Magnetic Sensor for Non-Invasive Detection of Blood Pulse and Estimation of Arterial Compliance

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***Abstract*— The modulated magnetic signature based method has been recently suggested for non-invasive detection of blood pulse. Here we present our experience with the use of a Giant Magnetic Resistance (GMR) based sensor for non-invasive detection of a bio-rhythm. The influence of the biasing magnetic field on the amplitude and shape of the detected signal is presented. Guidelines for the design of a bio-medical transducer using the principle are also provided. The detected biorhythm is compared to other bio signals such as the blood flow velocity and arterial distension to gain insight into the physiological significance of the detected signal. The analysis shows that the magnetic sensor provides a signal that is strongly correlated to the blood volume in the neighbourhood of the sensor. Finally, the possibility of using the GMR based sensor for estimation of arterial compliance is investigated. Simultaneous measurements performed at two different sites on the body show that this sensor can be used to measure arterial pulse wave velocity which is a clinically accepted measure of global arterial stiffness.**

***Keywords*— GMR sensor, blood pulse detection, pulse wave velocity**

I. Introduction

Non-invasive detection of blood pulse and flow velocity has received a lot of attention over the years. The modulated magnetic signature of blood (MMSB) has been recently proposed as a novel technique for non-invasively detecting the blood pulse [1][2]. However, a detailed analysis of the physiological significance of the bio-rhythm detected using this principle has not been presented yet. Here, we present our experience with the use of a GMR sensor for non-invasive detection of a bio-rhythm. The effect of the magnetic bias field and the influence of the relative geometry of the measurement setup on the shape and amplitude of the detected bio-rhythm have been studied. The signal detected using the GMR sensor is then compared with blood flow velocity waveforms measured using a B-mode ultrasound scanner, and also with arterial distension waveforms measured using a dedicated measurement system to clearly understand the physiological significance of the detected bio-rhythm. The design of a prototype transducer using a single element magnetic sensor for non-invasively detecting the blood pulse waveform is presented. The use of this principle to measure arterial pulse wave velocity is also presented in a later section.

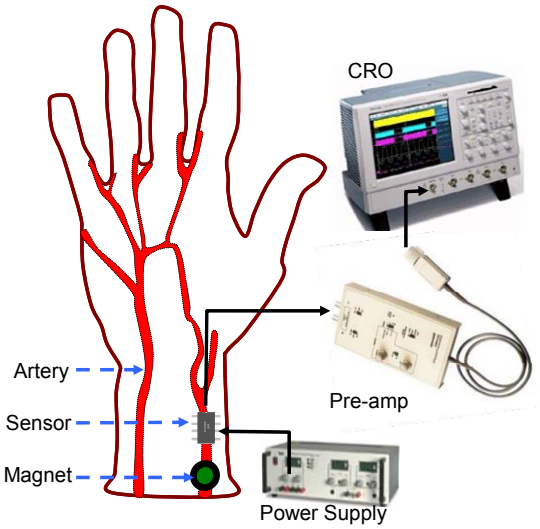

Fig. 1 Non invasive measurement of blood pulse using the GMR sensor

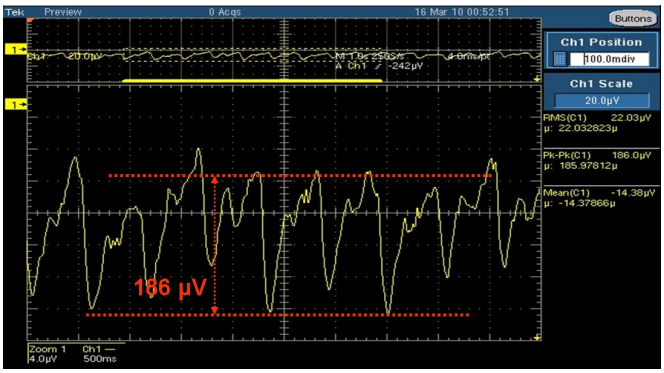

Fig. 2 Snapshot of the measurement made at the radial artery

II. Measurement Principle

We suggest the use of the GMR sensor AAH02-02 (NVE Corp) for non-invasive detection of blood pulse [3]. The sensor is designed using giant magnetic resistances in a bridge arrangement and gives an output voltage proportional to the intensity of the magnetic field at its vicinity. The basic arrangement for detecting blood flow pulse using this sensor is illustrated in Fig. 1.

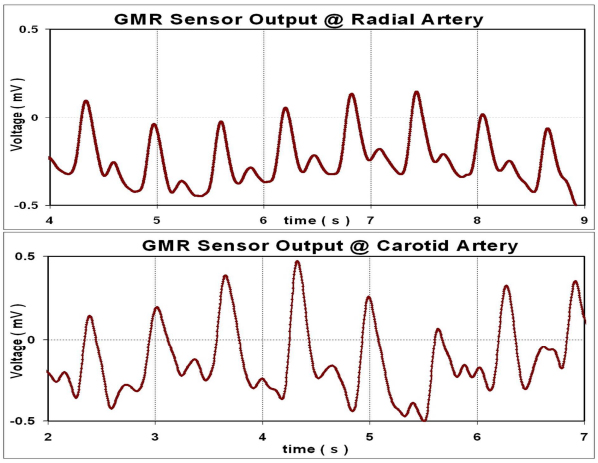

Fig. 3 Bio-rhythms detected at the radial and carotid arteries using the GMR sensor

A small 10 mm diameter permanent magnet is used to establish a magnetic bias field necessary for sensor operation. The sensor is placed a few millimeters away from the magnet. Both the sensor and the magnet are to be preferably placed over a surface artery such as the radial artery illustrated in Fig. 1. As blood flows below the sensor in a pulsating fashion, it alters the magnetic field intensity near the sensor [1]. This change in field is reflected as a change in the bridge output voltage of the sensor. This voltage is amplified using a pre-amp (ADA400A, Tektronics) and fed to a cathode ray oscilloscope for visualization. A snapshot of the measurement made at the radial artery using this arrangement is shown in Fig. 2. The measurement was repeated at the radial and the carotid artery as well, and the detected bio-rhythms are shown in Fig. 3. It may be noted that the dicrotic notch, caused due to the interaction of the forward going and reflected blood pulse is clearly visible in the detected waveforms. This gives us the first indication that the GMR sensor detects a bio-rhythm strongly related to blood flow.

It was observed that the position of the magnet in relation to the sensor was very critical in maintaining the integrity of the detected signal. In the initial trials, this was done on a trial and error basis. A formal procedure for the positioning of the magnet and sensor will be presented in the following section.

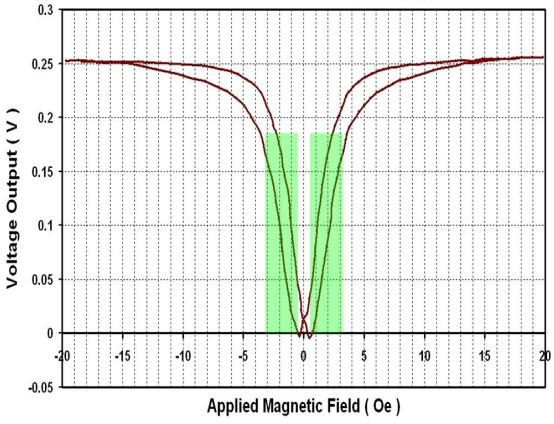

Fig. 4 Performance characteristic of AAH002-02 (5V supply)

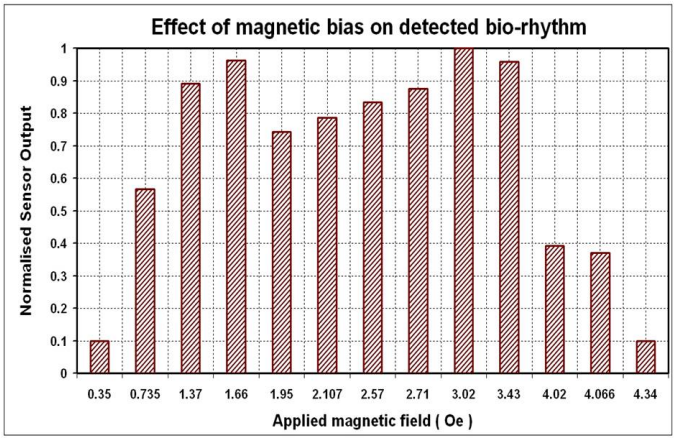

Fig. 5 Effect of magnetic bias field on the peak output of the sensor

III. Magnetic Bias and Signal Integrity

The typical performance characteristic of the AAH002-02 sensor is given in Fig. 4. It is evident that the sensor requires a biasing field to function in its linear region of operation between 100 – 300 μT (1 – 3 Oe). The purpose of the magnet is to provide this biasing field. In the initial experimentation, the position of the magnet in relation to the sensor was found to be very critical to maintaining output integrity. It has also been previously reported that the amplitude of the sensor output is maximum only at a particular distance between the sensor and the bias magnet [1]. Hence, an experiment was conducted to understand the influence of the bias field on the amplitude and shape of the detected signal. The sensor was fixed on the skin over the radial artery by the use of adhesive tape; while the magnet was positioned at different distances from the sensor to obtain different magnetic bias field intensities. The peak to peak amplitude of the bio-rhythms detected at different bias fields are indicated in Fig. 5.

As is expected from the performance characteristic of the sensor, the output amplitude drops off drastically outside the linear region of operation i.e. at fields less than 100 μT (1 Oe) and greater than 300 μT (3 Oe) . The maximum amplitude of the signal was observed around 160 μT (1.6 Oe) and 300 μT (3 Oe). However, it is interesting to observe the changes in the signal shape at different bias fields. The bio-rhythms detected at different fields are illustrated in Fig. 6.

The measurements illustrated in Fig. 6 were taken at the radial artery which branches very close to the site of measurement. In addition, the radial artery, being a peripheral artery is relatively in-elastic. Both these factors coupled with the high resistance of the peripheral end vascular bed leads to the occurrence of significant pulse wave reflections which are clearly observed as peaks in the diastolic phase of the detected signal. Even at a low biasing field of 70 μT (0.7 Oe), the systolic peak is clearly visible and three peaks, corresponding to reflected pulse waves, are observed in the diastole. As the bias field is increased, we observe that the systolic peak becomes more predominant. The initial two of the 3 peaks in the diastole phase dominates the signal up to a bias field of 200 μT.

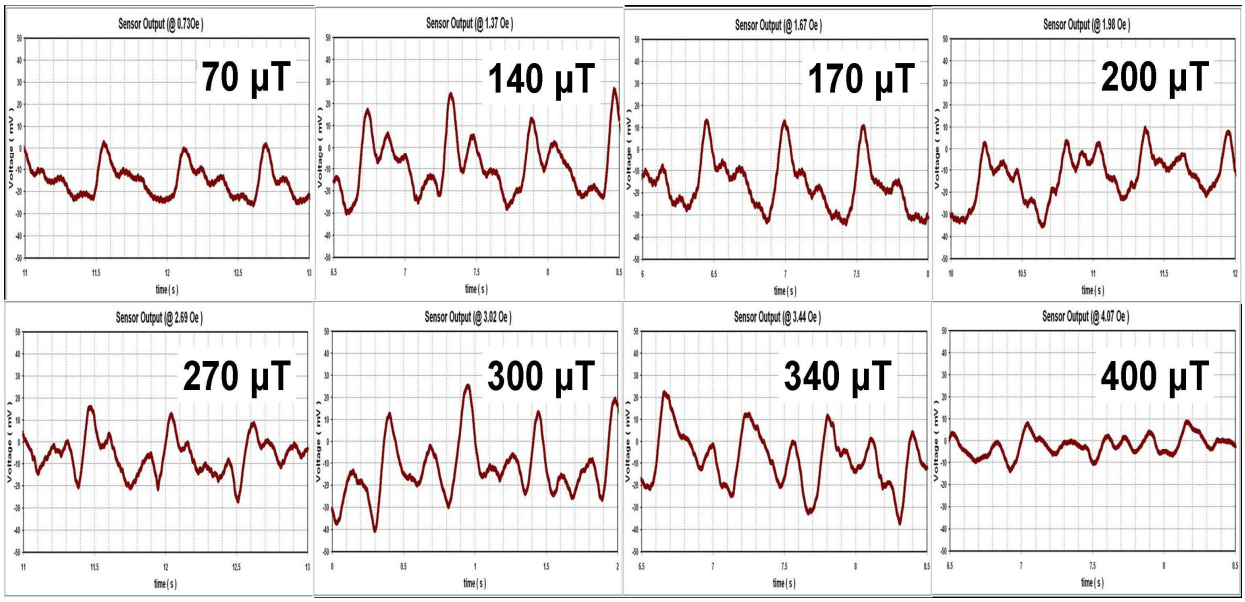

Fig. 6 Effect of magnetic bias on the shape of the detected signal

The third peak in the diastole, clearly seen at 70 µT and 140 µT is hardly visible at 200 µT. However, as we increase the field to 270 µT and 300 µT, this third peak in the diastole starts to become dominant. The third peak in the diastole is very clearly visible at 340 µT. As the bias field is further increased to 400 µT, the output integrity is lost as the sensor operating point is shifted out of its linear region of operation.

It may be remembered that the various bias fields reported in the above experiment were obtained by placing the permanent magnet at different distances from the sensor. The above observations point to the influence of the relative geometry of the sensor, magnet and the arterial section at the measurement site, on the shape of the detected signal. While maximizing the peak to peak output may be used as an initial criterion for positioning the magnet in relation to the sensor [1], the above observations indicate that the shape of the detected output signal may be altered by the relative geometry of the artery, magnet and the sensor. In this particular case of the radial artery, a bias field of around 70 µT would suffice to detect the systolic peaks, where as using a field of around 340 µT would allow clear visualization of even the latest of the reflected peaks occurring during the diastole. Hence, the design of the transducer would also be affected by the end user requirement. A comparison of the detected signals at different bias fields is presented in Fig.7. It would seem that for the given sensor, the optimum bias field would be around 100 µT or near 300 µT.

In summary, the experimental study showed that it is advisable to operate the sensor in its linear region of operation by providing proper magnetic bias field to get best output. The peak to peak value of the output signal need not be the only criterion for deciding upon the magnetic bias field. Keeping the sensor and the bias magnet as separate entities [2] is not recommended as significant alterations in signal shape were observed due to even slight relative motion between the two.

This led us to design a transducer using a single element GMR sensor and a permanent magnet mounted together, for more stable measurements.

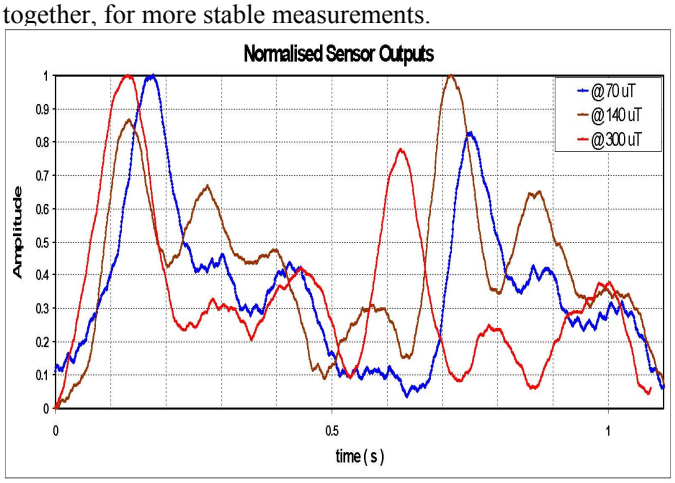

Fig. 7 Normalised sensor output at three different bias field conditions (70 µT, 140 µT and 300 µT)

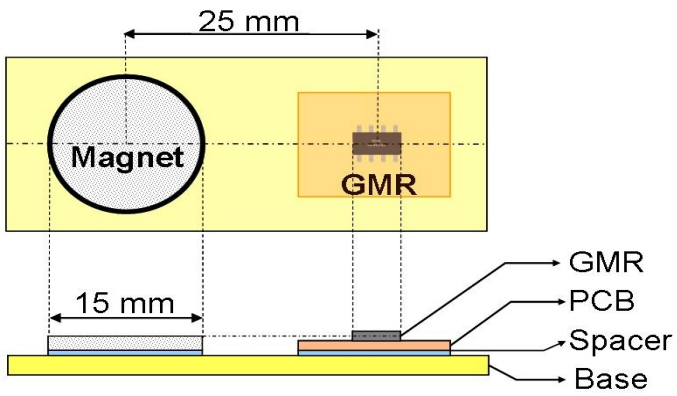

Fig. 8 Single element transducer using the GMR sensor

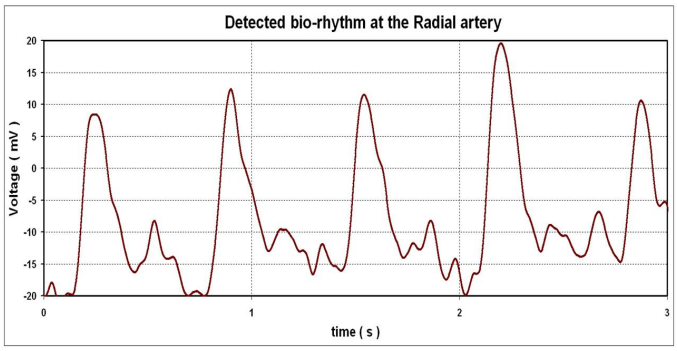

Fig. 9 Bio-rhythm detected at the radial artery using the single element transducer

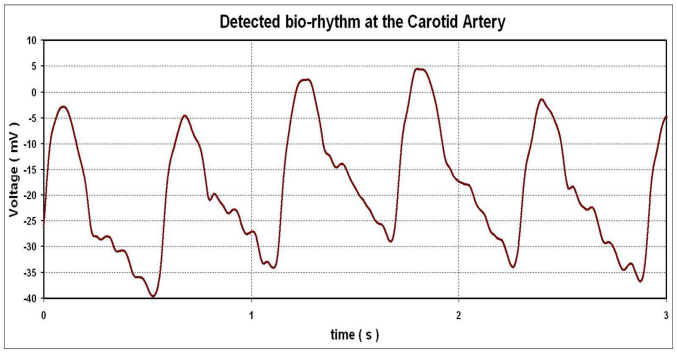

Fig. 10 Bio-rhythm detected at a site 2 cm below the carotid artery bulb

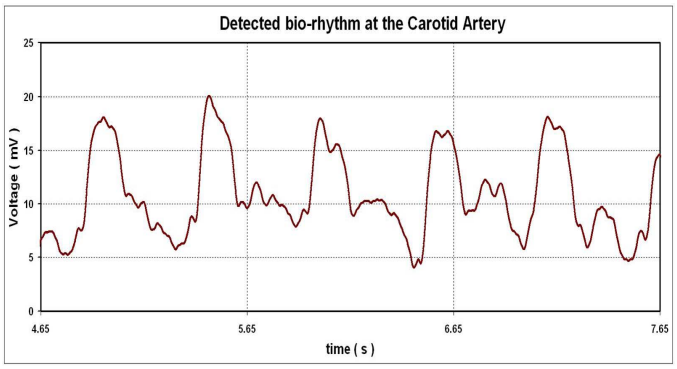

Fig. 11 Bio-rhythm detected close to the carotid artery bulb showing significant reflected waves in the diastole phase

IV. Single Element Transducer for Non Invasive Detection of Blood Pulse

The design of a transducer using a single GMR sensor and a permanent magnet is illustrated in Fig.8. A permanent magnet (circular with a diameter if 15 mm) placed 25 mm away biases the sensor at 280 μT (2.8 Oe). The relative motion between the magnet and sensor is minimized by mounting the two on a common base. It is important to ensure that the sensor and magnet are on the same plane to get optimum output. The sensor bridge is excited with 5 V, and the bridge output is amplified and digitized. The amplified signal is digitized at sampling rate of 1 kS/s with 16-bit resolution using the NI-ELVIS II platform. The transducer was used to detect the blood pulse at the radial artery of two different volunteers and one typical detected signal is shown in Fig. 9. The presence of reflected pulses in the diastole phase of the detected bio-rhythm validates the proper design of the transducer.

The transducer was also used to detect the blood pulse waveform at the carotid artery. The measurement performed at a site 2 cm below the carotid bulb is illustrated in Fig.10. Compared to the radial artery pulse wave, there are lesser reflected waves in this signal. However, a measurement performed at a site much closer to the carotid bulb (where the artery branches), shown in Fig. 11, shows significant amount of reflected waves. These results indicate that the GMR based sensor is able to detect the subtle variations in the blood flow pulse accurately. These points to the possibility of using this sensor as an effective means for measurement of blood flow. However further analysis is necessary to clearly understand the physiological significance of the bio-rhythm detected using the GMR based transducer.

V. Comparison with Standard Bio-Rhythms

While it has been established that the GMR based sensor can be used to detect a quasi-periodic bio-rhythm, possibly related to blood flow, the exact parameter that is being detected by the sensor has not been identified. Towards this end, the waveforms detected using the GMR based transducer were compared with other standard bio-signals, viz. blood flow velocity and arterial distension. The results of these comparisons are presented in this section.

The blood flow velocity at the carotid artery is non-invasively determined by using B-mode ultrasound scanner operating in the pulsed Doppler mode. A typical Doppler image is illustrated in Fig. 12. The B-mode image of the carotid artery cross section with color Doppler for flow visualization, as well as the Doppler flow waveform is visible in Fig. 12. The flow velocity waveform has been overlaid with the GMR signal for comparison. It is evident that there is very strong similarity between the flow waveform and the derivative of the bio-rhythm detected by the GMR sensor. A more quantitative comparison is shown in Fig. 13. The correlation coefficient between the first derivative of the GMR sensor output and the flow velocity waveform was 0.98 during the systolic phase and 0.92 during the diastole.

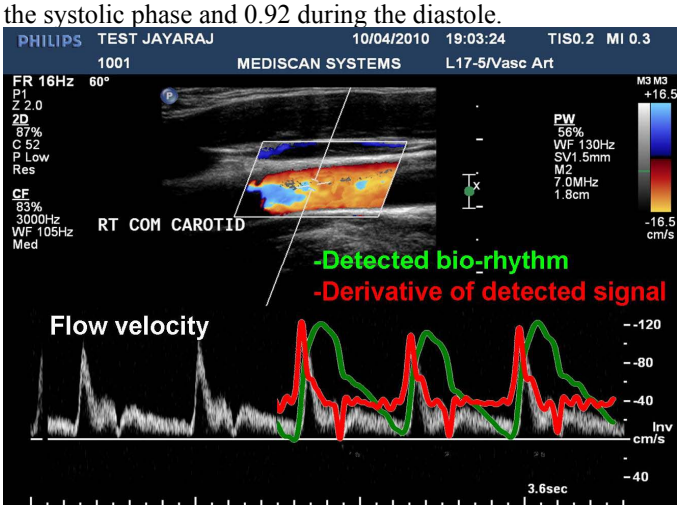

Fig. 12 Doppler image of the carotid artery showing the blood flow velocity waveform overlaid with the detected bio-rhythm and its derivative

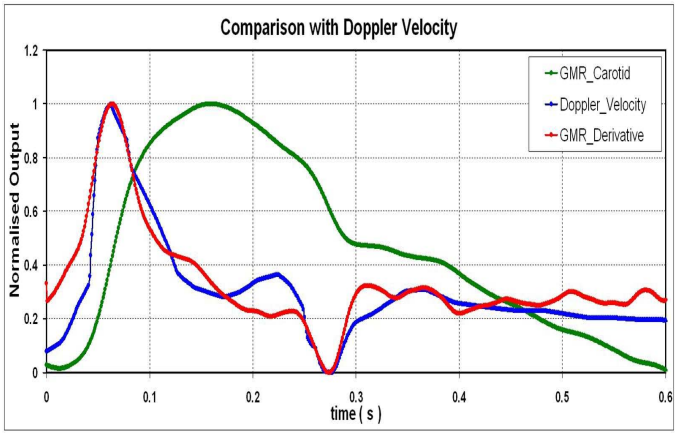

Fig. 13 Comparison of the detected bio-rhythm with Doppler blood velocity waveform at the carotid artery

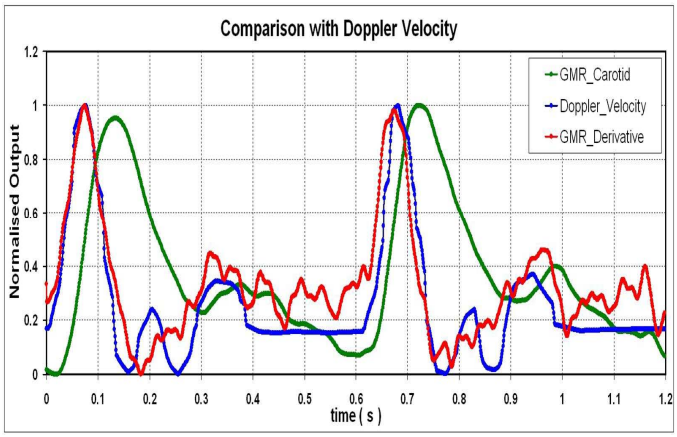

Fig. 14 Comparison of the detected bio-rhythm with Doppler blood flow velocity waveform at the radial artery

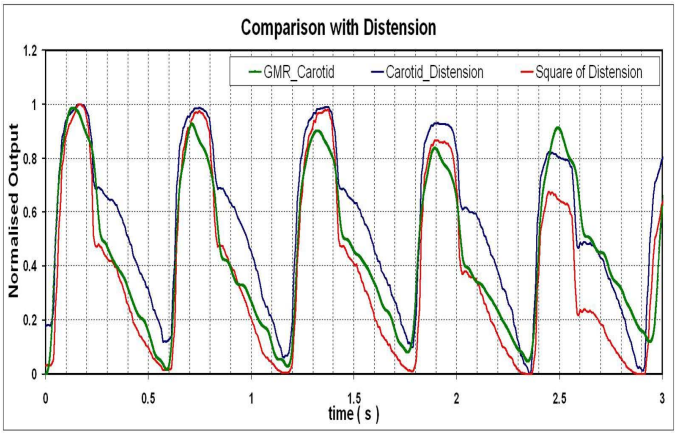

Fig. 15 Comparison of the detected bio-rhythm with arterial distension waveform at the carotid artery

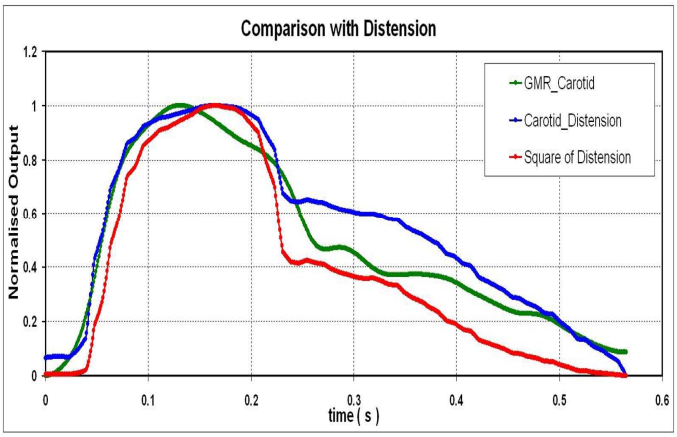

Fig. 16 A quantitative comparison of the detected bio-rhythm with distension waveform at the carotid artery

A similar comparison was also performed for the radial artery. Here again the similarity of the first derivative of the detected bio-rhythm with the Doppler flow velocity waveform is very evident. A quantitative comparison, illustrated in Fig.14, indicated a correlation coefficient of 0.9 between the two waveforms measured at the radial artery.

The above results again point to the fact that the GMR sensor based transducer is detecting a signal that is very strongly correlated to the integral of the blood flow velocity, i.e. volumetric flow. To further understand the nature of the detected bio-rhythms, a comparison was also made with arterial distension waveforms. The distension of the carotid artery was measured using a dedicated system for arterial compliance evaluation [4]. Fig. 15 shows a comparison of the GMR signal with the arterial distension waveform. The square of the distension waveform is also plotted as an indicator of the volumetric change of the artery over a cardiac cycle. Strong similarities are evident between the detected bio-rhythm and the distension waveforms. A single cycle of the data is presented in Fig. 16. The GMR signal shows a correlation coefficient of 97.3 % with the distension waveform, and 97.8 % with the volumetric change of the artery.

The above results strengthen the conjecture that the GMR sensor based transducer can be used for non-invasively detecting blood flow in surface arteries. Experience with the sensor so far has shown that the sensor is capable of detecting arterial flow of surface arteries and is relatively insensitive to micro circulation. However, accurate measurement of blood flow would require proper calibration of the amplitude of the detected output which has not yet been performed.

VI. Arterial Distensibility using the GMR-based Single Element Transducer

Non-invasive determination of arterial distensibility is a very important step in cardiovascular diagnosis. The arterial pulse wave velocity is a clinically accepted measure of global arterial stiffness [5]. Simultaneous measurement of the blood flow pulse at two different sites along the same arterial tree can be utilized to measure the arterial pulse wave velocity [6].

We suggest the use of the GMR-based sensor for detection of the blood pulse waveform at the radial artery and the carotid artery. Since both measurements have to be done simultaneously, two transducers are employed and each is strapped to the body at the desired measurement site. The detected signals were amplified using a dual channel amplifier

based around the INA2126 instrumentation amplifier. Differential filters were employed to remove dc drift as well as power line interference.

The detected bio-rhythms measured simultaneously at the radial and carotid arteries are illustrated in Fig.17. It is clear that the carotid waveform rises to the systolic peak much earlier than the radial artery waveform. The pulse transit time, which is the time taken by the blood pulse to travel from the carotid to the radial artery measurement site, can be evaluated by estimating the delay between the two waveforms using any of the standard algorithms [7]. The observation of a clear delay between the waveforms measured at the two sites indicates the utility of the GMR sensor for measuring the Pulse Transit Time (PTT) and Pulse Wave Velocity (PWV).

The pulse transit time was measured over multiple cardiac cycles using an automated algorithm that separated out the individual cycles from the detected bio-rhythm. We measured the delay by using three different methods, viz. a) by determining the time difference between the occurrence of the feet of the waveforms utilizing valley detection, b) by measuring the time delay between the occurrence of the rise of the systole (using a level based trigger) between the two waveforms, and c) by estimating the delay between the waveforms using cross correlation. The results are summarized in Table I. The distance between the two measurement sites were measured along the surface of the body using a measurement tape with a resolution of 1 mm. The mean and standard deviation of the pulse wave velocity measurements made over multiple cardiac cycles (N>20) is listed in Table I.

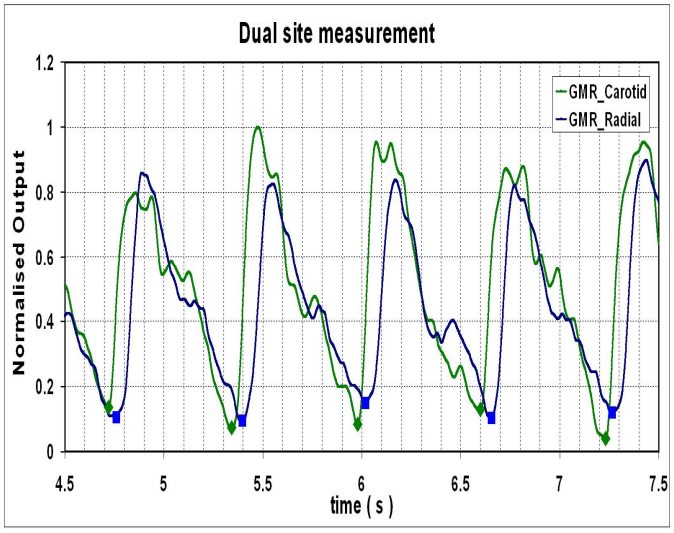

Fig. 17 Bio-rhythms measured simultaneously at the radial and the carotid arteries. The peaks and valleys of the waveforms are also indicated.

TABLE I. MEASUREMENT OF PULSE WAVE VELOCITY USING THREE DIFFERENT ALGORITHMS

Algorithm	Pulse Transit Time (ms)	Pulse Wave Velocity (m/s)
Valley Detection	54.98	13.96 ± 2.2
Level based trigger	66.19	11.39 ± 0.9
Correlation	50.42	15.25 ± 2.4

VII. CONCLUSION

The use of a GMR sensor based transducer for non-invasive detection of arterial blood flow has been investigated. The influence of the magnetic bias field on the shape of the detected signal has been studied. The design of a transducer based on thus concept should be done by considering the influence of the relative geometry of the magnet, sensor and the arterial section on the shape of the detected signal, and not just based on maximizing the peak to peak output. A prototype design of a single element transducer using the GMR sensor has been presented. Comparisons of the detected signal with other standard bio-rhythms indicate strong correlation between the volumetric flow of blood and the detected bio-rhythm. The use of dual transducers for measurement of pulse wave velocity has also bee demonstrated.

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