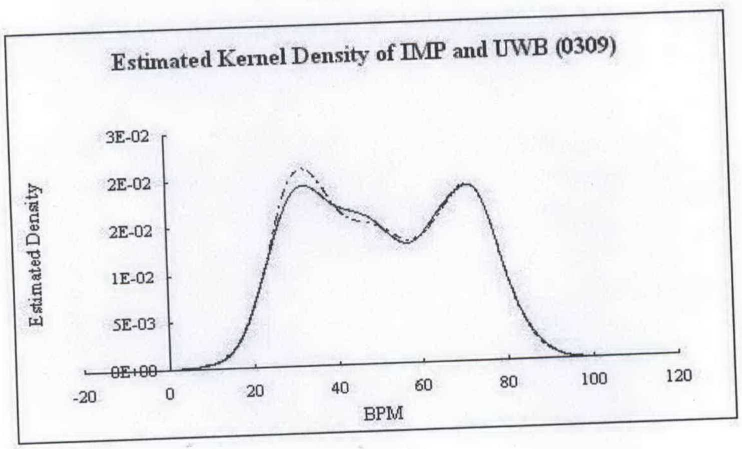

Fig. 17C.

Fig. 17. Kernel density distributions of IMP (dotted curve) and UWB (solid curve) for subject A tested in three separate days

digitized UWB and IMP breathing signals were transferred and displayed on a personal computer. They were stored in two data files. Data segments containing noises caused by excessive body movements, such as crying or during feeding, were excluded from the data files. The stored data were then

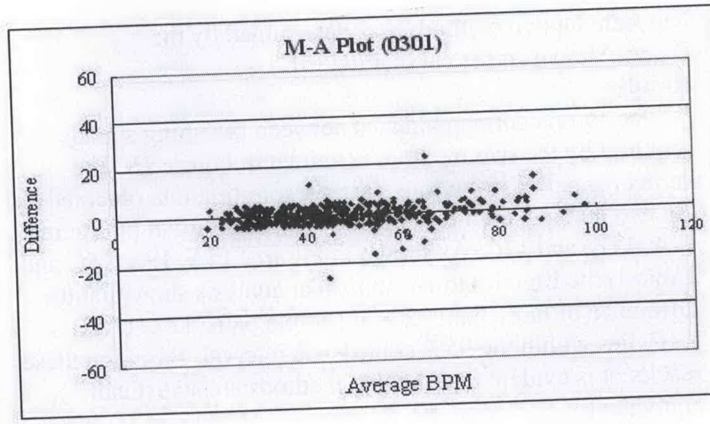

Fig. 18A.

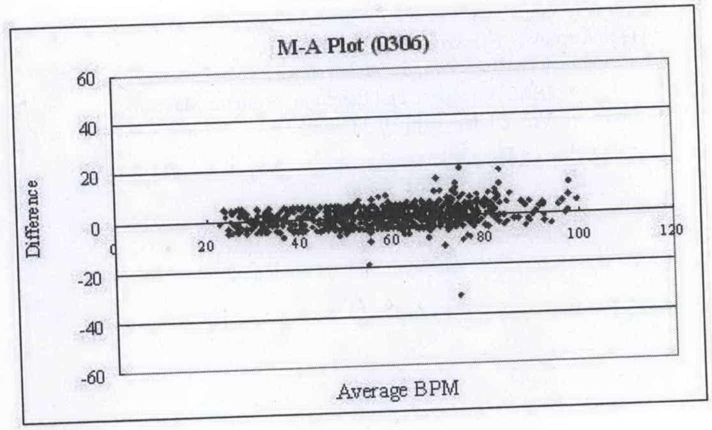

Fig. 18B.

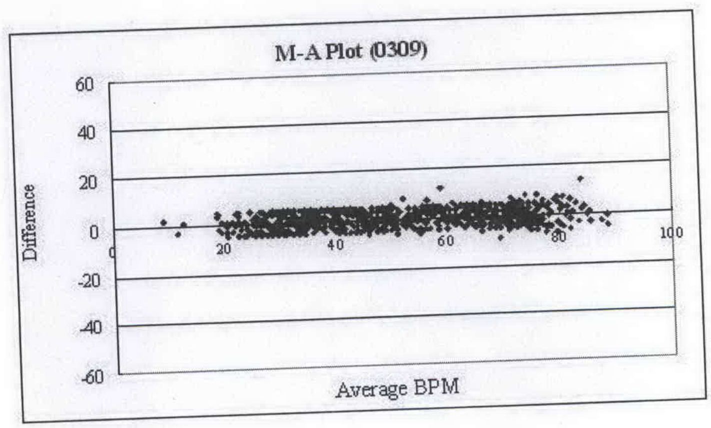

Fig. 18C.

Fig. 18. Agreement between the UWB and IMP methods. The level of agreement is represented by the % of sample pairs with their difference < ± 95% C.I.

averaged every 10 seconds and the subject's respiration rate (breaths/minute) was calculated for each method.

The kernel density distributions [4] of the calculated respiration rate were calculated and the level of agreement between the two methods was determined by the Bland-Altman statistical method [5].

Results

One-to-one correspondence between breathing signals acquired by the two methods is shown in Figure 16. The kernel density distributions of the respiration rate obtained by the two methods in three separate days are shown in Figures 17A, 17B, and 17C. As shown in Figures 18A, 18B, 18C and Table 1, the Bland-Altman statistical analysis show that the difference of more than 95% of sample pairs, i.e., (UWB – IMP) lies within the 95% confidence interval. Based on these results, it is evident that the two methods are statistically equivalent.

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