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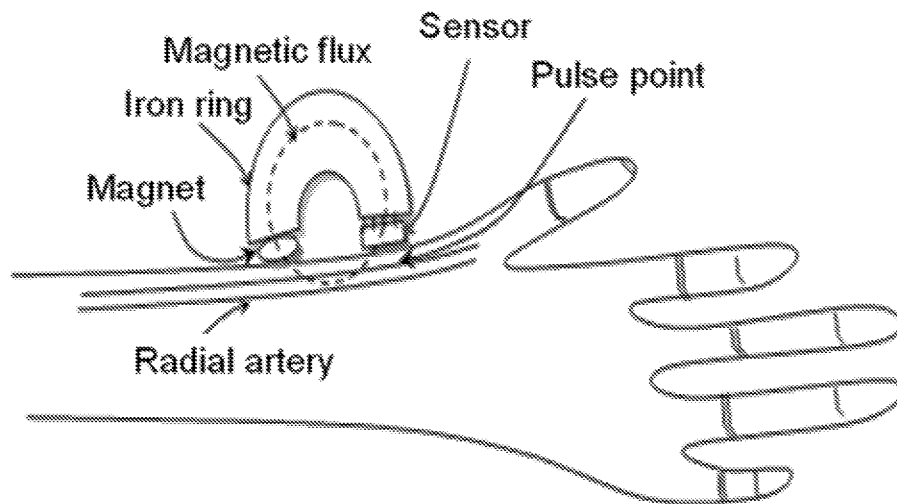


Figure 1

(57) Abstract: An apparatus for detecting heart rate at a member of a user, the apparatus comprising: at least one magnet; a retaining means to retain the at least one magnet in register to the member and apply a pre-calibrated pressure on the at least one magnet in relation to the member while allowing motion of the at least one magnet in response to pulsation in the member; a magnetic sensor configured to measure a change in a magnetic field in response to motion of the at least one magnet; one or more processors in communication with the magnetic sensor, the one or more processors configured to determine the heart rate at the member of the user based on a signal received from the magnetic sensor.



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Apparatus and Method for Detecting Heart rate

Technical Field

- 5 The present invention relates, in general terms, to apparatuses and methods for detecting heart rate in a user. In particular, the apparatus can detect heart rate at a member of the user.

Background

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Accurate measurement of heart rate (HR) is important as it is one of the vital signs of a human body. Current methods of HR measurements, be it electrical, magnetic, optical, microwave, acoustic, mechanical or other means, all have their own advantages and limitations in terms of cost-performance, portability, and ease of use. For example, while electrocardiography (ECG) is the gold standard for HR measurement, but it is inconvenient to use and sometimes causes discomfort. Therefore, there have been continuous efforts to develop alternative measurement and monitoring techniques, particularly those which are portable and wearable.

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One of the methods used is photoplethysmogram (PPG) which detects blood volume changes in the microvascular bed of tissue via an optical pulse oximeter. In addition to HR measurement, the optical pulse oximeter allows continuous monitoring of oxygen saturation in arterial blood without blood sampling. It is based on tracking haemoglobin molecules, the main carrier of oxygen transport in the blood, which turns bright red when it is oxygenated (HbO₂) and dark red when it is deoxygenated (Hb), and in turn causes a difference in light absorption by HbO₂ and Hb in the wavelength range of 600 nm – 1000 nm. Through calibration with other quantitative methods, the pulse oximeter is able to measure both oxygen saturation in arterial blood (SaO₂) and arterial oxygen partial pressure (PaO₂), both have major clinical and physiological significance. As the absorbance of both wavelengths has a pulsatile component proportional

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to the amount of blood flowing in a region of interest, the pulse oximeter can be readily used to measure the heart rate. Furthermore, the pulse transient time extracted from two PPG waveforms acquired simultaneously at two different locations along the arterial tree can be used to estimate the blood pressure.

5 There are typically two types of designs for PPG sensors, one is the transmission type and the other is based on light reflection. In both cases, as the gap between the skin and the device is part of the light path for the measurement system, the PPG inherently suffers from instability caused by body motion, tone of skin, and changes in ambient lighting. Furthermore, the PPG is unsuitable for

10 circumstances where the light path between human skin and the light source or detector is blocked by opaque substances such as gloves.

In order to address the motion artefact and skin tone or optical path blockage issues faced by PPG and drawbacks of other techniques,

15 magnetoplethysmograph (MPG) has been proposed which measures the heart rate based on the electromagnetic response of blood. Blood circulation is an essential function for our body as it supplies oxygen and nutrients to various organs for them to operate. Over 98 % of the oxygen in the blood is carried by haemoglobin molecules, and the remaining slightly less than 2% is carried in

20 physically dissolved form. The haemoglobin is derived from two words: 'heme' and 'globin', meaning iron and its globular shape, respectively. The heme iron transitions from a diamagnetic low-spin state in oxyhemoglobin to a paramagnetic high-spin state in deoxyhemoglobin. This oxidation state dependence of haemoglobin's magnetic properties has been used to measure

25 the blood oxygen level using magnetic resonance imaging (MRI). However, the MRI requires large magnetic field and specialized imaging devices, and therefore it is not suitable for wearable health monitoring applications. To address this issue, several prototype MPG devices based on off-shelf Hall sensor or giant magnetoresistance (GMR) sensors have been developed. A typical design

30 involves the use of a permanent magnet (PM) placed on the artery and a Hall effect or GMR sensor which is placed about 1-2 cm away from the PM (Figure 1). The underlying principle is still not well understood. Two types of

mechanisms have been proposed: one is based on the aforementioned oxidation state dependence of haemoglobin's magnetic properties and the other relies on relative motion of the PM and sensor due to mechanical vibrations caused by the blood flow. Irrespective of the underlying mechanism, the MPG devices reported to date still suffer from low sensitivity and bulkiness compared to other type of HR monitoring devices. The low sensitivity is mainly caused by the fact that the GMR sensor used has a zero-response at low field and therefore, the GMR has to operate under a large bias field. This would unavoidably lead to a low sensitivity as the magnetic field change caused by the blood flow is 10^{-6} - 10^{-8} times (according to the aforementioned first mechanism) smaller than that of the bias field. The bulkiness is due to the fact that some designs require the use of a soft magnetic yoke to guide the magnetic flux from the magnet to the sensor, as shown in Figure 1. As the artery is quite narrow, any lateral motion of the magnetic with respect to the skin will result in degradation or fluctuation of the measured signals. As there is no self-adjusting mechanism to ensure good contact between the magnet and the skin, the amplitude of the signal is expected to fluctuate in a large range, even when the lateral motion is suppressed.

It is therefore desirable to provide a method and an apparatus for detecting the heart rate which address or ameliorate at least one of the aforementioned problems and/or provides a useful alternative.

Summary

Some embodiments relate to an apparatus for determining heart rate in a member of a user, the apparatus comprising:

- at least one magnet, including a first magnet;
- a retaining means to retain the first magnet and apply a pre-calibrated force to maintain the first magnet in register to the member while permitting motion of the at least one magnet in response to a pulse in the member;

- c) a magnetic sensor configured to measure a change in a magnetic field in response to the motion; and
- d) one or more processors in communication with the magnetic sensor, the one or more processors configured to determine the heart rate based on the
5 measured change in the magnetic field.

The pre-calibrated pressure may be substantially similar to a pressure generated by the pulse. The pre-calibrated pressure may be in the range of 40 to 200 mmHg.

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- In some embodiments, the at least one magnet comprises a second magnet, at least one of the first magnet and the second magnet being held, in use, in register to the member by an attractive force between the first magnet and second magnet, wherein; the pulse causes relative movement between the first
15 magnet and the second magnet; and the magnetic sensor is configured to measure a change in a magnetic field in response to the relative movement.

- In some embodiments, the relative movement between the first magnet and second magnet comprises at least one of: relative lateral movement along an
20 axis defined by the first magnet and the second magnet; and relative rotation of at least one of the two magnets with respect to the axis.

In some embodiments, the magnetic sensor is a 3-axis sensor.

- 25 In some embodiments, the magnetic sensor is positioned at a magnetic field local minimum of the at least one magnet, where a principal component of the magnetic field is zero or approaches zero or is smaller than a saturation field of the magnetic sensor.

- 30 In some embodiments, the magnetic sensor is provided: between the first magnet and second magnet with respect to the magnetic field; or midway

between the first magnet and second magnet, with respect to the magnetic field; or between the first magnet and the member.

5 In some embodiments, the retaining means comprises a cavity containing the first magnet, the cavity permitting motion of the first magnet in response to the pulse.

The apparatus of some embodiments further comprises a piezoelectric sensor positioned between the member and a magnet of the at least one magnet, to
10 measure pressure changes induced by blood flow in the member, the piezoelectric sensor being configured to transmit the signals to the one or more processors.

The apparatus of some embodiments further comprises a PPG sensor positioned
15 between the member and a magnet of the at least one magnet to measure pressure changes induced by blood flow in the member, the PPG sensor being configured to communicate signals of the measured pressure changes to the one or more processors.

20 In some embodiments, the first magnet and the second magnet form part of a resonant circuit, the resonant circuit configured to measure capacitance across the member.

The apparatus of some embodiments further comprises a plurality of magnets
25 for positioning on a further member of the user, the magnetic sensor being positioned to detect a change in a magnetic field generated by the further plurality of magnets to determine a heart rate associated with the further member.

30 The one or more processors of some embodiments are further configured to determine a time difference between the heart rate associated with the member

and the heart rate associated with the further member to generate a heart rate difference signal.

5 In some embodiments, at least one of the first magnet and the second magnet is fixed, in use, in position relative to the member.

10 In some embodiments, the magnetic sensor is positioned at a relative location with respect to the at least one magnet such that strength of a magnetic field generated by the plurality of magnets at the relative location is less than a dynamic range of the magnetic sensor.

15 In some embodiments, the magnetic sensor is positioned at a relative location with respect to the at least one magnet such that changes to the magnetic field caused by pulsation in the member is at or proximate to a maxima.

In some embodiments, the at least one magnet comprises a plurality of nanomagnets embedded in a flexible substrate forming a part of the apparatus.

20 Some embodiments relate to a method of detecting heart rate at a member of a user, comprising:

- a) retaining the member in register to at least one magnet by a retaining means, wherein the retaining means applies a pre-calibrated pressure on the at least one magnet in relation to the member while allowing motion of the at least one magnet in response to pulsation in the member;
- 25 b) measuring a change in magnetic field via a magnetic sensor, the change in magnetic field being generated in response to motion of the at least one magnet;
- c) receiving by one or more processors, signals generated by the magnetic sensor; and
- 30 d) processing the received signals by the one or more processors to determine a heart rate at the member of the user.

Some embodiments relate to a method of fabrication of an apparatus for detecting heart rate at a member of a user, the method comprising:

- a) providing a body of the apparatus, the body comprising a retaining means to retain the at least one magnet in register to a receivable member and apply
5 a pre-calibrated pressure on the at least one magnet in relation to the member while allowing motion of the at least one magnet in response to pulsation in the member; and
- b) providing a magnetic sensor in the body, the magnetic sensor configured to measure a change in a magnetic field in response to motion of the at least
10 one magnet and make available measured change signal data for transmission to one or more processors in communication with the magnetic sensor.

Brief description of the drawings

- 15 Embodiments of the present invention will now be described, by way of non-limiting example, with reference to the drawings in which:

Figure 1 shows a MPG device of prior art.

- 20 Figure 2a shows a schematic of a heart rate measurement device in accordance with the present invention.

Figure 2b shows an example of circuitry means.

Figure 3a shows a schematic of a heart rate measurement device in accordance with the present invention which consists of two magnets and a sensor.

- 25 Figure 3b shows the calculated magnetic flux distribution surrounding the magnets. The parameters for the magnets are: diameter = 10 mm, thickness = 5 mm, and $B_r = 1.27$ T.

Figure 4a shows the measured pulse signal using the device shown in Fig.3a.

Figure 4b shows the normalized waveform corresponding to one cycle of cardiac activity (left axis: amplitude; right axis: first derivative).

- 30 Figure 5 shows cross-section views of two different magnet configurations: a) magnets are placed at the nail and its opposite side; b) magnets are placed at two-sides of the finger.

- Figure 6 shows the devices with curved magnets in a) top and b) side configuration.
- Figure 7 shows an exemplary device with a fixture to hold the magnets.
- Figure 8a shows a schematic of a heart rate measurement device with repulsive magnetic configuration.
- Figure 8b shows the calculated magnetic flux distribution surrounding the repulsive magnets showing in Fig.8a. The parameters for the magnets are: diameter = 10 mm, thickness = 5 mm, and $B_r = 1.27$ T.
- Figure 9 shows a schematic of a device which can detect the blood flow from two fingers simultaneous using a single sensor.
- Figure 10 shows a schematic of a heart rate measurement device which consists of a sensor and an array of magnets formed on flexible substrate.
- Figure 11 shows a schematic of a heart rate measurement device having a piezoelectric sensor.
- Figure 12 shows the schematic of a heart rate measurement device having capacitive sensing capabilities.
- Figure 13 shows a flowchart of a method of detecting heart rate.
- Figure 14 shows schematics of an apparatus and measurement setup. 14(a) illustrates a measurement set up. 14(b) is a photograph of an apparatus in use.
- Figure 15 shows graphs of magnetic and vibrational signals obtained from two healthy subjects.
- Figure 16 shows results of pulse measurements with the fingertips (a) wrapped by a black tape, (b) wrapped by a plaster, and (c) immersed in water.
- Figure 17 shows a comparison of single pulse signal magnetic and vibrational signals.
- Figure 18 shows magnetic contour plots of an apparatus under varying conditions.
- Figure 19 shows a comparison of field change obtained by COMSOL simulation (symbol) and corresponding dipole approximation (solid-line).
- Figure 20 illustrates a method of fabrication of an apparatus for detecting heart rate.

Detailed description

The exemplary embodiments relate to the heart rate detection device in accordance with this invention are described below. The following description is presented to enable one of ordinary skill in the art to make and use the invention and is provided in the context of a patent application and its requirements. Various modifications to the exemplary embodiments and the generic principles and features described herein will be readily apparent. The exemplary embodiments are mainly described in terms of particular designs and methods provided in particular implementations. However, the designs and methods can operate effectively in other implementations. Phrases such as "exemplary embodiment", "one embodiment" and "another embodiment" may refer to the same or different embodiments as well as to multiple embodiments. The embodiments will be described with respect to material and sensor/component used to construct said device, and experimental verification of the device's functionalities. The exemplary embodiments will also be described in the context of particular methods comprising certain types of magnets and sensors. However, by no means does it exclude other methods having different and/or additional sensors/magnets that are not inconsistent with the exemplary embodiments. Thus, the present invention is not intended to be limited to the embodiments shown, but is to be accorded the widest scope consistent with the principles and features described herein.

Further, other desirable features and characteristics will become apparent from the subsequent detailed description and the appended claims, taken in conjunction with the accompanying drawings and this background of the disclosure.

Accurate measurement of HR is important as it is a vital sign of the health of a human body. Current methods of HR measurements, be it electrical, magnetic, optical, microwave, acoustic, mechanical or other means, all have their own advantages and limitations in terms of cost-performance, portability, accuracy

and ease of use. For example, electrocardiography (ECG) and sphygmomanometer methods are the respective gold standard for HR and BP measurements, but they are inconvenient to use and sometimes cause discomfort. Therefore, there have been continuous efforts to develop alternative measurement and monitoring techniques, particularly those which are portable and wearable. One of the key challenges in these devices, however, is the contamination of measured signals by motion artefacts. The devices described herein provide a low artefact, low cost and energy efficient solution to HR monitoring.

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There are several publications discussing how to use magnetic sensors to detect blood volume pulse. The devices reported in prior works consist of a permanent magnet producing an ambient field and a Hall-effect or giant-magnetoresistance (GMR) sensor that measures the pulse signal corresponding to the volumetric change of blood in the artery. When the sensor is placed on the skin above an artery, the magnetic sensor measures the modulated magnetic signature of blood (MMSB) caused by the pulsatile blood flow. Analysis of the arterial blood pulse is possible because the output voltage of the sensor is directly proportional to the amplitude of the pulse. There are several limitations or drawbacks of the prior designs:

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- (1) There is no fixing mechanism to stabilize the magnet. Although, during measurement, one can press the magnet manually against part of the human body containing the artery, the force varies in each measurement. It is thus difficult to obtain reproducible signals as the magnet and part of human body form a magnetic circuit based on the MMSB mechanism proposed in prior art.
- (2) Hall-effect and GMR sensors used are not sensitive at low field and the power consumption is also high.
- (3) In order to increase the detection sensitivity, some of the designs use very complicated magnetic circuits that are unsuitable for practical applications.
- (4) The detection mechanism is unclear as to whether or not the signal originates from MMSB.

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In contrast, the presently disclosed apparatus has at least one of the following features:

- (1) At least one magnet attached to the finger using a retaining means or a self-attractive force when two magnets are used which, when optimized, can significantly reduce the motion induced artefacts. In this sense, the force applied by the retaining means to one or more of the magnets "pre-calibrated", pre-calibration involving determining a force that is sufficiently low to enable the pulse to cause motion of each said magnet, thereby to change the magnetic field of the magnet (e.g. to change the orientation or strength or both of that magnetic field), but is sufficiently high so as to substantially remove motion induced artefacts resulting from movements of the member other than the pulse. The necessary pressure (due the attractive force) can be readily determined without undue experimentation, and has been found to be in the range of 40 to 200 mmHg for a healthy adult user. It should be understood that the exact pressure can be adjusted by changing the magnets or its spacing and the values given here just serve as a rough guideline. The same or other ranges may be applied depending on the user group – "pre-calibration" may therefore comprise pre-calibration based on one or more characteristics of the user, such as age, weight, blood pressure, and disease conditions that affect strength of the pulse.
- (2) The magnets can be configured to produce field-free points or lines nearby the magnets. For example, one or more of the positions of the magnets relative to each other, the strength of the magnetic field produced by each magnet, and the shape of the magnet can be selected to produce field-free points or lines. This provides a wider choice of different types of magnetic sensors, facilitating enhancement of sensitivity and reduction of power consumption. It should be understood that it is not necessary to place the sensor precisely on the field-free point or line; anywhere near these points or lines should work effectively.
- (3) As the signal mainly originates from the motion of the at least one magnet or relative motion of the magnets instead of the previously proposed MMSB

mechanism, the proposed devices are much more sensitive to blood flow due to differential detection.

- (4) In some embodiments, it is possible to detect the signal from multiple magnets attached to different fingertips (or other members of the user) using a single sensor. This allows the processor or processors of the device to determine the time difference between the arrival of blood at different fingers, which can be subsequently processed to detect clinically significant conditions. One can also use the same sensor to measure the time difference between fingers and toes, or other parts of the body.
- (5) The proposed device allows detection of the pulse signal even when the fingers are covered by opaque materials or immersed in a liquid.
- (6) The proposed device can be readily integrated with other types of sensors such as PPG, force sensor, etc. The fusion of different types of sensors will significantly increase the accuracy of detected physiological signals.
- (7) Unlike devices described in the prior art where the detection mechanism is unclear, the devices taught herein clearly detect the vibration of magnet (or equivalently changes in magnetic field) induced by blood flow.

Some embodiments were evaluated using a fingertip-type magnetic device, allowing simultaneous measurement of the magnetic and vibrational signals using a magnetic sensor and a laser Doppler vibrometer. In practice, the pulse in other members of the user can instead be measured. The member includes any suitable part of the body including a digit, earlobe, part of an arm (such as wrist) etc. The retaining means applies a pre-calibrated pressure on the at least one magnet – for illustration purposes, the retaining means will apply force to a single magnet, though it will be understood that it may similarly apply force to more than one magnet or to a substrate with multiple magnets embedded therein. The force is pre-calibrated to maintain the single magnet in register with the member while allowing motion of the single magnet in response to the pulse in the member. The pre-calibrated pressure is calibrated such that the at least one magnet can move in response to pulsation in the member while still being retained in the apparatus. In some embodiments, the pre-calibrated

pressure may be in the range of 40 to 200 mmHg. The pre-calibrated pressure is substantially similar to the pressure generated by pulsation in the member to allow the at least one magnet to move to an extent necessary to generate changes in its magnetic field that can be measured to determine heart rate. The
5 retaining means may be any elasticated or resilient means such as a rubber band etc. that provides predictable pressure to the single magnet against the member while also securely retaining the single magnet on the member. The magnetic sensor of some embodiments may be a 3-axis sensor configured to measure three dimensional changes in the magnetic field.

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Some embodiments incorporate two magnets on opposite sides of a fingertip (e.g. the top side where the fingernail is located, and the bottom side where the finger pad or print is located) where magnetic attraction between the magnets significantly improves the stability of both magnetic and vibrational signals.
15 Experiments using a vibration measurement device demonstrated that the magnetic and vibrational signals were closely correlated with each other, and the average deviation between the two signals is less than 5%. Since the magnetic signal is minimal when the magnets are not in contact with the skin, it can be concluded that the detected signal is dominated by the vibration of the
20 magnet, and the contribution from the MMSB mechanism is negligible. Both analytical and numerical simulation results were in good agreement with the experimental observations. The apparatus can detect clear pulsation signals under several finger exposure or access conditions – a task which is challenging for existing pulse detectors.

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The apparatus of some embodiments comprises a PPG sensor positioned between the member and the at least one magnet to measure pressure changes induced by blood flow in the member. The PPG sensor provides additional data of a distinct modality to the one or more processors. The additional data from
30 the PPG sensor can be used to validate the heart rate measurements or be used as an input to signal processing models to derive clinically relevant inferences. Thus such embodiments advantageously provide sensor data of multiple

modalities that can be used by the processor or processors to determine heart rate or make other clinically relevant inferences using data generated by the apparatus.

- 5 Figure 2a illustrates a schematics of the non-invasive heart rate detection apparatus 100. The apparatus comprises a plurality of magnets. Figure 2a shows two magnets (first magnet 101 and an optional second magnet 102) placed on the opposite sides of a member of a user (such as finger 104) when in use. The magnets each have a proximal face and a distal face. This is shown
- 10 for magnet 101, which has a proximal face 101a and a distal face 101b. The proximal faces of the magnets 101 and 102 are facing each other and the magnets 101 and 102 are spaced apart from each other. The magnets 101 and 102 are aligned along a Cartesian axis. In this example, it is the z axis. The finger is along a Cartesian plane; i.e. xy plane. The magnets 101 and 102
- 15 generate a magnetic field (not shown) in the vicinity of the magnets. A magnetic sensor 103 is positioned within the generated magnetic field of the magnets 101 and 102 to detect changes in the magnetic field of the magnets. The changes in the magnetic field are due to the relative movement of the magnets 101 and 102 in response to relative movement such as pulsation from an artery in the
- 20 finger. For example, when blood pulse through the finger, the finger cyclically expands and contracts, moving the magnets further apart and closer together, respectively. The magnets 101 and 102 have their remanent magnetization aligned perpendicularly (along z axis) to the finger 104 and they are placed in such a way that they attract each other across the fingertip 104. The magnets
- 25 may be permanent magnets such that static magnetic fields are generated from the permanent magnets (or magnet with remanent magnetization when external field is removed). The strength of the attractive force can be adjusted by varying the magnetic properties, dimension and shape of the magnets. As a rule of thumb, the member is held in register against the magnets 101 and 102
- 30 via the attractive force of the magnets when in use. As used herein, the term "in register" refers to a magnet being held in a position that it can move in response to pulsation in the member – e.g. in response to a heart beat in a

finger. Additionally, the attractive force can be comparable to the force exerted against the artery walls by blood pumping through the finger. When the attractive force is optimized, it compresses the member via the elastic peripheral arterial beneath the skin, thereby narrowing the pathway of arterial vasculature. Blood flow volume changes with the systolic and diastolic cycle of heart. Therefore, when the vasculature is compressed but blood flow is maintained, it will force the vasculature to restore to normal width, causing the spacing between the two magnets to change. This induces a change of magnetic field nearby the magnets 101 and 102, which can be detected by the magnetic sensor 103. The signal detected by the magnetic sensor 103 can be directly related to the cardiac cycle activity as well as vascular elastic properties. Appropriate circuitry and/or processors may be used to receive the signal from the magnetic sensor, process the detected signal and extract vital signs such as the heart rate of the user (Figure 2b). The circuits may consist of a preamplifier 201, a low-pass filter 202, a high pass filter 203, a microprocessor 204 and a display unit 205. Other circuits can be added as is necessary.

To further improve the signal generation of magnetic field variations, the finger can be positioned such that it intersects the axis of the magnets 101 and 102. In other words, the Cartesian axis (z axis) intersects the Cartesian plane (xy plane).

When two magnets are used, it was found that the signal is optimised when the two magnets are sandwiching the member containing the artery. It would be clear that there can be other alternative placements of the magnets by for example using magnets with customized shape and dimension, and these are also included within the scope of the invention.

Figure 3a is a close-up view of the fingertip shown in Figure 2a along with the magnetic field lines. In this embodiment, the finger 104 faces up as opposed to Figure 2a in which it faces down. The two magnets 101 and 102 have a disc shape and are magnetized vertically to the disc surface (axially magnetised).

The proximal faces of the magnets 101 and 102 are facing each other and spaced apart. The S-pole of magnet 101 and N-pole of magnet 102 face each other across the finger 104 such that they attract each other. The finger is positioned within the space between the two magnets 101 and 102, and
5 preferably in register with the two magnets 101 and 102. The magnetic sensor can be positioned between the first magnet and second magnet with respect to the magnetic field – e.g. in the magnetic field passing between the closest pair of opposite poles of the magnets 101, 102. In some embodiments, the magnetic sensor is positioned midway between the first magnet and second magnet, with
10 respect to the magnetic field – to this end, the magnetic sensor may be positioned to the side of the finger, with the magnets positioned on the top and bottom of the finger. Alternatively, the magnetic sensor can be disposed between the first magnet and the member.

15 The phrase "with respect to the magnetic field" refers to the sensor being positioned in the magnetic field generated by the at least one magnet. The skilled person will understand from present teachings that in embodiments with two magnets this can include the magnetic sensor being physically in-between the first magnet and second magnet, or not directly in-between the first magnet
20 and second magnet but nevertheless in the magnetic field passing between the closest poles of those magnets.

A magnetic field generated by a permanent magnet can easily saturate the sensor unless sensors with a large dynamic range are used. This would lead to
25 a very small output signal as the change of magnetic field caused by blood flow is very small. This is especially so when a single magnet is used. By using a plurality of magnets, a zero-field plane, line or point can be formed in some embodiments, such that sensors with small dynamic range but high sensitivity can be used (as long as they are placed at or in close proximity to zero-field
30 plane, line or point) to generate a large output signal corresponding to the blood flow.

Referring to Figure 3a, the dotted lines 105 represent the combined magnetic field lines generated by the two magnets. These are shown as vector lines with arrows indicating the direction of the vectors. The magnetic field has a principal component along a first axis (x or y axis) and a secondary component along a second axis (y or x axis) perpendicular to the first axis. The magnetic sensor can have a sensing axis parallel to the first axis (x or y axis). To facilitate explanation of the working principle of this method, a Cartesian coordinate is shown with its origin at the middle of the rotational axis of the two magnets 101 and 102 (presently cylindrically-shaped magnets), and z-axis perpendicular to the magnetic discs 101, 102 and y along the finger direction. The magnets 101 and 102 are aligned along the z axis. It is assumed that the magnets are stationary at diastolic half cycle during which the artery vasculature 104 between the magnets is compressed to a certain extent. The magnets can be identical to each other. The magnets can also be additionally placed parallel to the xy-plane – i.e. a plane passing through each magnet, between the poles of that magnet, is parallel to a plane defined by the x and y axes. When arranged as such, the magnetic field only has a z-component on the xy-plane. This can be seen more clearly in the calculated flux line on yz plane, as shown in Figure 3b. When in this configuration, the magnetic field strength surrounding the finger 104 exhibits local minimum points or lines, and the field strength at some of these local minima approaches zero, allowing the xy-plane to effectively serve as a field-free plane (FFP) if the sensing axis of the magnetic sensor is in the same plane. In other words, the magnetic sensor can be positioned at a magnetic field local minimum where the principal component approaches zero; i.e. the magnetic field vector in the x and/or y axis is zero or approaches zero. The corollary of this is that the magnetic sensor is placed at or near where changes in the magnetic field induced by pulsation in the member are at a maximum. When the magnets move relative to each other, as the sensor is in a field-free plane (xy plane), the movement can translate to a relatively large output in the x and/or y vector direction of the magnetic field. Such a field configuration brings two significant benefits: 1) it increases the choice of magnetic sensors as all linear magnetic sensors exhibit maximum sensitivity at

zero-field, and 2) it is very sensitive to the movement of magnets as it detects the differential field from the two magnets instead of the field from a single magnet. High sensitivity sensors with small dynamic range to detect small changes of magnetic field induced by the blood flow can be used. In Figure 3a, 5 the sensor 103 is placed on the xy-plane with its sensing axis along y-axis. As the field generated by a cylindrical magnet has a rotational symmetry around its center axis, the sensing axis can be aligned to any radial direction of the magnets. The magnetic sensor 104 needs not to be exactly on the xy plane, it can be varied within a certain range along z-direction from the xy plane. In 10 other words, it is sufficient if the magnetic sensor 104 is perpendicular to the z axis. This is to ensure that the field change caused by the movement of one of the magnets is maximum at the sensor position. It will be understood that, in practice, the magnetic sensor may be placed a small distance from the field-free plane, while still enjoying significant change in different field strength due 15 to relative movement between the magnets. As such, statements to the effect that the magnetic sensor is positioned at a field-free plane, line or similar will be understood to refer to placement of the magnetic sensor at a position where changes in relative position between the magnets causes a change in the differential magnetic field that facilitates detection of heart rate.

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When blood flows, the magnets move relative to each other. In particular, and with reference to the finger, one of the magnets will move more than the other one. While this can lead to change of all field components felt by the sensor, only change in the detection of the sensing axis will be detected by the sensor 25 in some embodiments.

The magnets can be any type as long as they produce a reasonably large attractive force. In addition to compressing the vascular, the attractive force advantageously also contributes to the reduction of motion artefacts. Due to 30 presence of FFP and region surrounding it, any type of magnetic sensor can be used to implement the heart rate detection device in accordance with the present invention, such as a Hall effect sensor, AMR sensor, GMR sensor, TMR

sensor, SMR sensor, and STG sensor, or any other type of magnetic sensor that can detect magnetic field in either one or multiple directions. The exact position of the sensor will be determined by the dynamic range of the sensor and its sensitivity.

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As an example, Figure 4a shows the output signal of the magnetic sensor obtained from a male subject by using the device in accordance with this invention. It was confirmed that the periodic signal corresponds to the systolic and diastolic cycle of cardiac activities. Each period consists of two main peaks, with the first peak (with larger magnitude) corresponding to the systolic peak and the second one being the diastolic peak. In addition, there is a third peak which is very weak. From the oscillation frequency, the heart rate can be extracted, which in this particular case, is 74.7 beats per minute. The small baseline variation is presumably caused by respiration which can be used to extract the respiration rate, another important vital sign. It is important to note that Figure 4a shows raw data without any post-processing. This signal is of very high quality with very little noise. The signal shown in Figure 4a is further processed by extracting the individual peaks, normalizing to amplitude of unity, and averaging all the peaks to generate a pulse corresponding to one systolic and diastolic cycle. The result is shown in Figure 4b (left axis). As averaging significantly suppresses the already low noise, one can obtain a very smooth first derivative signal (right axis).

In the example shown in Figure 3a, one of the magnets is placed at the nail side of the finger and the other at the opposite side. The magnets can also be placed at the two lateral sides of the fingertip. Figure 5a and Figure 5b show the cross-section view of the two configurations. In addition to disc-shaped magnets, curved magnets can also be used as illustrated in Figure 6 in which the arrow indicates the magnetization direction.

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Although the attractive force between the magnets helps to hold them on the finger, additional retaining means such as mechanical fixtures can be used to

further enhance the stability of the magnets. The retaining means retains the first magnet and second magnet within a cavity, or respective cavity, and permits relative movement between the first magnet and second magnet along a predetermined direction. Figure 7 shows one example of such fixtures. The retaining means can include fixtures 105a and 105b which can be made of non-magnetic materials, e.g., aluminium or plastic with sufficient rigidity to avoid deformation during relative movement of the magnets induced by the pulse in the finger. The two parts 105a and 105b can be mated together to form a single entity or be an integrated piece of cylindrically shaped material inside which there is a cavity to house or contain the magnets 101 and 102. The magnets can be connected or glued at a distal face to at least one an adjusting means such as T-shaped fixtures 106a and 106b. The adjusting means can be freely movable along the first Cartesian axis within a finite range. The adjusting means allows a user to re-position the magnets depending on the size of the finger. A side hole allows a finger to access the cavity formed by the magnets 101 and 102. The sensor 103 can be placed external to the retaining means to detect the magnetic field generated by the magnets. The magnetic field depends strongly on the gap length between the two magnets, which in turn varies with the blood flow volume in the finger. Therefore, when the position of the sensor is optimized, it will respond sensitively to blood flow in the finger, thereby generating the pulse signal corresponding to cardiac activity.

Figure 8a shows another embodiment of the heart rate detection device. The two magnets 101 and 102 are positioned such that they repel each other and stay apart with a finite spacing. The first magnet 101 can be fixed to a base of the retaining means (shown as a cylinder 107) which is made of a non-magnetic material. The second magnet 102 is attached to an adjusting means 108 made of same or different non-magnetic material as that of 107 and is movable along the central axis when there is a force applied to the fixture 108. When a finger 104 is in register with or pressed against adjusting means 108 with an appropriate force, second magnet 102 will move downward for a certain distance. A mechanical stopper may be used to ensure that, at steady state, the

fixture 108 and second magnet 102 will move up and down slightly in response to the blood flow in the finger. This induces a small change of magnetic field near the gap region which can then be detected using the magnetic sensor 103. As shown in Figure 8b, the vertical component of the field will be small on the xy-plane. Therefore, the sensing direction will be aligned parallel to z-axis. Based on the same principle as that of the first embodiment heart rate can be extracted from the measured signal. In this embodiment, the magnetic sensor can be positioned directly between the magnets and, in some embodiments, in the middle of the gap directly between the magnets.

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Figure 9 shows the third embodiment of the heart rate detection device. As shown in Figure 4, the MPG waveform contains both efferent waves, from the aortic valve down to peripheral arteries, and afferent/reflected wave from the end-arterial tree backwards. The detailed morphology of the waveform is a sum of the efferent and reflected waves at the measuring site, which depends on the strength of the heart pulsation and the stiffness of the arteries. In addition to the fine details of the waveform measured at a single site, it can be beneficial if the waveforms of multiple sites can be acquired simultaneously. Although this can be readily be done using multiple sensors, it remains a great challenge to interpret the results due to different sensitivity and time response of individual sensors. Therefore, it would be highly desirable if the measurements can be performed using a single sensor, which is a formidable challenge if not impossible for existing techniques such as PPG. As illustrated in Figure 9, the pulse signal from two fingers placed in close proximity with each other can be readily obtained using a single magnetic sensor. In one exemplary configuration, the two fingers 104a and 104b from the left and right hands respectively are each attached with a pair of mutually attractive magnets 101 and 102 and are placed nail-to-nail. In other words, a further plurality of magnets is positioned on a further member of the user when in use. A magnetic sensor 103 is placed between the two pairs of magnets to detect the combined and overlapping magnetic field. The magnetic sensor can be placed in such a way that it can detect the magnetic field from the magnets attached to different

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fingers. Since the magnetic field change represents the pulse signal, the signal detected by a single sensor is a superposition of two pulse signals. In this way, the device is able to detect the difference of pulse signals between two fingers, including both amplitude and phase variations, which reflect the potential occurrence of vascular thrombosis inside the circulatory system. Take two fingers from two hands as an example, if there is no vascular thrombosis the pulse is supposed to arrive at almost the same time with equal amplitude (no or little time difference), which otherwise would suggest partial obstruction of blood flow in some parts of the blood circulation system. The design illustrated in Figure 9 can be easily modified to allow the measurement of blood flow in two fingers on the same hand or one on a hand finger and the other on a foot finger. It can also be configured to perform simultaneous measurement between a finger and any other part of the circulation system in the body which can be reached by hand. For example, the apparatus can be placed on a finger and a radial artery.

Figure 10 shows the fourth embodiment of the heart rate detection device. In this embodiment, the pair of magnets is replaced by a nanomagnet array 304 formed on flexible substrate 301. A magnetic sensor 303 is then formed atop the magnetic array via an insulating layer 302. The entire structure is flexible and stretchable which can be attached to any part of the member through adhesives or placed on the finger by rolling it up into a ring shape. The material can be an elastomer. The spacing between the small magnets or magnetic particles is optimized such that when there is a small strain occurring in the elastomer, it will induce a detectable change in the magnetic field on its surface. When it is attached to the finger or body part, the spacing between the nanomagnets would change in response to blood flow. This would in turn cause change in the stray field, which can be detected by the sensor. The flexible nanomagnet array 304 can take any form (e.g., a ring or a patch) as long as it produces a measurable change in the magnetic field in response to pulsation in blood flow.

Figure 11 shows a fifth embodiment of the heart rate detection device. In this embodiment, all the configurations are the same as that of the first embodiment except that a piezoelectric sensor (or any type of force/pressure/strain sensor) 109 is inserted between the fingertip and magnet 102, in addition to the original magnetic sensor 103 (note: the piezoelectric sensor 109 can be placed on the opposite side of the finger). In this case, in addition to the pulse signal detected by the magnetic sensor 103, the piezoelectric sensor 109 can also detect pressure change induced by the blood flow. The combination of the two types of signals will further enhance the detection accuracy. The piezoelectric sensor 109 can be readily attached to the finger using the attractive force between the two magnets 101 and 102 and it does not require any other fixture to secure the sensor. A second piezoelectric sensor may be placed between magnet 101 and the finger, if necessary. Data obtained from the one or more piezoelectric sensors may be provided to other data processing models that may use the signals to estimate blood pressure. Alternatively, the piezoelectric sensor 109 may be replaced by a PPG sensor to acquire additional physiological signals.

Figure 12 shows the sixth embodiment of the heart rate detection device. In this embodiment, all the configurations are the same as that of the first exemplary embodiment except that two electrical contacts 110 and 111 drawn from the two magnets 101 and 102, are used to measure the capacitance between the magnets. This is motivated by the fact that the two magnets and the finger form a natural parallel plate capacitor. When the blood flows, the spacing between the two magnets will vary accordingly, which in turn will cause a change in the capacitance. The small change in the capacitance can be detected using standard resonant circuits, thereby producing the pulse signal. For example, a resonant circuit comprising a resistor, an inductor and a capacitor formed by the magnets and the finger can be used. When at resonance, the vibration in the magnets caused by blood flow can be detected either in the form of impedance or resonant frequency change. The combination of the two types of signals will further enhance the detection accuracy.

The present disclosure also provides a method of detecting a heart rate at a member of a user. The member is inserted between a plurality of magnets comprising a first magnet and a second magnet such that the plurality of magnets is held in register to the member by an attractive force between the
5 first magnet and second magnet, wherein pulsation in the member causes relative movement between the first magnet and second magnet. The change in magnetic field is measured via a magnetic sensor, the change in magnetic field being generated by the plurality of magnets in response to the relative movement. The exemplary embodiments used a fingertip as examples to
10 illustrate the designs and methods provided in particular implementations. However, the designs and methods can operate effectively in other body parts such as waist, arm, chest, toes, etc.

Figure 14 shows an example of embodiment of the apparatus in accordance with
15 the present invention. The apparatus comprises two cylindrical magnets (1402, optionally 1404) attached to a fingertip. One of the magnets is firmly attached to a mechanical fixture in the apparatus and the other is movable in response to blood flow-induced skin movement (Fig. 14). Figure 14(a) illustrates a schematic of an arrangement for measurement of a relationship between
20 vibration of the magnet and changes in magnetic field. Figure 14(b) is a photograph of an apparatus positioned on a fingertip. A magnetic sensor 1406 is placed near the movable magnet (approximately 1.5 cm in some embodiments), which detects changes in the magnetic field of the magnet. Depending on the magnet chosen and positioning of the sensor, various types
25 of magnetic sensors can be used, including a spin-orbit torque enabled magnetic sensor. In some embodiments, the magnetic sensor may be implemented using a tunnel magnetoresistance sensor with a dynamic range around 100 Oe and sensitivity of 1.28mV/Oe.

30 The correlation between the vibration and magnetic signals was evaluated by probing the movable magnet using a laser Doppler meter (Polytec VibroGo). The VibroGo signal acquisition unit has two input channels which can be used to

measure the vibration and magnetic signals simultaneously. This greatly facilitates the comparison of two signals as the time difference caused by measurement electronics is presumably negligible. The experiments were performed on multiple fingers of healthy subjects of different gender and age to
5 evaluate accuracy of the magnetic sensor data and its relationship to the changes in magnetic field produced by pulsation in the finger of a subject. The embodiments in use do not incorporate the laser Doppler meter. The laser Doppler meter was merely used for unveiling the detection mechanism and evaluation or calibration of the apparatus.

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Figure 15 shows exemplary magnetic and vibrational signals obtained simultaneously from two healthy subjects. Figure 15a is the pulsatile signal of subject A (male at late 50's) measured by a magnetic sensor for a duration of 16 seconds. The aspiratory baseline shift has been removed and the data have
15 been smoothed with a band pass filter with a bandwidth of 0.8~10 Hz. Comparison with a commercial PPG sensor confirmed that the periodicity of the signal corresponds to the heart rate of the subject. Figure 15b shows the corresponding average single pulse signal with the mean subtracted out and normalized by the standard deviation. The overall shape resembles well the PPG
20 waveform with clear systolic peak, dicrotic notch and diastolic peak. A high degree of similarity with PPG is also seen in the acceleration pulse waveform (or second derivative), as shown in Figure 15c, which is useful for evaluating cardiovascular conditions.

25 Figure 15d-15f show the same set of data for subject B (female at early 20's). The basic characteristics are the same as those obtained from Subject A, though some subtle differences in the shape of the pulse and acceleration waveform. These results demonstrate that the magnetic signals are reproducible and of good quality. The pulsatile signals showing in Figure 15g and 15h are the time-
30 dependent displacement signals, whereas Figure 15i is the acceleration signal measured directly by the Doppler meter. The experiments demonstrate a close correlation between the magnetic and vibrational signals in terms of both

periodicity and waveform including the characteristic peaks. The subtle difference in systolic peak position is presumably due to the different time response of the two measurement channels. The correlation coefficient is in the range of 0.9527 - 0.9924, which is even higher for the averaged single pulse.

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Pulse monitoring under multiple conditions

To demonstrate the 'varying-condition' pulse monitoring capability of the device, experiments were conducted for fingers under different conditions: (a) wrapped by a black tape, (b) wrapped by a plaster, and (c) immersed in water, and the results are shown in Figure 16a-16c, respectively. As shown in the left panel of Figures 16a and 16b, the contact area of the skin and magnet is completely covered by a black tape or a plaster. The former completely blocks the light whereas the latter is semi-transparent. Should a PPG sensor be used for the detection, one would not expect any measurable signal in (a) or a clear signal in (b). But, as shown in the right panel of Figures 16a and 16b, clear signals are obtained in both cases, indicating that the black tape or plaster has very little effect to the MDVS detector. To demonstrate that the MDVS is immune to body fluid too, measurements were performed while immersing the fingertip and magnets in water. As shown in the right panel of Figure 16c, very clear pulse signals were obtained. Although the test was done using clear water, similar results can be obtained when there is body fluid such as sweat and blood on the finger. Repeated experiment shows that the signals detected under all the three conditions are stable and reproducible, with clear systolic peak, diastolic peak, and equal peak-to-peak span. There is very little difference compared to the results obtained from bare hand in air. These results clearly demonstrate the advantages of the apparatus according to the embodiments over existing pulse detectors such as PPG, in coping with challenging circumstances.

Bland-Altman plot analysis of magnetic and vibration signal

To obtain a more quantitative comparison of the magnetic and vibration signal, Bland-Altman analysis was performed on normalized magnetic and vibrational

data with the results illustrated in Fig.17. The Bland-Altman plot is used to analyze the correlation between two methods of measurement for the same variable. It plots the difference against the mean of two sets of measurement values, highlighting the degree of agreement between the two measurement methods. The recommended limit of agreement is that 95% of the data points should lie within ± 1.96 times of standard deviation (SD) of the mean difference. Figure 17(a) and 17(b) show the average single pulse of magnetic (1702, 1706) and vibrational signal (1704, 1708) measured simultaneously from subject B. The vibrational signals are obtained using two different models of vibrometers: VibroFlex QTec for Fig. 17a and VibroGo for Fig. 17b. Other than a slight difference in surface roughness requirements, there are no key technical differences between the two models of vibrometers. The main purpose of using two different models of vibrometer is to check the correlation between magnetic and vibrational signals. The correlation coefficient between magnetic and vibrational signals in Fig. 16a is 0.99, indicating the same origin of the two signals.

To quantify the difference statistically, more datasets were considered to produce the Bland-Altman plot in Fig. 17c. The two dashed-lines denote ± 1.96 SD. Except for a few outliers, the majority of the data points fall within the difference range of - 0.15 to 0.12, with a mean bias of $- 2.5 \times 10^{-4}$. Similar results are obtained for signals measured by the VibroGo, with a correlation coefficient of 0.99, and difference between -0.09 and 0.1 and mean bias of 5.1×10^{-3} in the Bland-Altman plot (Fig. 17d). The maximum deviation between the two measurement methods is 6.77% and 2.99%, respectively, for vibration measurements using VibroFlex QTec and VibroGo. In addition to the use of different types of vibrometer, experiments were also performed using different types of magnetic sensors. The results suggest that the close correlation between magnetic and vibrational signal is a generic phenomenon which does not depend on the vibrometer or magnetic sensor used to measure the signals.

Analytical model of heart rate determination based on magnetic sensor data

The signal generated by the magnetic sensor is interpreted as magnetic signature induced by blood flow. Change of magnetic sensor's detection axis caused by blood flow may also play a role in influencing the observed signal. The magnets of the apparatus are attached to a fingertip which consists of nail, skin, muscle, bones, arterial/vein vessels, and capillaries. When the blood flows through the vessels, it generates pressure wave on the vessel walls which can propagate through the thick tissue and cause vibration of the skin. Therefore, without losing generality, the output signal of the magnetic sensor may be expressed as:

$$\Delta V_{\text{mag}} = S \hat{s} \cdot \left(\frac{\partial \vec{H}}{\partial (\vec{r}_s - \vec{r}_m)} \Delta(\vec{r}_s - \vec{r}_m) + \frac{\partial \vec{H}}{\partial \vec{m}} \Delta \vec{m} + \frac{\partial \vec{H}}{\partial \chi} \Delta \chi \right) \quad (1)$$

where S is the sensitivity of the sensor and $\hat{s}$ is its sensing axis direction, $\vec{H}$ is the magnetic field at the sensor location, $\vec{r}_m(\vec{r}_s)$ is the position of the magnet (sensor), $\vec{r}_m(\vec{r}_s)$ is the magnetic moment of the magnet, χ is the magnetic susceptibility of the blood, and $\Delta(\vec{r}_s - \vec{r}_m)$, $\Delta \vec{m}$, and $\Delta \chi$ are the corresponding changes induced by the blood flow. The first two terms of Eq. (1) are corresponding to signals induced by parallel displacement and rotation of the magnet, respectively, whereas the last term is due to change in magnetic susceptibility of the blood. Before performing numerical simulations to calculate the overall signal, it is instructive to examine the first two terms analytically using the magnetic dipole approximation, which is valid when the distance between the magnet and sensor $|\vec{r}_s - \vec{r}_m|$ is much larger than the size of the magnet.

Signal due to magnet displacement

It is assumed that the sensor is stationary, and only one of the magnets is moving, which describes well the actual measurement setup. In this case, the

magnet position may be defined as $\vec{r} = (x, y, z)$ in a Cartesian coordinate system with its origin at the sensor position. Then, the output signal may be written as $\Delta V_{\text{mag}}^D = S\hat{s} \cdot \frac{\partial \vec{H}}{\partial \vec{r}} \Delta \vec{r}$, where $\vec{H} = \frac{1}{4\pi} \left(\frac{3\vec{r}(\vec{m} \cdot \vec{r})}{|\vec{r}|^5} - \frac{\vec{m}}{|\vec{r}|^3} \right)$ and $\Delta \vec{r} = (\Delta x, \Delta y, \Delta z)$. When the detection axis of the sensor and dipole moment of the magnet are aligned along

5 x- and z-axis, respectively, i.e., $\hat{s} = (1, 0, 0)$, $\vec{m} = (0, 0, 1)$, ΔV_{mag}^D is calculated as:

$$\Delta V_{\text{mag}}^D = \frac{3mS}{4\pi} \frac{1}{r^7} [(x^3 + xy^2 - 4xz^2)\Delta z + (z^3 + zy^2 - 4zx^2)\Delta x - 5xyz\Delta y], \quad (2)$$

where $r = (x^2 + y^2 + z^2)^{1/2}$. When $x \gg z, y$, which represents the actual experimental setup, ΔV_{mag}^D is approximately given by $\Delta V_{\text{mag}}^D \approx (3mS/4\pi)(\Delta z/x^4)$.

- 10 On the other hand, when the laser beam is aligned in z-direction, Δz is nothing else but the displacement measured by the vibrometer. Therefore, the first term of Eq. (1) is directly proportional to the vibration signal. The difference, if any, is mainly caused by the transverse movement of the magnet, i.e., Δx and Δy , with respect to the laser beam direction, which can be minimized by optimizing
- 15 the sensor position with respect to the magnet, i.e., to make $x \gg z, y$.

Signal due to magnet rotation

- Next, we consider the contribution due to rotation of the dipole which is initially aligned in z-direction, i.e., $\vec{m} = (0, 0, 1)m$. Without losing generality, we assume
- 20 that the yaw, pitch and roll angles are α , β , and γ , respectively, and the change of $\vec{m}$ due to rotation is given by $\Delta \vec{m} = R(\alpha, \beta, \gamma)\vec{m} - \vec{m}$, where $R(\alpha, \beta, \gamma)$ is the rotation matrix. The signal induced by the dipole rotation can be calculated directly from Eq. (1) which reads

$$\Delta V_{\text{mag}}^R = \frac{3S}{4\pi} \frac{1}{r^5} \left[\left(x^2 - \frac{r^2}{3} \right) \Delta m_x + xy\Delta m_y + xz\Delta m_z \right] \quad (3)$$

- 25 where Δm_x , Δm_y , and Δm_z are the changes of magnetic moment in the three coordinate axis directions. When α, β , and γ are very small and x is much larger

than z and y , ΔV_{mag}^R is approximately given by $\Delta V_{mag}^R = (Sm/2\pi)(\beta/x^3)$. The result shows that the magnetic signal induced by the rotation is directly proportional to the pitch angle β , *i.e.*, the angle of rotation around y -axis. Although the dipole approximation is valid in calculating the magnetic signal, to estimate the displacement signal measured by the vibrometer, we have to consider the finite size of the magnet. It is assumed that the laser beam is initially focused at $\vec{L} = (L_x, L_y, L_z)$ on the top surface of the magnet with respect to the rotational center and its direction is parallel to z -axis. In this case, the displacement in z -direction is given by $\Delta L_z = \hat{k} \cdot (R(\alpha, \beta, \gamma)\vec{L} - \vec{L})$ and when α, β , and γ are small, it reduces to

5 $\Delta L_z \approx \gamma L_y - \beta L_x$.

Therefore, the displacement signal contains two components which are proportional to the pitch and roll angles, respectively. In other words, depending on the rotation directions, the displacement measured by the vibrometer may not be exactly the same as that of the output signal from the magnetic sensors. The ratio between ΔV_{mag}^D and ΔV_{mag}^R is on the order of $(\Delta z/x)/\beta$. Based on the displacement measured by the vibrometer, $\Delta z/x$ is on the order of $10^{-3} - 10^{-2}$, which corresponds to a rotation angle of $0.06^\circ - 0.6^\circ$, which means that ΔV_{mag}^R can be comparable to or even larger than ΔV_{mag}^D , depending on the particular measurement setup. This may explain why the agreement between measured magnetic and vibration signals is generally better in the systolic than the diastolic half-cycle of the heartbeat (Fig.15 and Fig.17), as the sudden decrease of blood pressure after the systolic peak may result in not just parallel displacement but also rotation of the magnet.

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Evaluation using simulation of signals

Contributions of each term in Eq. (1) was numerically evaluated under typical measurement conditions using the Software for Multiphysics Simulation (COMSOL). The coordinate system was setup as follows: x -axis and y -axis are parallel and transverse to the finger (1802), respectively, z -axis is perpendicular to the cylindrical magnet surface, and the coordinate origin is at the middle of

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the magnet with z-axis passing through the rotational center of both magnets. Figure 18a shows the calculated contour lines of H_x on the xz plane in the range of ± 100 Oe, superimposed with the cross-sections of the magnets and fingertip. The two rectangular boxes denote the cylindrical magnets (1804, 1806) with
 5 thickness $T = 5$ mm radius $R = 5$ mm, and saturation magnetization $M_s = 962.9$ kA/m. The large rectangular box defined by $|x| \leq 10$ mm and $|z| \leq 4.5$ mm represents the fingertip with $|yy| \leq 5$ mm. The spacing between the bottom surface of the upper magnet (1804) and top surface of lower magnet (1806) is initially set at 9 mm. The bottom magnet is fixed, whereas the top magnet is
 10 movable in response to the skin movement. The magnetizations of both magnets are pointing in the positive z-direction.

To maximize the detection signal, the sensor must be placed at a location where the field strength is below the sensor's dynamics range (favourable condition 1)
 15 and at the same time the change caused by sensor displacement or rotation is largest (favourable condition 2). For the particular sensor used in the experiment which has a dynamic range of ± 100 Oe, the simulation results in Fig. 18a show that favourable condition 1 is satisfied as long as the sensor is placed in the region where the contour lines are shown ($|H_x| < 100$ Oe). However, when the
 20 sensor is too far away from the magnet, it may not be able to detect the small change of field caused by the blood flow, which may originate from magnetic displacement/rotation or blood susceptibility change, or the combination of all these factors. We first calculate the field change (ΔH_x) caused by magnet displacement or rotation under typical measurement conditions. Figure 5b
 25 shows the contour of ΔH_x caused by the movement of the top magnet in z-direction by $50 \mu\text{m}$, which corresponds to the typical displacement of magnet measured by the vibrometer due to blood flow. Similarly, Fig. 18c shows the change caused by rotating the magnetization of the top magnet by 3.3×10^{-3} rad away from z axis around y-axis (i.e., $\beta = 0.19^\circ$). The rotation angle is
 30 chosen such that the maximum deflection of the edge of the magnet is comparable to the vertical displacement used for obtaining the results in Fig. 18b. From both figures, it is observable that maximum change appears along

the middle line of the top magnet in x-direction with its magnitude decreasing quickly away from the magnet. Within the range of $15 \text{ mm} < |x| < 20 \text{ mm}$ and $5 \text{ mm} < z < 10 \text{ mm}$, it is possible to obtain a change of $0.5 - 1 \text{ Oe}$ for H_x , which is detectable by the sensor.

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The field change caused by susceptibility change of the blood is also simulated for evaluation. Due to the difference in magnetic responses of HbO_2 and Hb , the magnetic susceptibility of oxygenated and de-oxygenated blood varies slightly and its difference relative to water $\Delta\chi$ can be approximated as follows:

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$$\Delta\chi = Hct(\Delta\chi_{do}(1 - \text{HbO}_2) + \Delta\chi_{oxy}) \quad (4)$$

where Hct is the volume fraction of red blood cell, $\Delta\chi_{oxy}$ is the susceptibility difference between fully oxygenated blood and water, $\Delta\chi_{do}$ is the susceptibility difference between fully oxygenated and deoxygenated red blood cells, and HbO_2 ranges from 0 (fully deoxygenated) to 1 (fully oxygenated). $\Delta\chi/H_{ct}$ is about -2×10^{-8} at fully oxygenated state and 2.5×10^{-7} at deoxygenated state. Since the magnetic susceptibility of water is 7.18×10^{-7} and H_{ct} is around 0.4-0.5, the magnetic susceptibility of blood is between $2.8 \times 10^{-7} - 4.8 \times 10^{-7}$, depending on its oxygenation state. The maximum change is less than 0.1ppm. To simulate its effect on field distribution, the simulation involved calculating the field difference caused by the variation of magnetic susceptibility in the fingertip region by 0.1 ppm, and results are shown in Fig. 18d. As can be seen, the change in H_x is on the order of 10^{-5} Oe in the region of interest, i.e., $15 \text{ mm} < |x| < 20 \text{ mm}$ and $5 \text{ mm} < z < 10 \text{ mm}$, which is too small to be detected by magnetic sensors incorporated in the apparatuses (note: the unit in Fig. 18d is 10^{-4} Oe). The above results demonstrate clearly that the pulsatile signals detected by the magnetic sensor are dominantly of mechanical origin, the contribution because of changes in the oxygenation station of blood, if any, is negligible.

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Validity of the dipole approximation was evaluated by comparing the analytical and COMSOL simulation results. Figure 19a shows ΔH_x obtained by the two methods as a function of vertical displacement of the top magnet (Δz) at different radial position (x) of the magnetic sensor along the middle line of the magnet. Similar results are shown in Fig. 19b for pitch angle β . Solid-lines are results obtained from the dipole approximation and symbols are from COMSOL simulations. As expected, good agreements are obtained when both Δz and β are small, and x is about 3 times larger than that of the radius of the magnet. Therefore, the dipole approximation can be used to optimize the position of the sensor with respect to the magnet.

Signal processing and statistical analysis

The detected signals are processed using signal processing software such as MATLAB as follows. First, the raw data with a sampling rate of 240Hz is segmented into sequences with a duration of 30s. Second, a bandpass filter with a passband of 0.8Hz - 10Hz is used to remove high-frequency noise and baseline shift. Third, z-score analysis is used to transform two types of signals (magnetic sensor data and vibration sensor data) with different amplitudes and units into similar range, as shown in Figure 15a, 15d and 15g. Fourth, single pulse is extracted by averaging all pulses of the period of data sequence, and the results are shown in Figure 15b, 15e and 15h. Figure 15c and 15f are second derivative of the single pulse signals. Finally, Bland-Altman plot is analyzed based on 60 pulses from 3 sequences of signals.

Simulation of magnetic signals was performed using COMSOL Multiphysics® software. The initial distance between the body centers of the two magnets is set at 14 mm with a finger diameter of 9 mm. When simulating the effect of vertical vibration, only the position of magnet in positive z-axis is varied to simulate the expansion of finger due to blood circulation. A cuboid is used to simulate the susceptibility change inside the finger. When simulating the effect of rotation, only magnet in positive z-axis is rotated around the center of bottom surface.

In summary, the present invention relates to a heart rate monitoring device which can be low-cost and energy efficient with high immunity to motion artefacts. In the simplest embodiment, the heart rate (HR) monitoring device consisting of at least two magnets placed on the fingertip and a magnetic sensor to detect the blood flow induced magnetic field change as pulse signals. When the magnets are placed at the opposite sides of the fingertip, the attractive force firmly attaches the magnets to the fingertip. The magnetic sensor can be fixed rigidly on a fixture with one of the magnets such that the relative motion between the sensor and magnets or finger is suppressed or eliminated. At least one magnet is able to move in response to the expansion force caused by blood flow. Such a combination significantly reduces or eliminates the motion artifacts. The strength of the static magnetic field surrounding the fingertips can vary in a large range depending on its location. This allows the use of a variety of magnetic sensors with different dynamic range and sensitivity to implement the said heart rate monitoring device. When the sensor is properly chosen, it would lead to a device with extremely low power consumption and high sensitivity. In addition to the blood flow induced expansion force, the magnetic field change also contains the intrinsic magnetic response of the blood, and therefore, the device can also produce other clinically relevant information by extracting this response, which cannot be obtained from other type of monitoring devices. When magnets are placed on different fingers, the signal detected by a single sensor can determine the relative timing or velocity of blood flow in different fingers, a feature completely lacking in other types of monitoring devices. The device can also be configured to obtain other types of signals such as capacitive signal. The magnets and/or sensor can also be formed on flexible or wearable materials.

Figure 13 illustrates a method of detecting heart rate at a member of a user. The method is performed by use of the apparatus of any one of the disclosed embodiments. Step 1030 comprises inserting a member between a plurality of magnets of the apparatus. The plurality of magnets comprise a first magnet and

a second magnet such that the plurality of magnets is held in register to the member by an attractive force between the first magnet and second magnet. After the member is received in the apparatus, pulsation in the member causes relative movement between the first magnet and second magnet. The relative
5 movement causes changes in the magnetic field generated by the plurality of magnets which is measured by the magnetic sensor at step 1320. The signal measured by the magnetic sensor is received by one or more processors at step 1330. At step 1340, the one or more processors process the received signals to estimate a hear rate of the user.

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Figure 20 illustrates a method of fabrication of an apparatus for detecting heart rate at a member of a user. Step 2010 comprises providing a body of the apparatus. The body comprises regions to position a plurality of magnets comprising a first magnet and a second magnet held in register to a cavity in
15 the body. The cavity is provided for receiving a member. The attractive force between the first magnet and second magnet is transmittable through the body onto a receivable member to secure the apparatus on the member. Step 2020 comprises providing a magnetic sensor in the body. The magnetic sensor configured to measure a change in a magnetic field in response to a relative
20 movement of the plurality of magnets and make available measured change signal data for transmission to one or more processors in communication with the magnetic sensor.

The one or more processors of the embodiments may be replaced with
25 alternative circuitry for processing the signals received from the magnetic sensor. The alternative circuitry may include a microprocessor, a microcontroller, an application specific integrated circuit etc. The apparatus of some embodiments may also comprise a display for presenting the measured heart rate data. The display receives an output from the one or more processors
30 and presents the received output for operators or users of the apparatus.

It will be appreciated that many further modifications and permutations of various aspects of the described embodiments are possible. Accordingly, the described aspects are intended to embrace all such alterations, modifications, and variations that fall within the spirit and scope of the appended statements.

5

Throughout this specification and the statements which follow, unless the context requires otherwise, the word "comprise", and variations such as "comprises" and "comprising", will be understood to imply the inclusion of a stated integer or step or group of integers or steps but not the exclusion of any

10 other integer or step or group of integers or steps.

Throughout this specification and the statements which follow, unless the context requires otherwise, the phrase "consisting essentially of", and variations such as "consists essentially of" will be understood to indicate that the recited

15 element(s) is/are essential i.e. necessary elements of the invention. The phrase allows for the presence of other non-recited elements which do not materially affect the characteristics of the invention but excludes additional unspecified elements which would affect the basic and novel characteristics of the method defined.

20

The reference in this specification to any prior publication (or information derived from it), or to any matter which is known, is not, and should not be taken as an acknowledgment or admission or any form of suggestion that prior publication (or information derived from it) or known matter forms part of the

25 common general knowledge in the field of endeavor to which this specification relates.

Claims

1. An apparatus for determining heart rate in a member of a user, the apparatus comprising:
 - a) at least one magnet, including a first magnet;
 - b) a retaining means to retain the first magnet and apply a pre-calibrated pressure to maintain the first magnet in register to the member while permitting motion of the at least one magnet in response to a pulse in the member;
 - c) a magnetic sensor configured to measure a change in a magnetic field in response to the motion; and
 - d) one or more processors in communication with the magnetic sensor, the one or more processors configured to determine the heart rate based on the measured change in the magnetic field.
2. The apparatus of claim 1, wherein the pre-calibrated pressure is substantially similar to a pressure generated by the pulse.
3. The apparatus of claim 1, wherein the pre-calibrated pressure is in the range of 40 to 200 mmHg.
4. The apparatus of any one of claims 1 to 3, wherein the at least one magnet comprises a second magnet, at least one of the first magnet and the second magnet being held, in use, in register to the member by an attractive force between the first magnet and second magnet, wherein; the pulse causes relative movement between the first magnet and the second magnet; and the magnetic sensor is configured to measure a change in a magnetic field in response to the relative movement.
5. The apparatus according to claim 4, wherein the relative movement between the first magnet and second magnet comprises at least one of:

relative lateral movement along an axis defined by the first magnet and the second magnet; and relative rotation of at least one of the two magnets with respect to the axis.

6. The apparatus according to any one of claims 1 to 5, wherein the magnetic sensor is a 3-axis sensor.
7. The apparatus according to any one of claims 1 to 6, wherein the magnetic sensor is positioned at a magnetic field local minimum of the at least one magnet, where a principal component of the magnetic field is zero or approaches zero or is smaller than a saturation field of the magnetic sensor.
8. The apparatus according to claims 4, wherein the magnetic sensor is provided: between the first magnet and second magnet with respect to the magnetic field; or midway between the first magnet and second magnet, with respect to the magnetic field; or between the first magnet and the member.
9. The apparatus according to any one of claims 1 to 8, wherein the retaining means comprises a cavity containing the first magnet, the cavity permitting motion of the first magnet in response to the pulse.
10. The apparatus according to any one of claims 1 to 9, further comprising a piezoelectric sensor positioned between the member and a magnet of the at least one magnet, to measure pressure changes induced by blood flow in the member, the piezoelectric sensor being configured to transmit the signals to the one or more processors.
11. The apparatus according to any one of claims 1 to 8, further comprising a PPG sensor positioned between the member and a magnet of the at least one magnet to measure pressure changes induced by blood flow in the

member, the PPG sensor being configured to communicate signals of the measured pressure changes to the one or more processors.

12. The apparatus according to claim 4, wherein the first magnet and the second magnet form part of a resonant circuit, the resonant circuit configured to measure capacitance across the member.
13. The apparatus according to any one of claims 1 to 12, comprising a further plurality of magnets for positioning on a further member of the user, the magnetic sensor being positioned to detect a change in a magnetic field generated by the further plurality of magnets to determine a heart rate associated with the further member.
14. The apparatus according to claim 13, wherein the one or more processors are further configured to determine a time difference between the heart rate associated with the member and the heart rate associated with the further member to generate a heart rate difference signal.
15. The apparatus according to claim 4, wherein at least one of the first magnet and the second magnet is fixed, in use, in position relative to the member.
16. The apparatus according to any one of the claims 1 to 15, wherein the magnetic sensor is positioned at a relative location with respect to the at least one magnet such that strength of a magnetic field generated by the plurality of magnets at the relative location is less than a dynamic range of the magnetic sensor.
17. The apparatus according to any one of the claims 1 to 16, wherein the magnetic sensor is positioned at a relative location with respect to the at least one magnet such that changes to the magnetic field caused by pulsation in the member is at or proximate to a maxima.

18. The apparatus of any one of claims 1 to 17, wherein the at least one magnet comprises a plurality of nanomagnets embedded in a flexible substrate forming a part of the apparatus.
19. A method of detecting heart rate at a member of a user, comprising:
 - a) retaining the member in register to at least one magnet by a retaining means, wherein the retaining means applies a pre-calibrated pressure on the at least one magnet in relation to the member while allowing motion of the at least one magnet in response to pulsation in the member;
 - b) measuring a change in magnetic field via a magnetic sensor, the change in magnetic field being generated in response to motion of the at least one magnet;
 - c) receiving by one or more processors, signals generated by the magnetic sensor; and
 - d) processing the received signals by the one or more processors to determine a heart rate at the member of the user.
20. A method of fabrication of an apparatus for detecting heart rate at a member of a user, the method comprising:
 - a) providing a body of the apparatus, the body comprising a retaining means to retain the at least one magnet in register to a receivable member and apply a pre-calibrated pressure on the at least one magnet in relation to the member while allowing motion of the at least one magnet in response to pulsation in the member; and
 - b) providing a magnetic sensor in the body, the magnetic sensor configured to measure a change in a magnetic field in response to motion of the at least one magnet and make available measured change signal data for transmission to one or more processors in communication with the magnetic sensor.

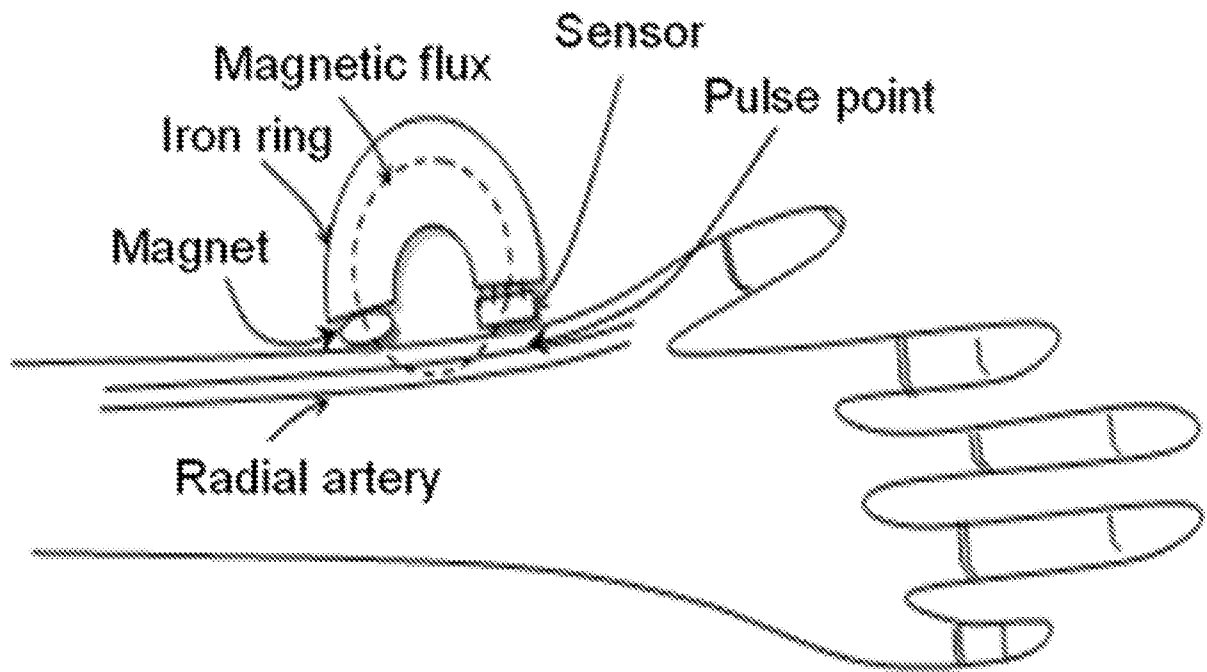


Figure 1

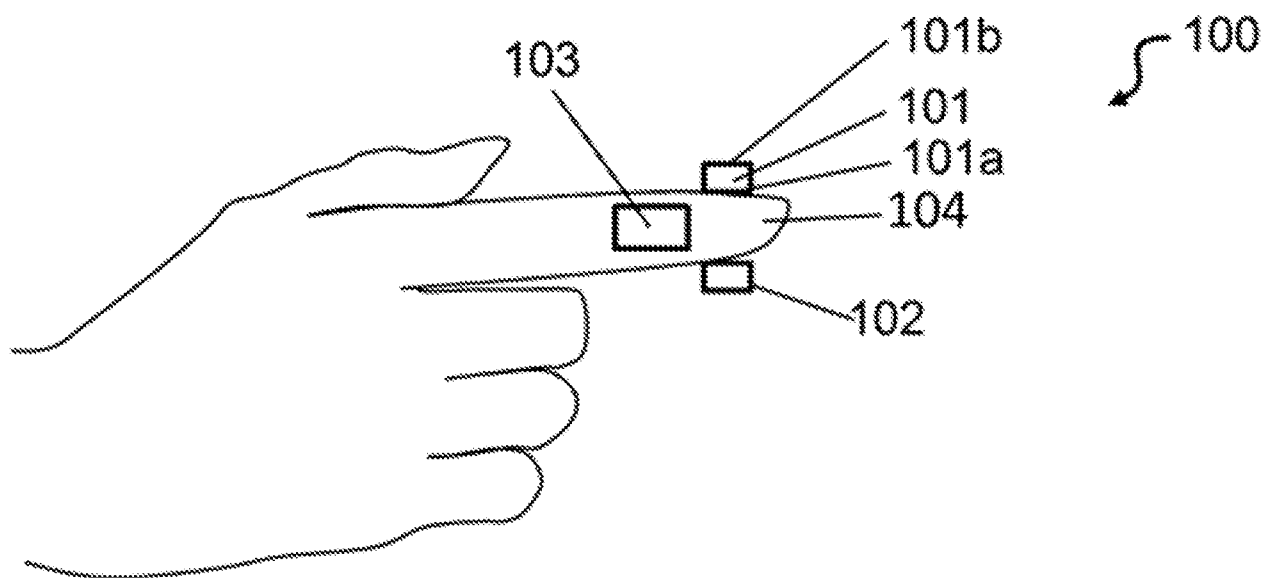


Figure 2a

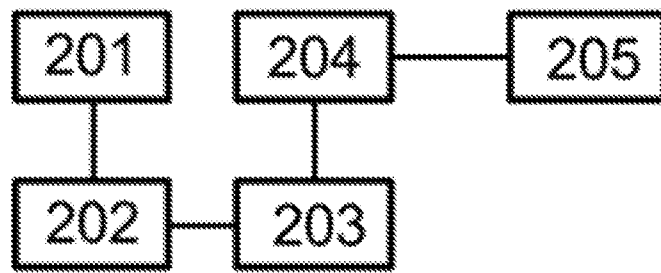


Figure 2b

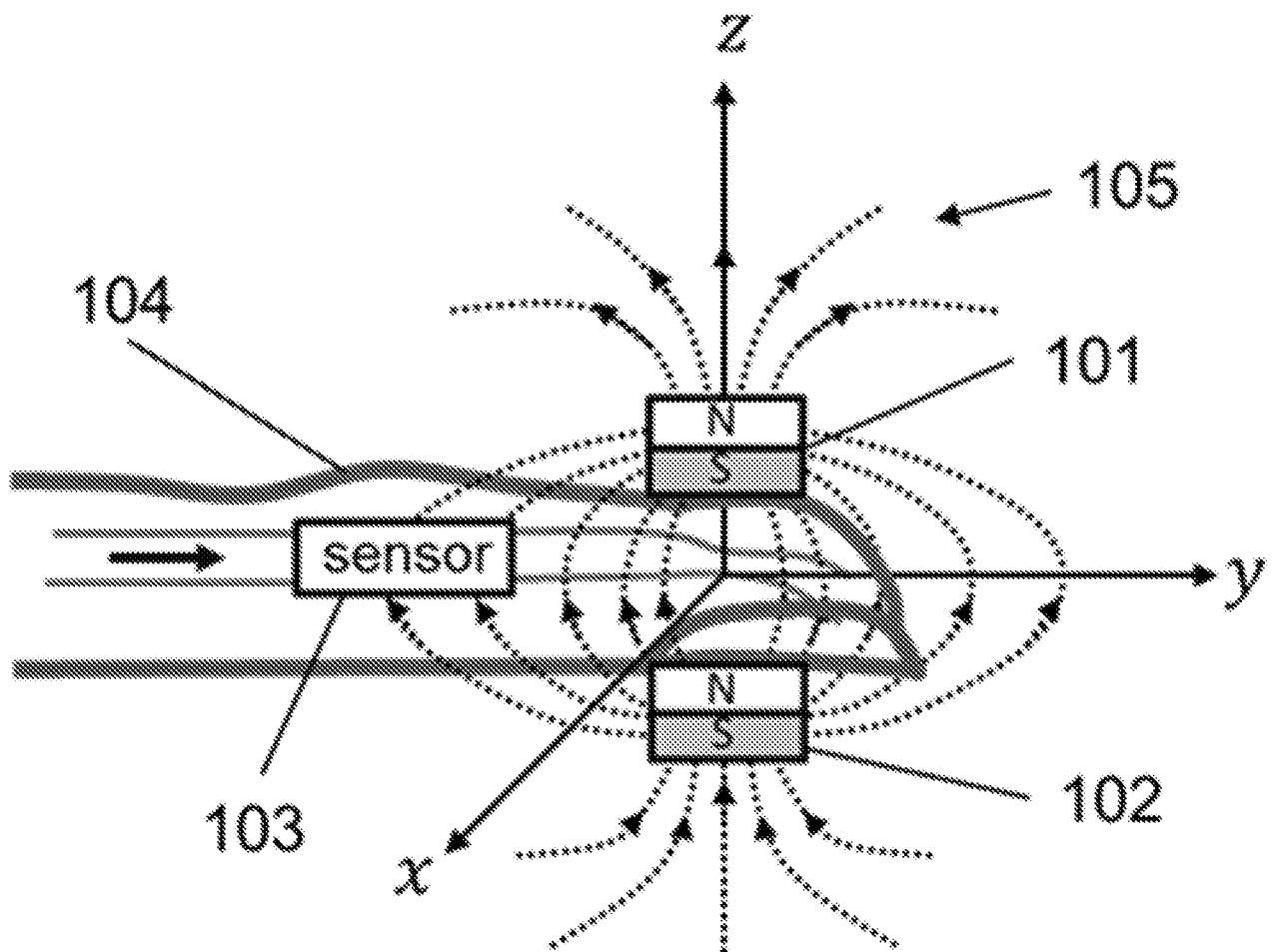
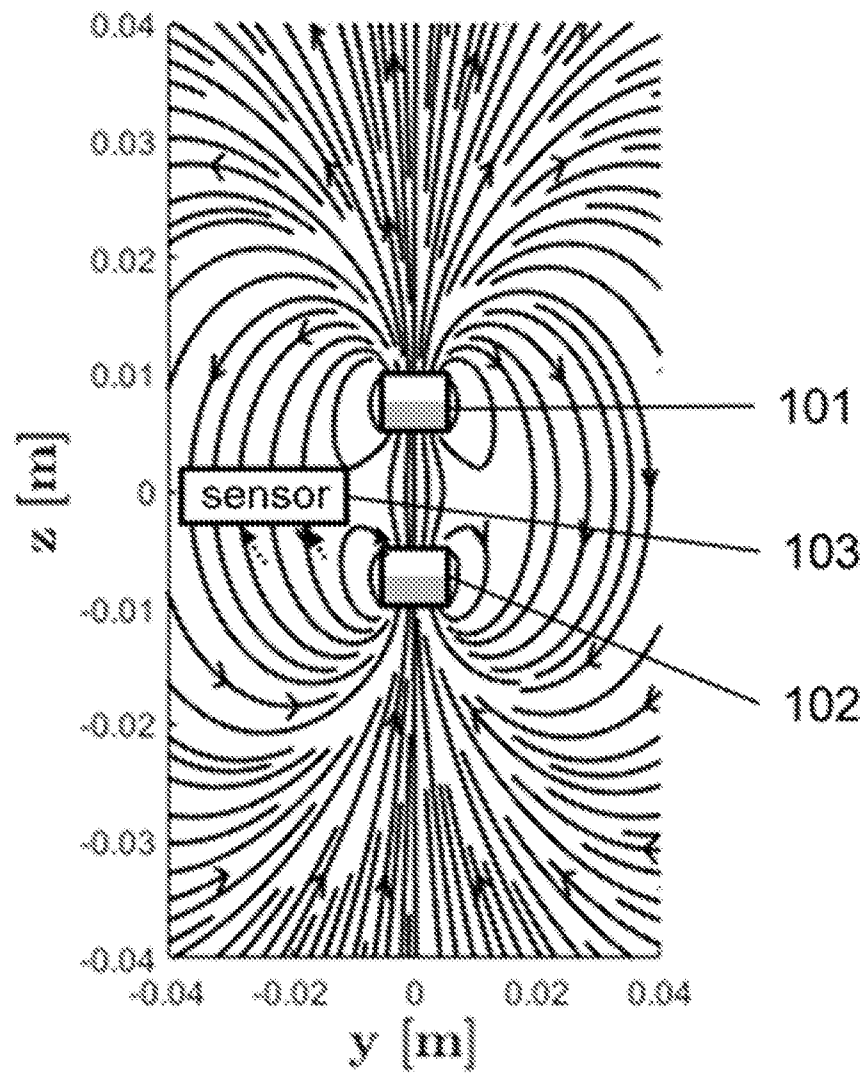
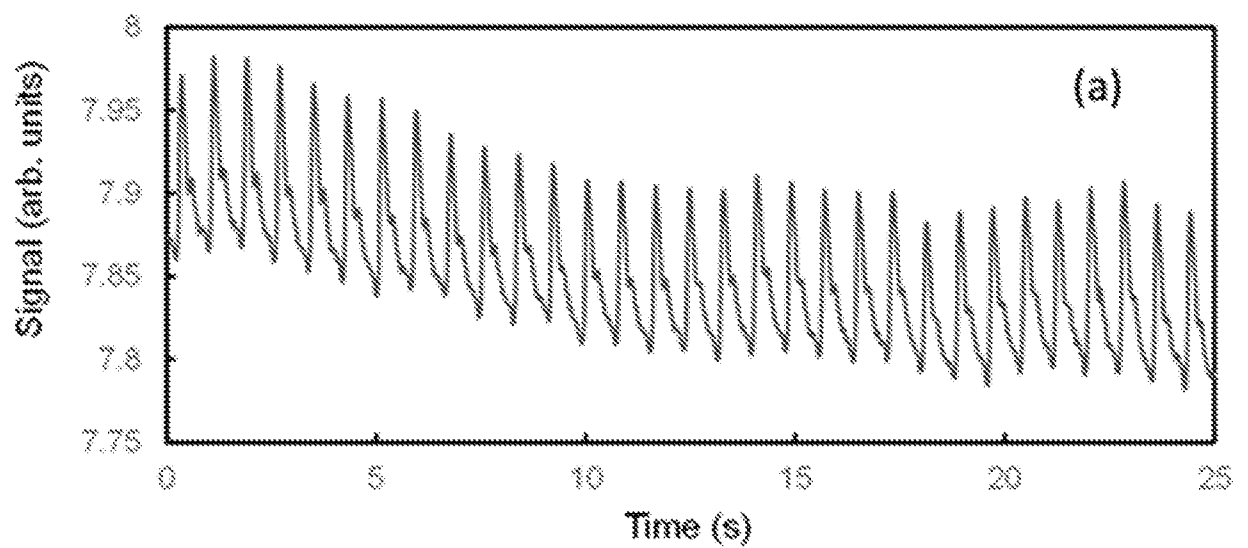


Figure 3a

**Figure 3b****Figure 4a**

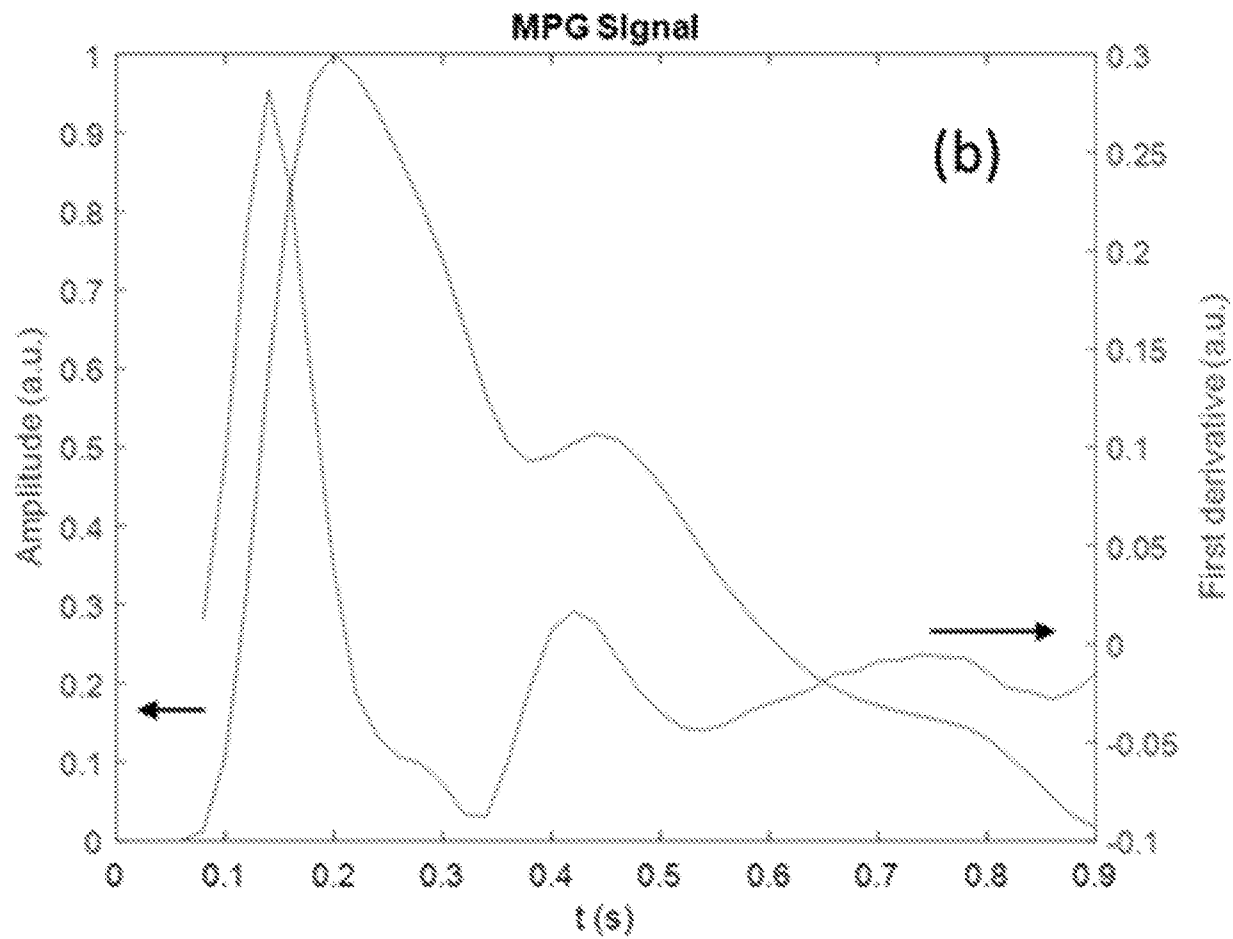


Figure 4b

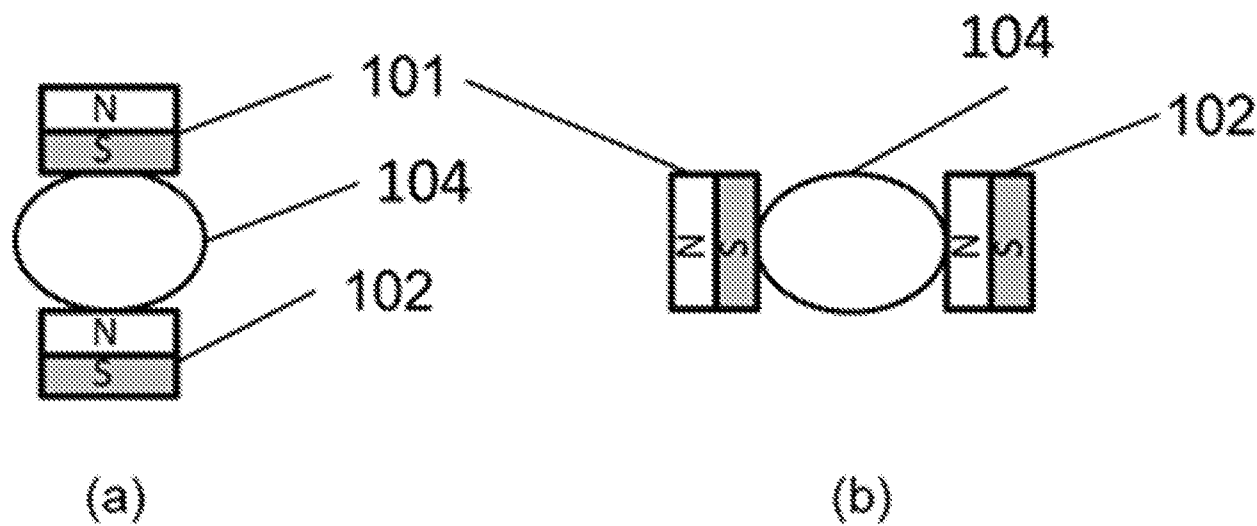


Figure 5

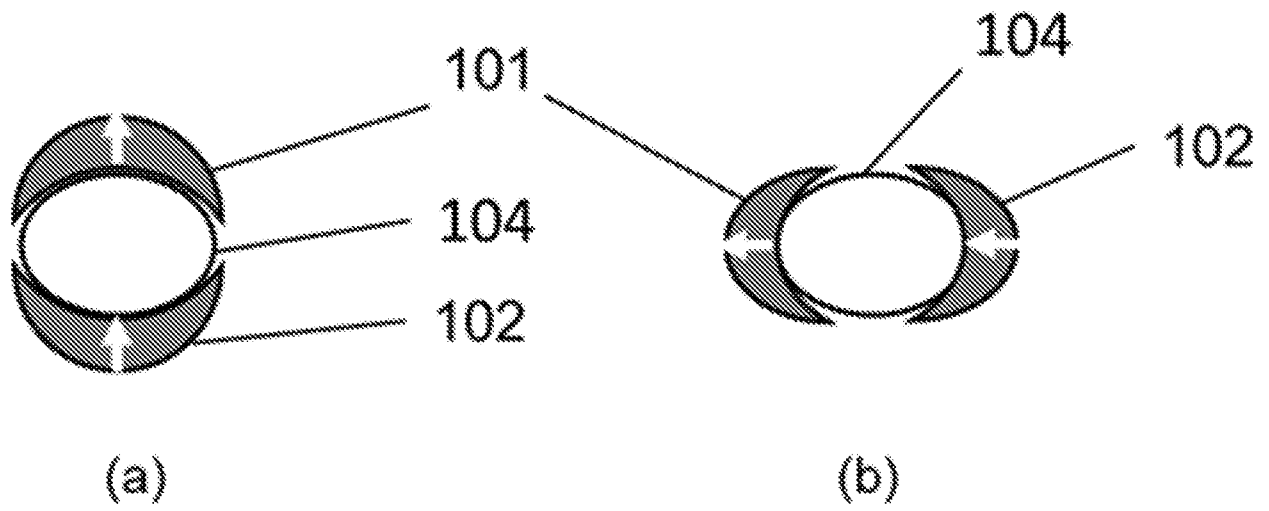


Figure 6

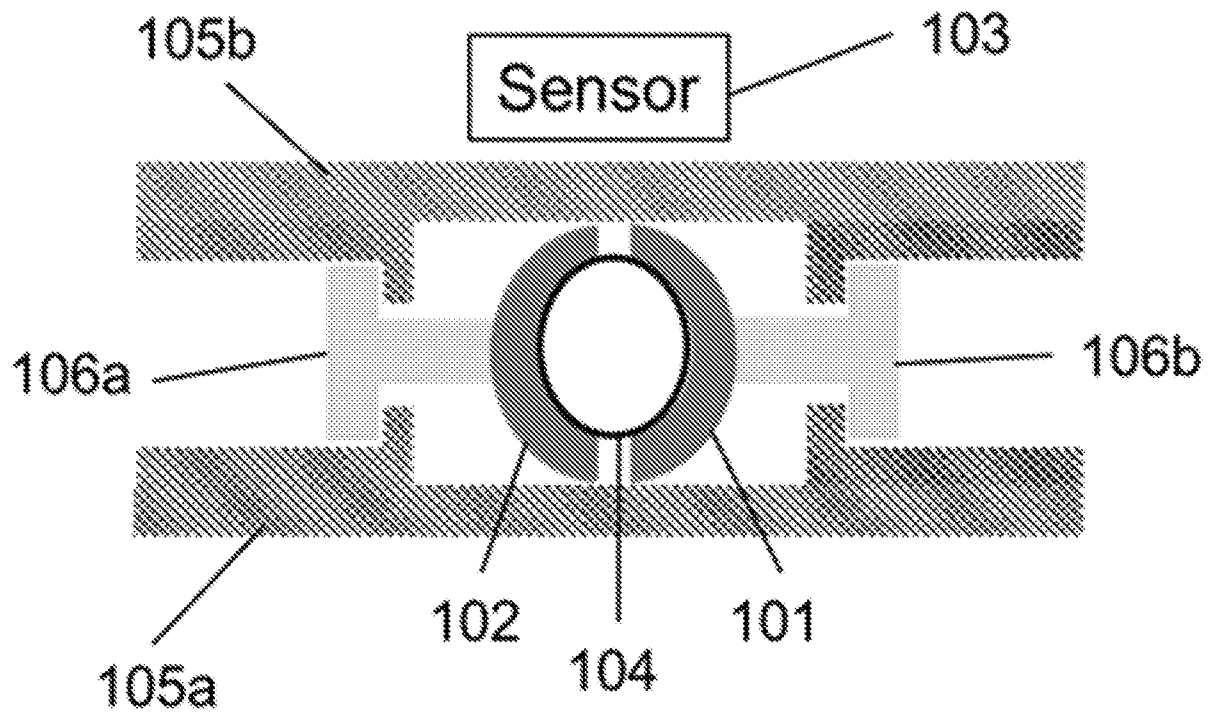


Figure 7

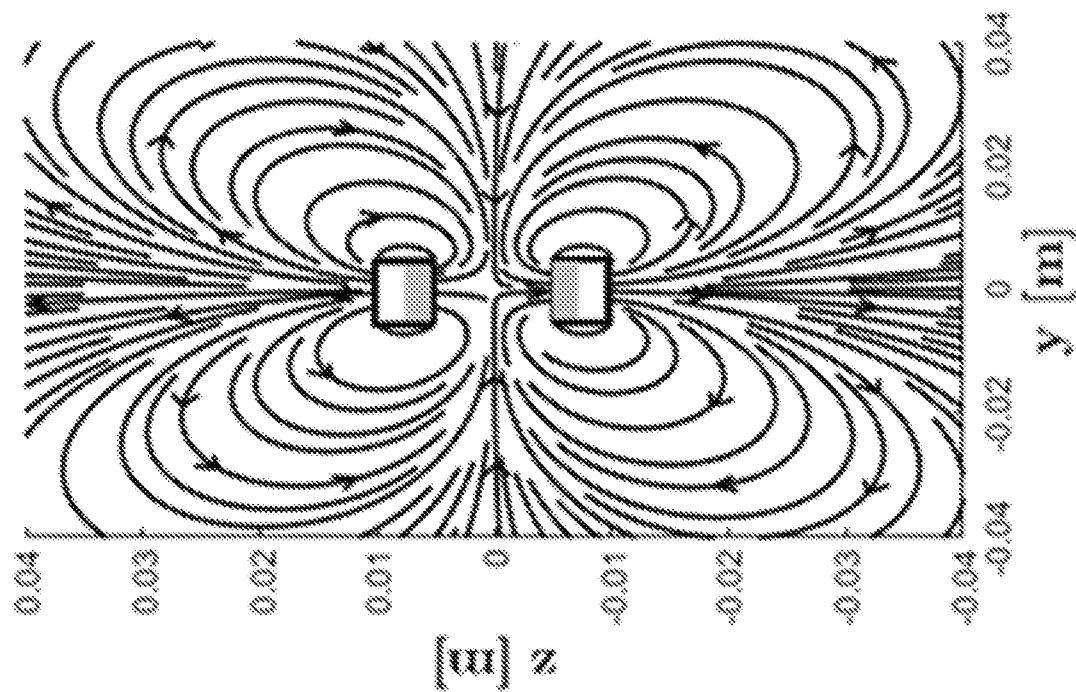


Figure 8b

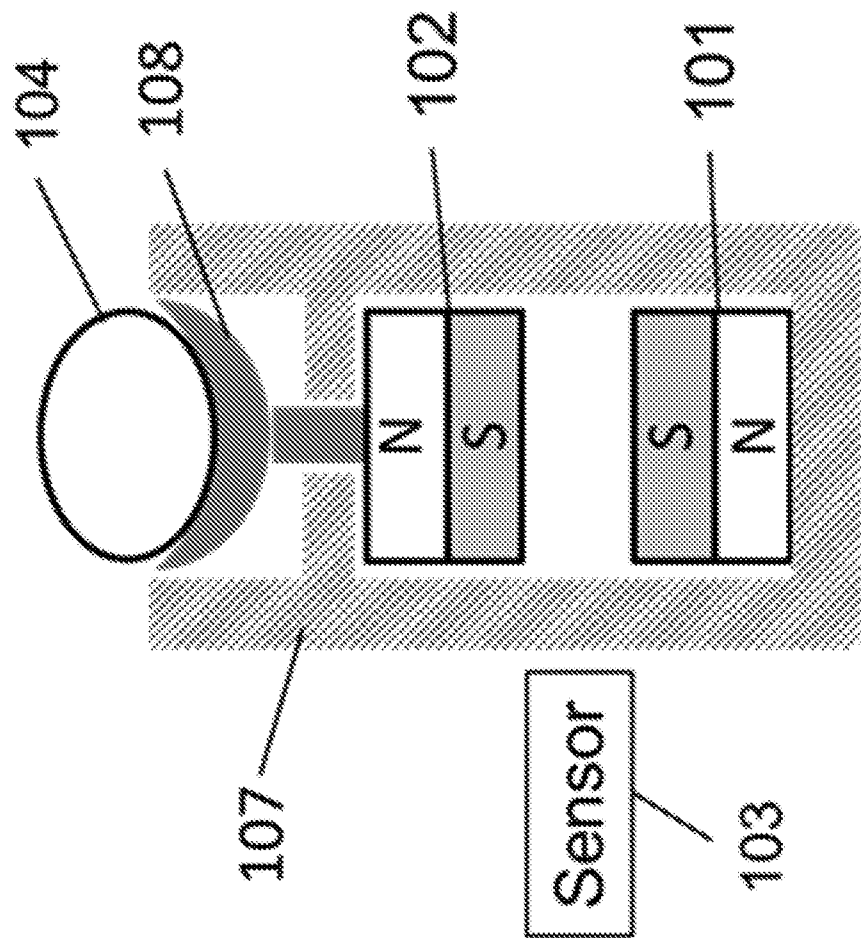


Figure 8a

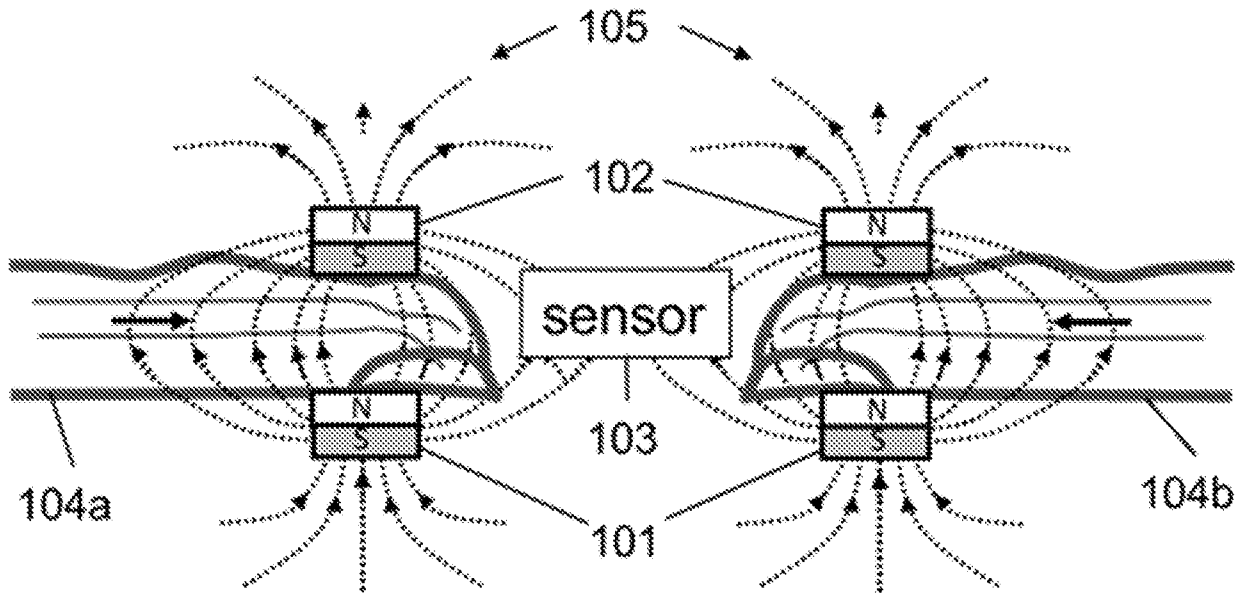


Figure 9

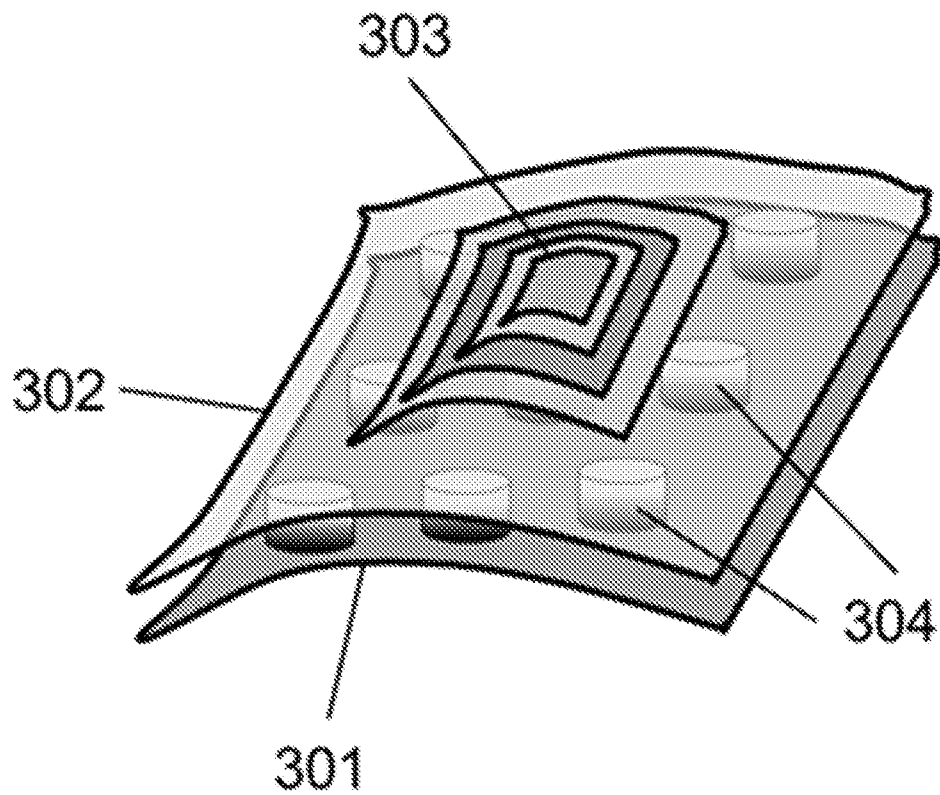


Figure 10

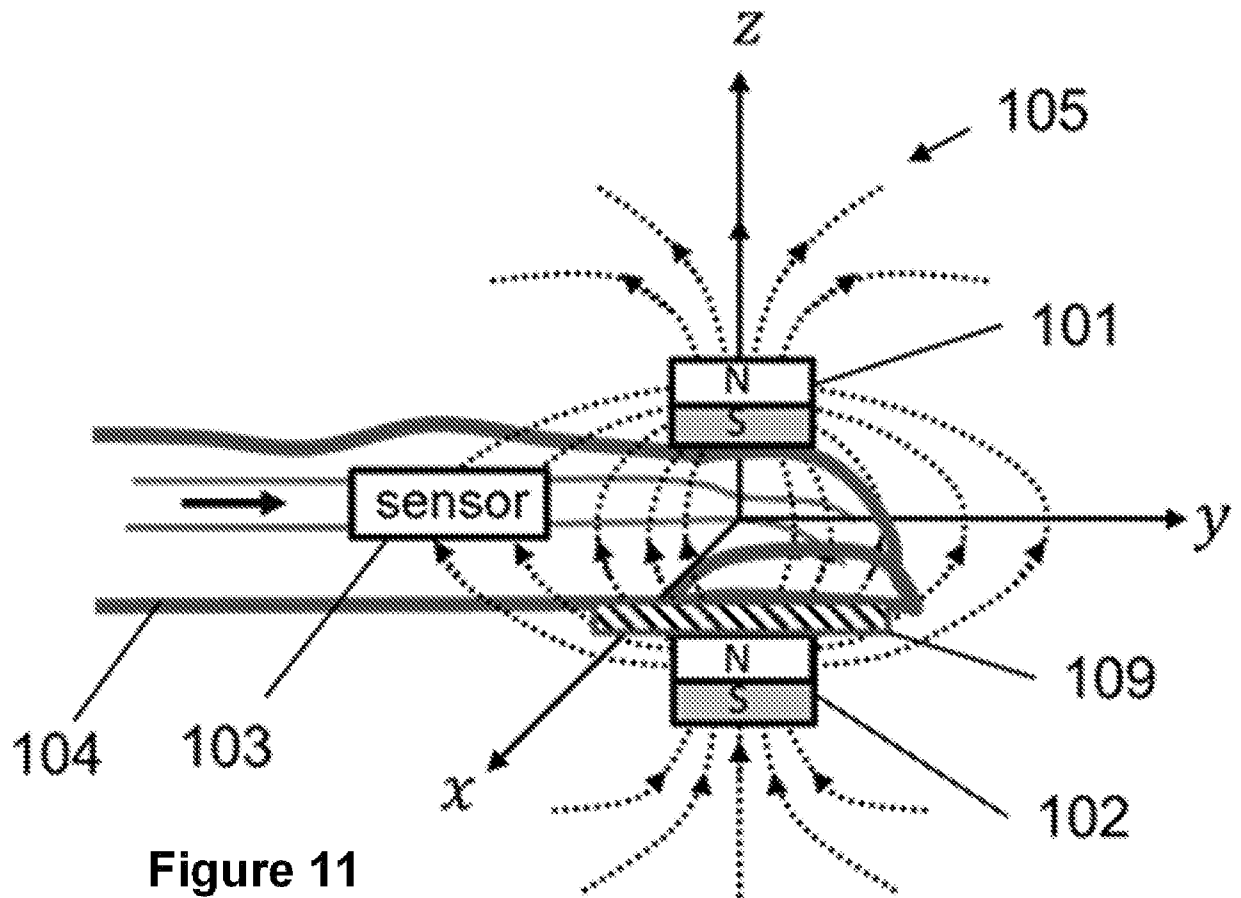


Figure 11

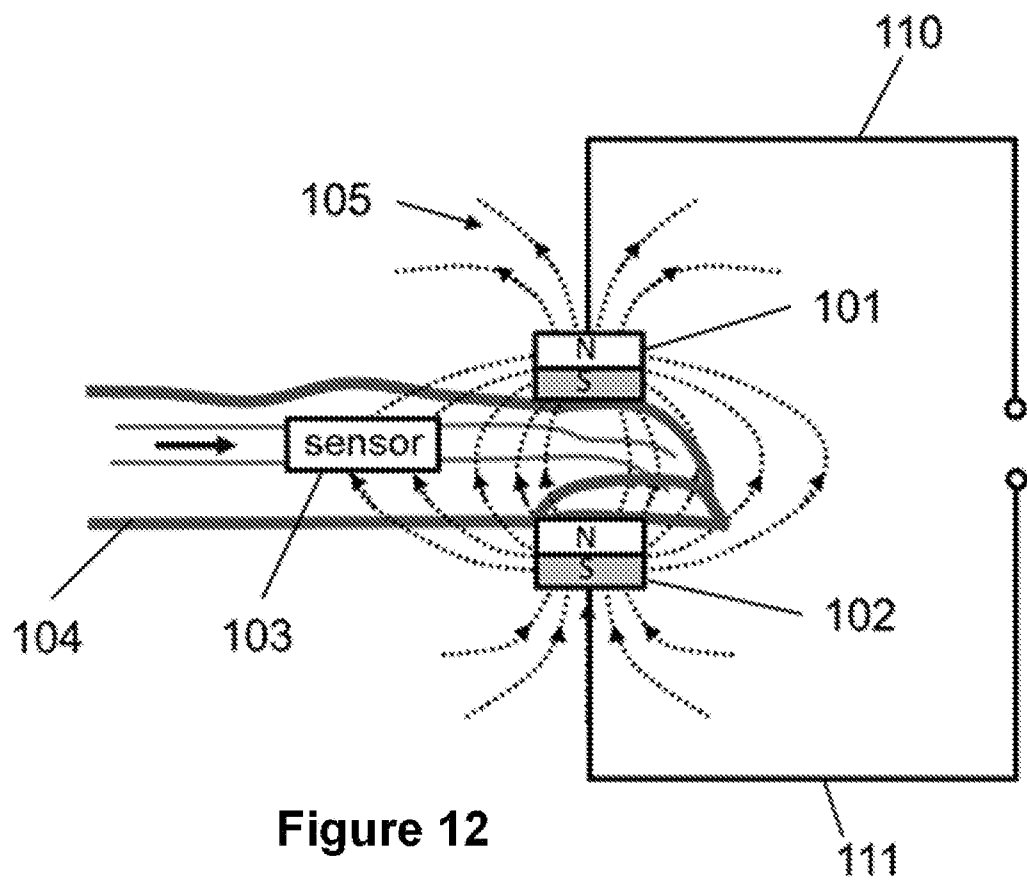
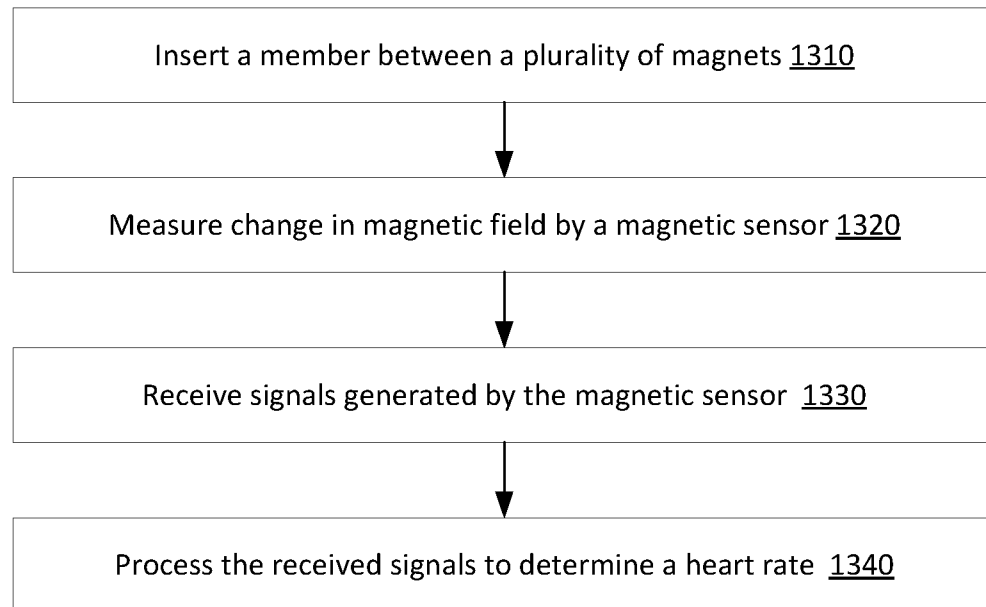
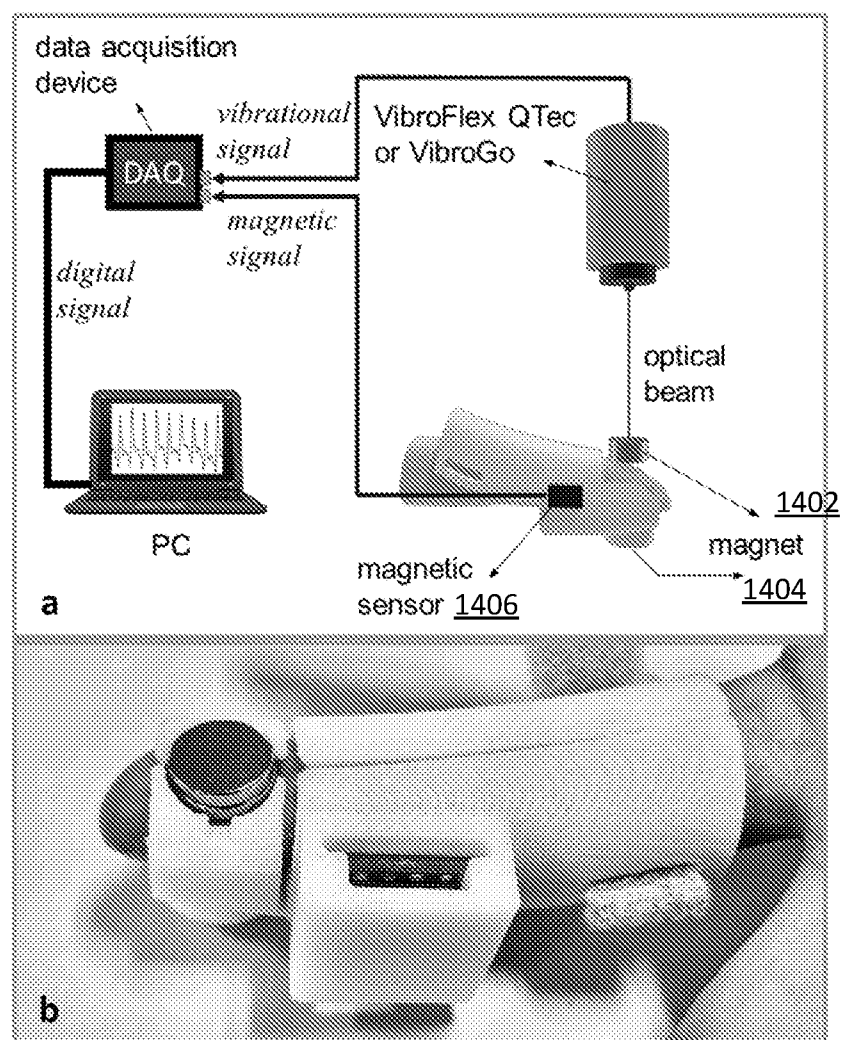


Figure 12

**Figure 13****Figure 14**

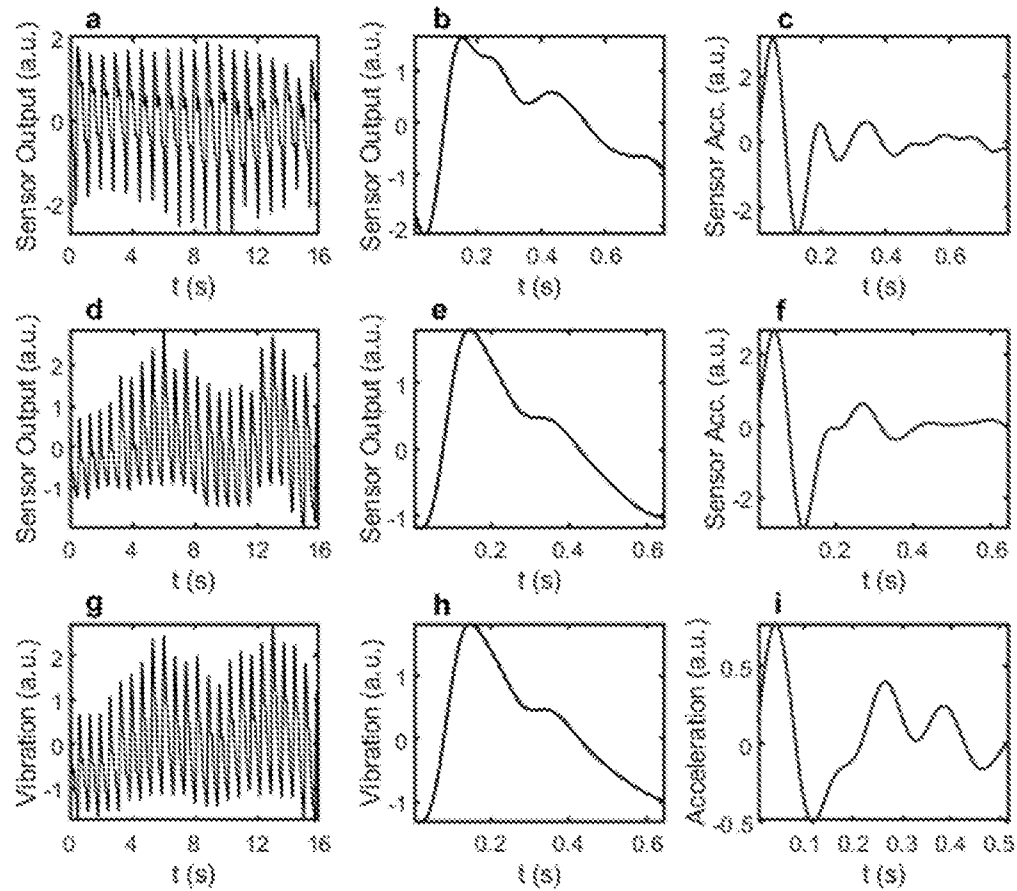


Figure 15

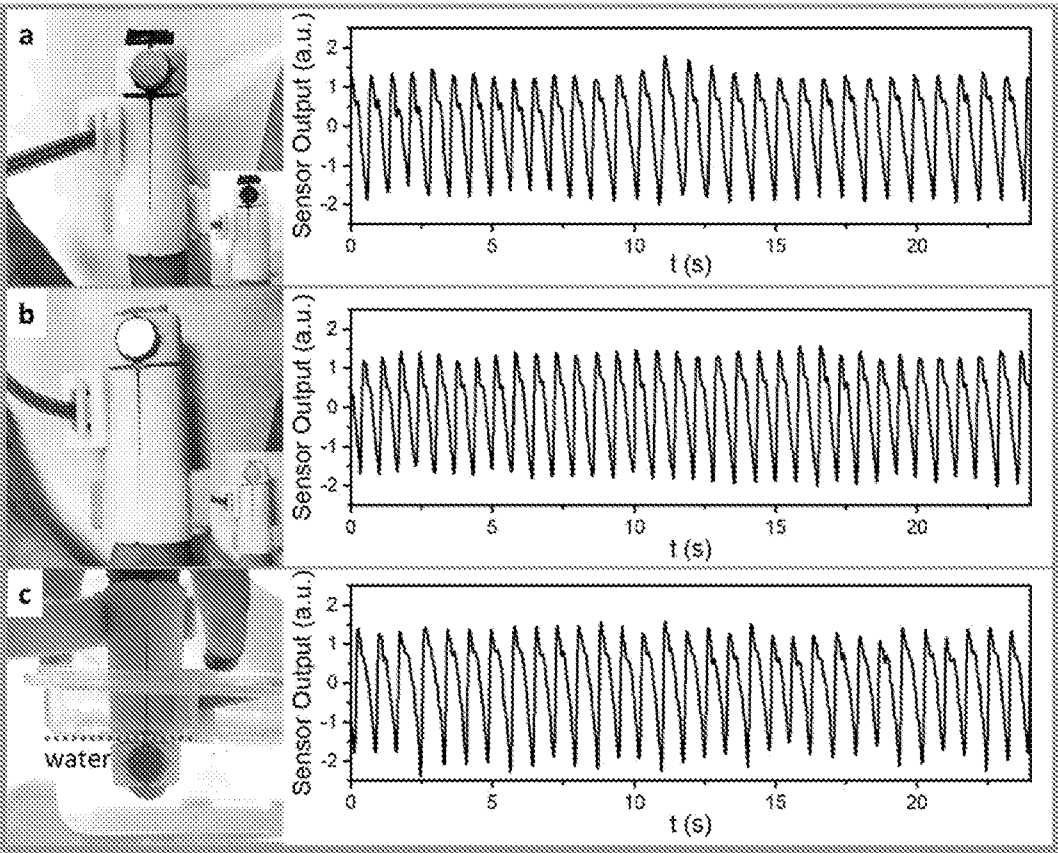


Figure 16

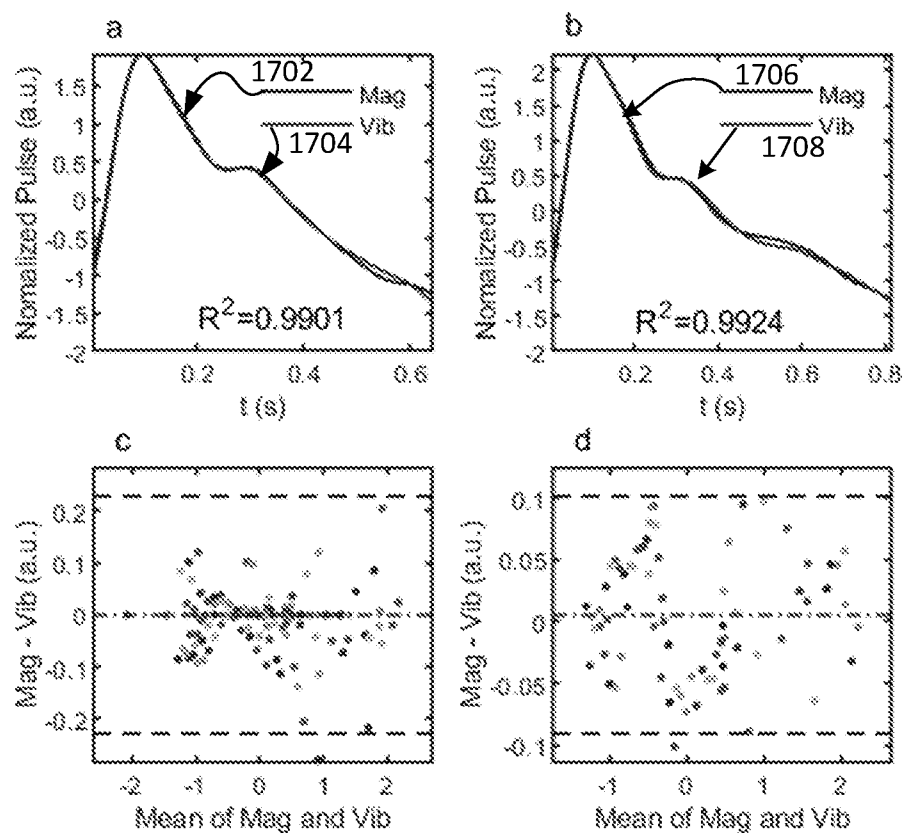


Figure 17

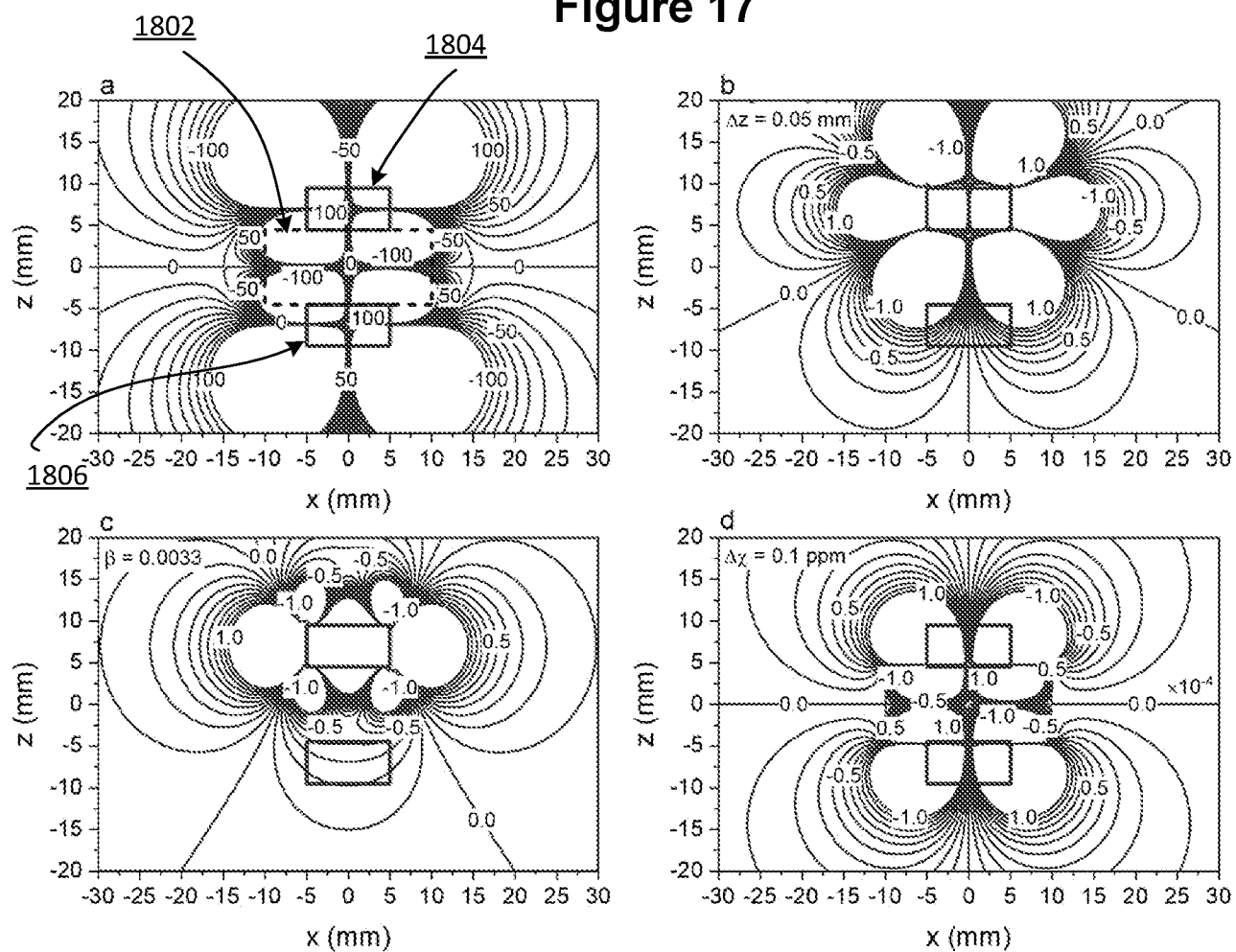


Figure 18

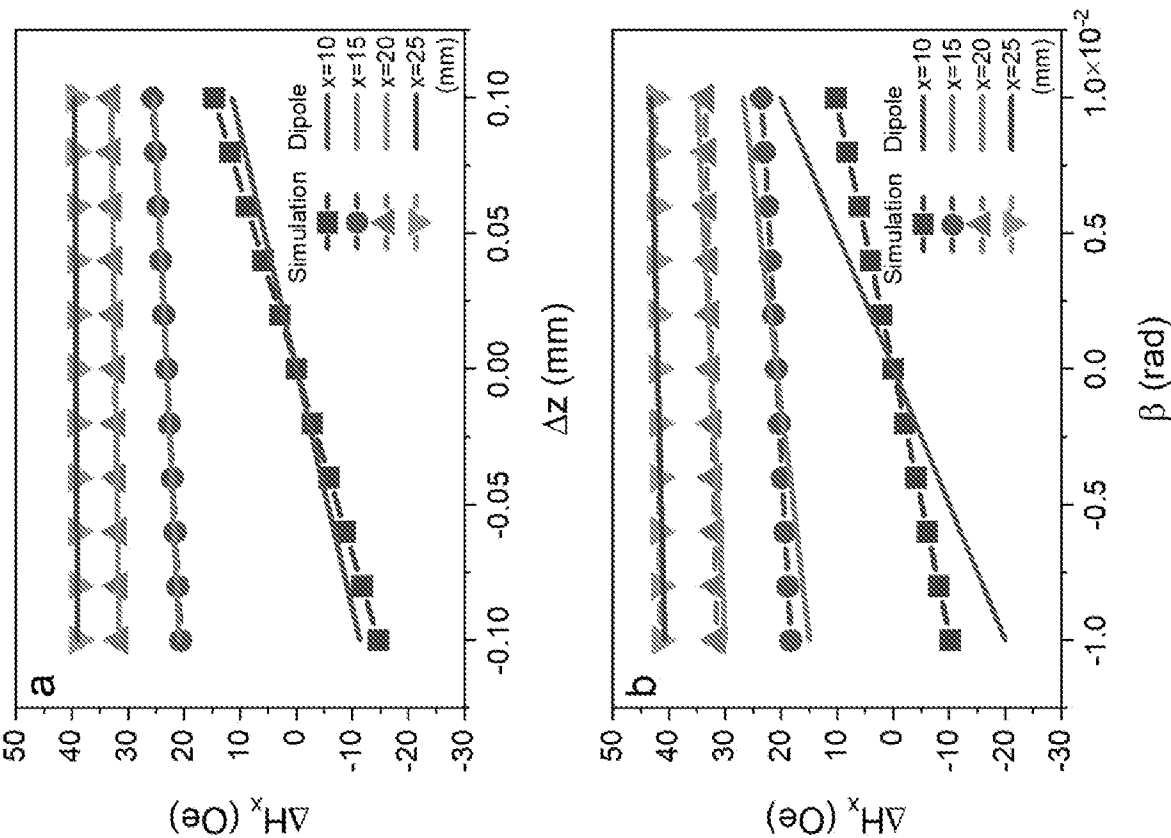


Figure 19

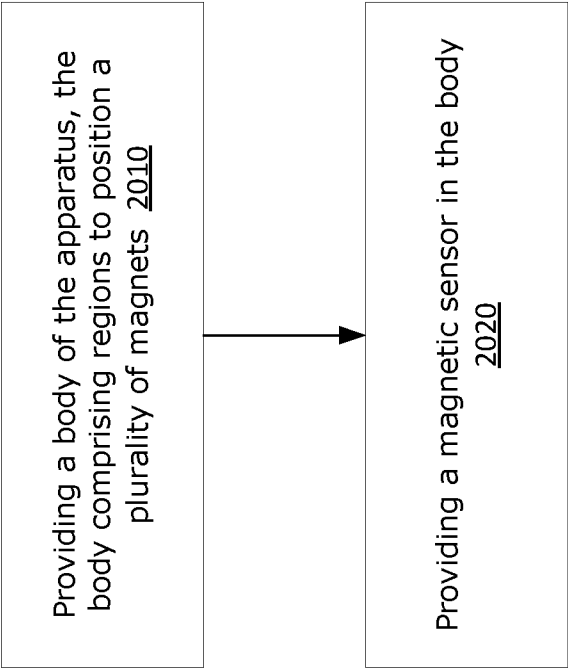


Figure 20