



US010165956B2

(12) **United States Patent**
Jacofsky et al.

(10) **Patent No.:** **US 10,165,956 B2**
(45) **Date of Patent:** **Jan. 1, 2019**

(54) **COMPARTMENT SYNDROME
MONITORING SYSTEMS AND METHODS**

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(*) Notice: Subject to any disclaimer, the term of this
patent is extended or adjusted under 35
U.S.C. 154(b) by 308 days.

(21) Appl. No.: **15/130,625**

(22) Filed: **Apr. 15, 2016**

(65) **Prior Publication Data**

US 2016/0331253 A1 Nov. 17, 2016

Related U.S. Application Data

(63) Continuation of application No. 12/832,767, filed on
Jul. 8, 2010, now Pat. No. 9,314,175.

(51) **Int. Cl.**
A61B 5/00 (2006.01)
A61B 5/03 (2006.01)
A61B 5/07 (2006.01)

(52) **U.S. Cl.**
CPC **A61B 5/036** (2013.01); **A61B 5/0031**
(2013.01); **A61B 5/03** (2013.01); **A61B 5/076**
(2013.01);

(Continued)

(58) **Field of Classification Search**
CPC A61B 5/03; A61B 5/031; A61B 5/033;
A61B 5/036–5/038

See application file for complete search history.

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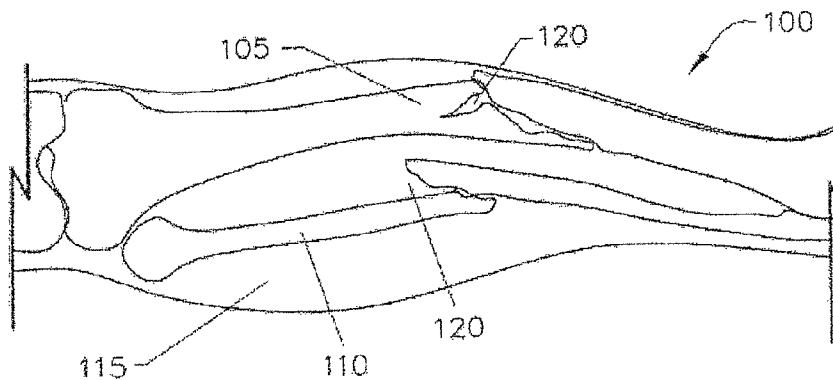
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(57) **ABSTRACT**

Embodiments of a compartment monitor that can be
implanted and left in situ to continuously (or semi-contin-
uously) measure compartment pressures are presented. An
exemplary monitor includes a pressure sensor adapted to be
implanted in a compartment, a transmitter external to the
compartment and coupled to the pressure sensor, and a
receiver in communication with the transmitter to receive
and process pressure data received from the transmitter. The
monitor may also be configured to transmit measured pres-
sure data to a networkable device. The networkable device
can then communicate the patient's status and condition to
a healthcare provider through a local area network (LAN) or
wide area network (WAN). This communication allows the
healthcare provider to remotely monitor a patient. The
networkable device, or associated computing system, can
record and display trends in the pressure data over time, and
log the data to the patient's electronic health records.

20 Claims, 17 Drawing Sheets



(52) U.S. Cl.

CPC *A61B 5/4519* (2013.01); *A61B 5/6828*
 (2013.01); *A61B 5/6833* (2013.01); *A61B*
5/6853 (2013.01); *A61B 5/7275* (2013.01);
A61B 5/7282 (2013.01); *A61B 5/746*
 (2013.01); *A61B 2562/0247* (2013.01); *A61B*
2562/168 (2013.01)

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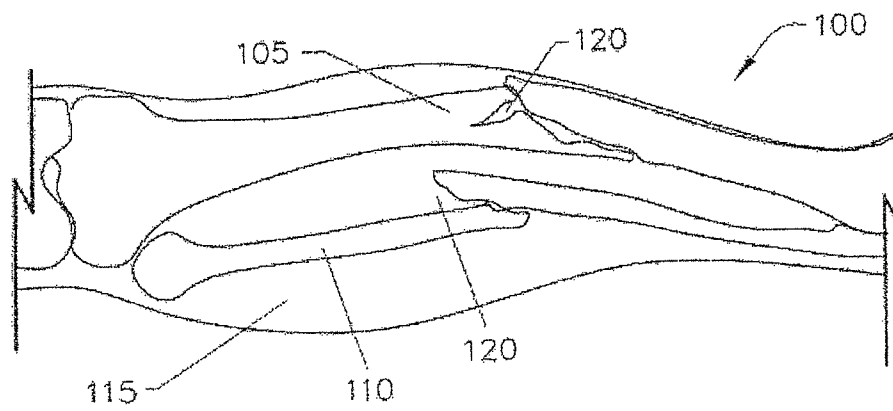


FIG. 1

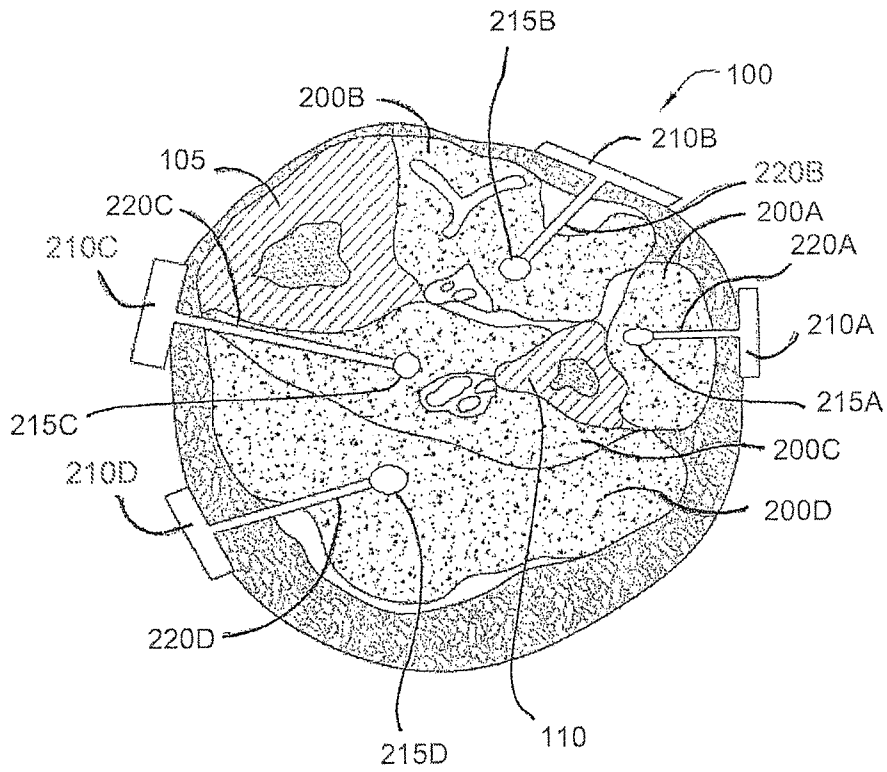


FIG. 2

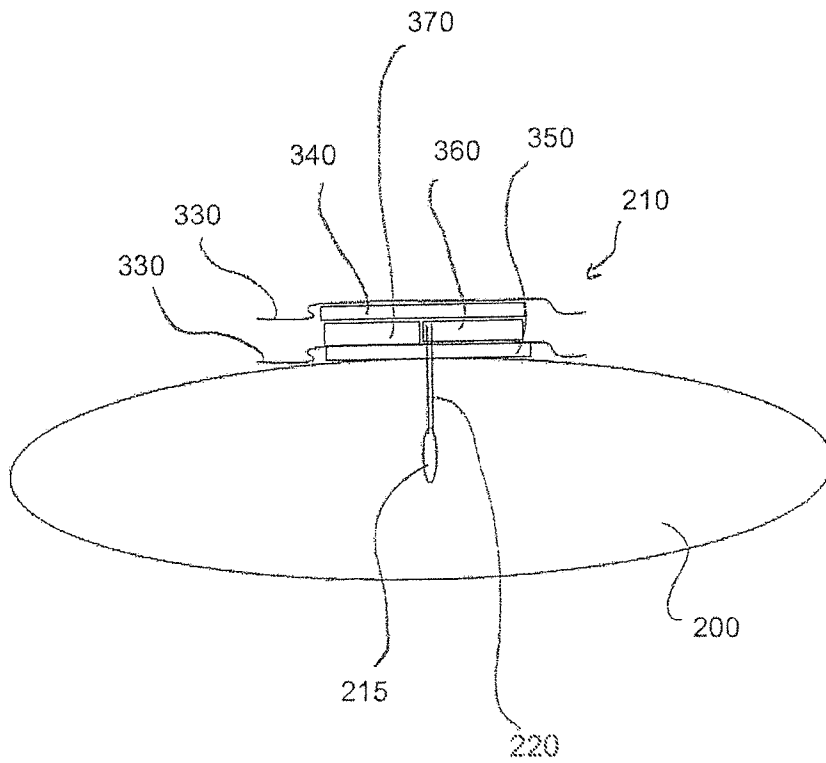


FIG. 3

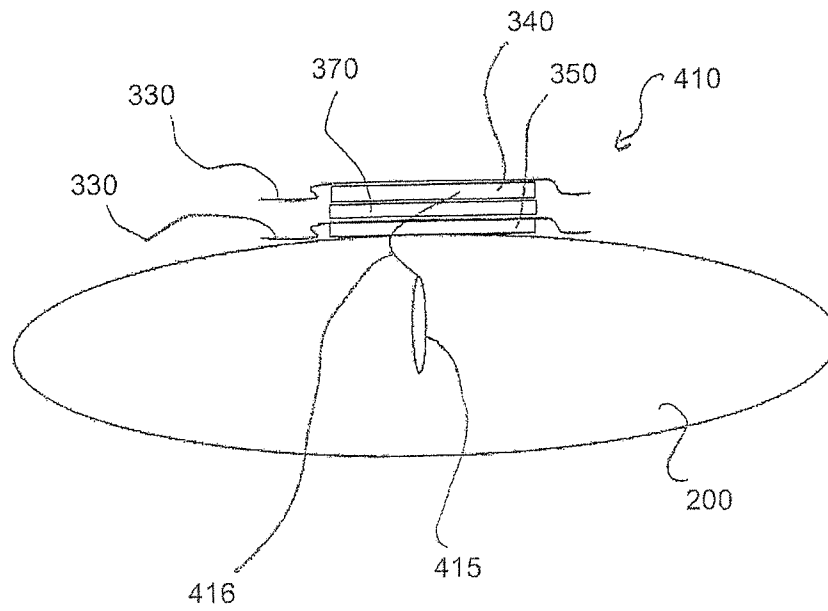


FIG. 4

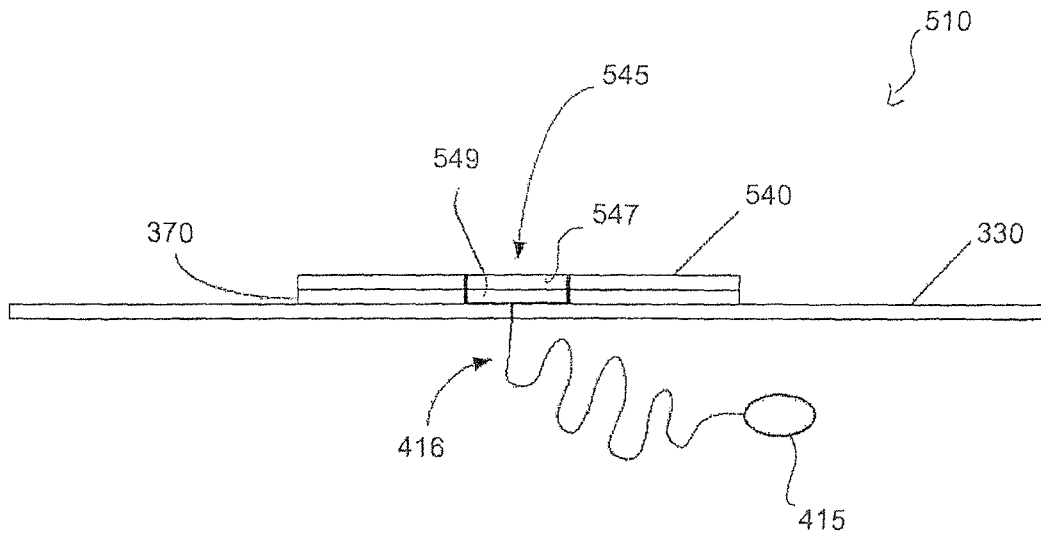


FIG. 5

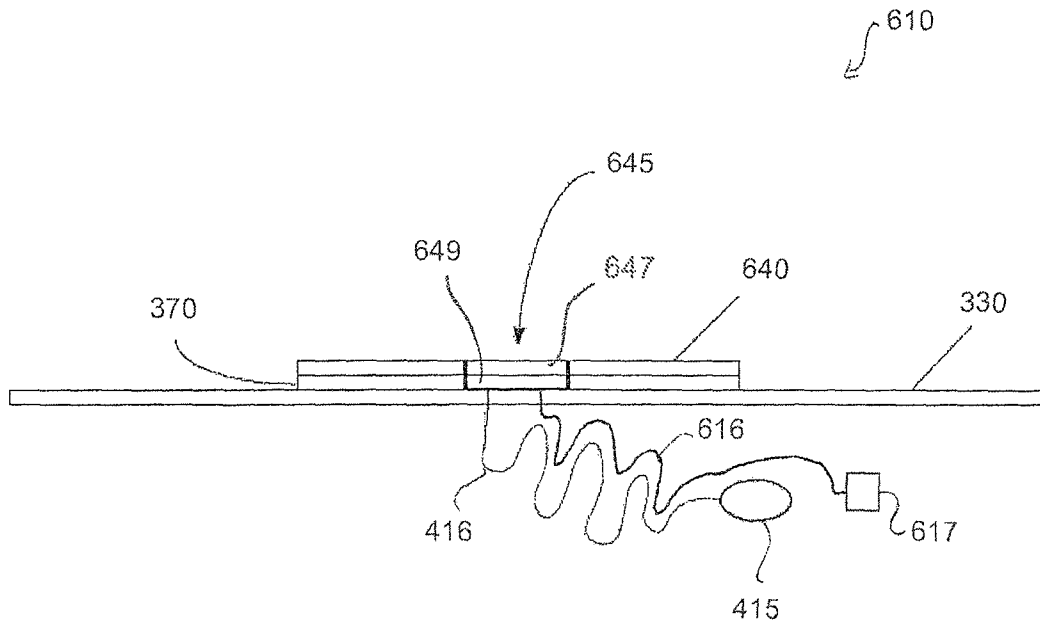


FIG. 6

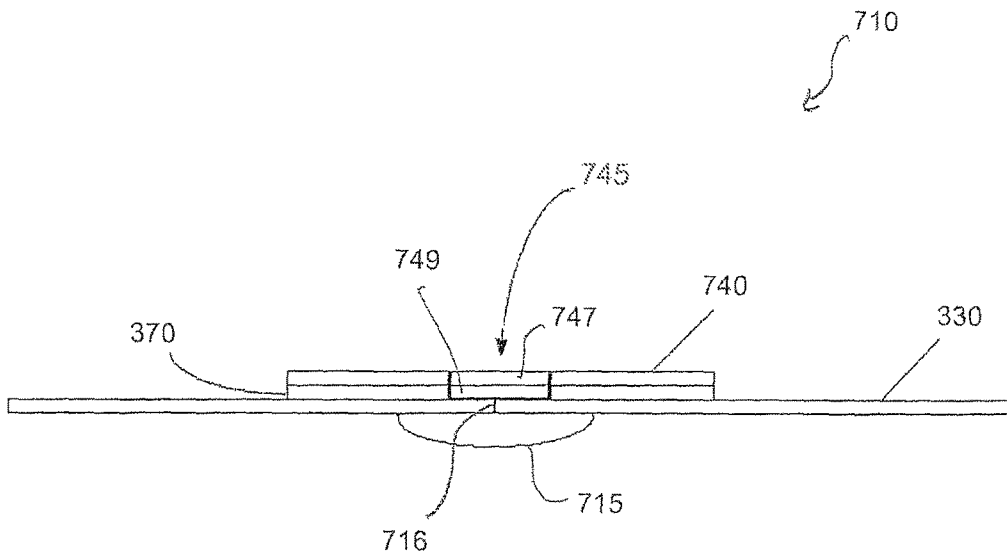


FIG. 7

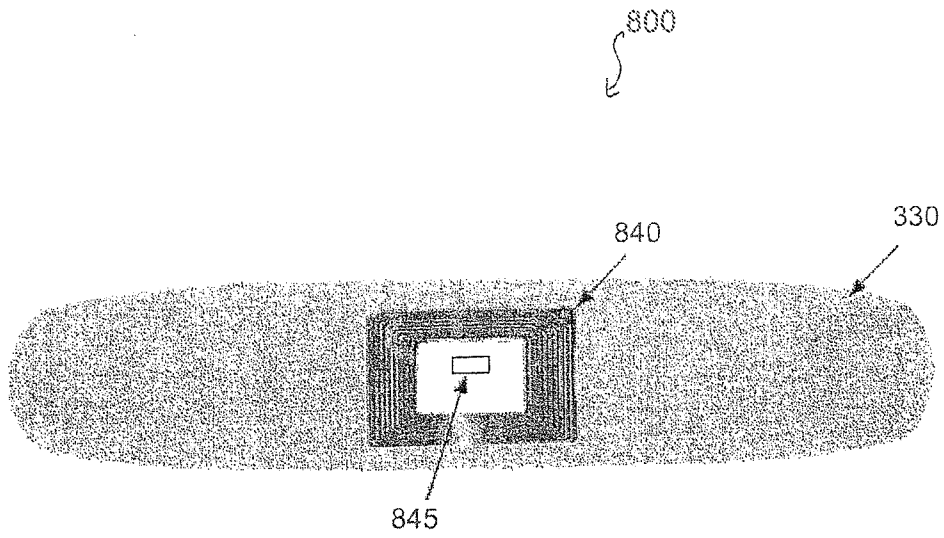


FIG. 8

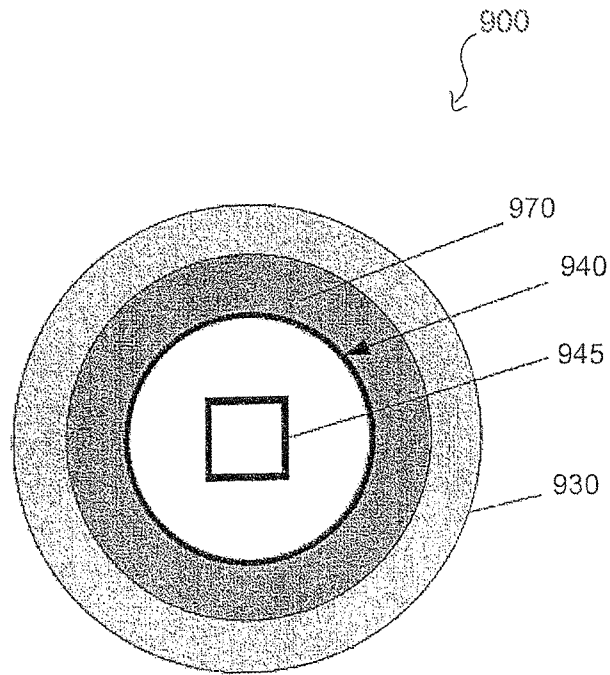


FIG. 9

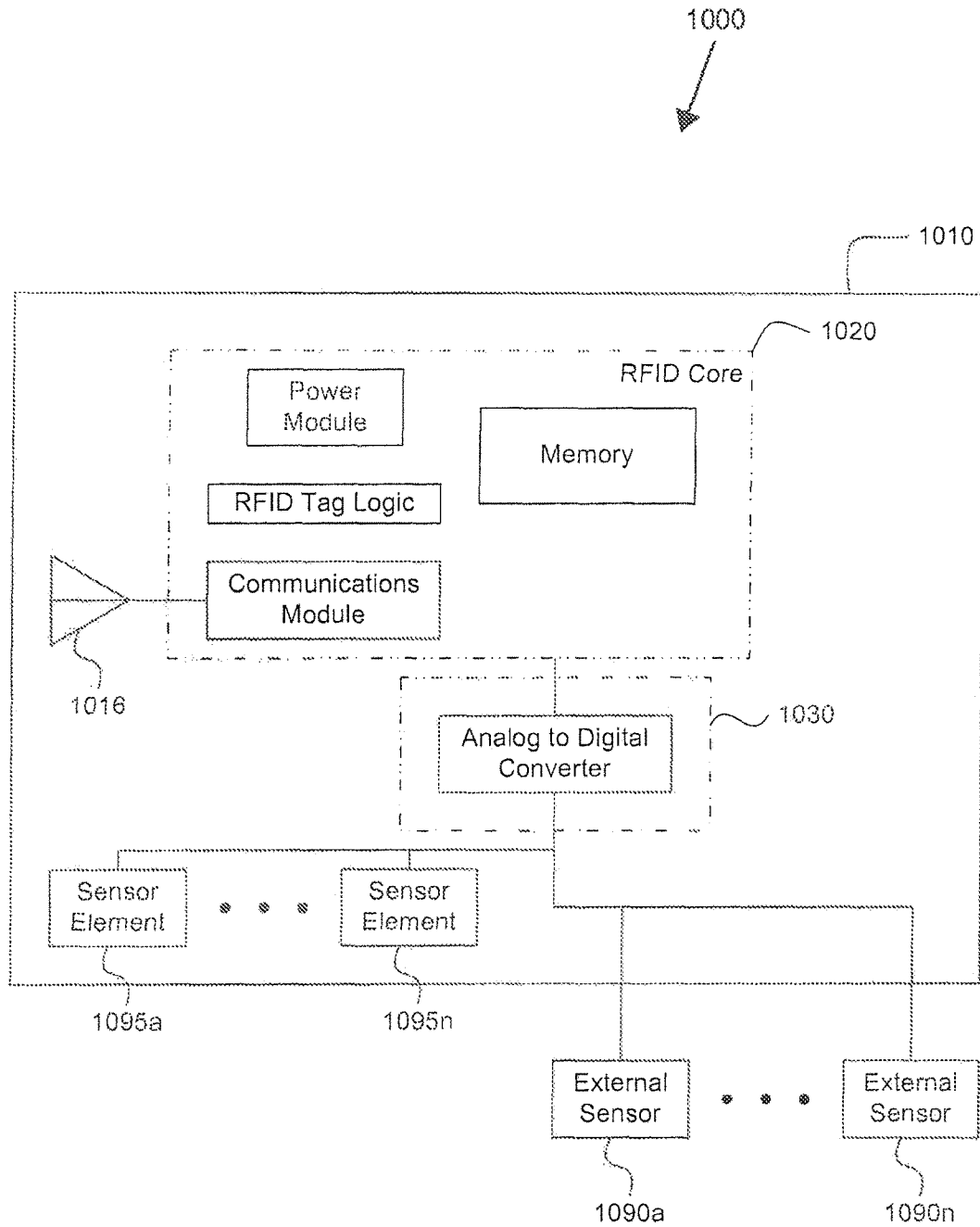


FIG. 10

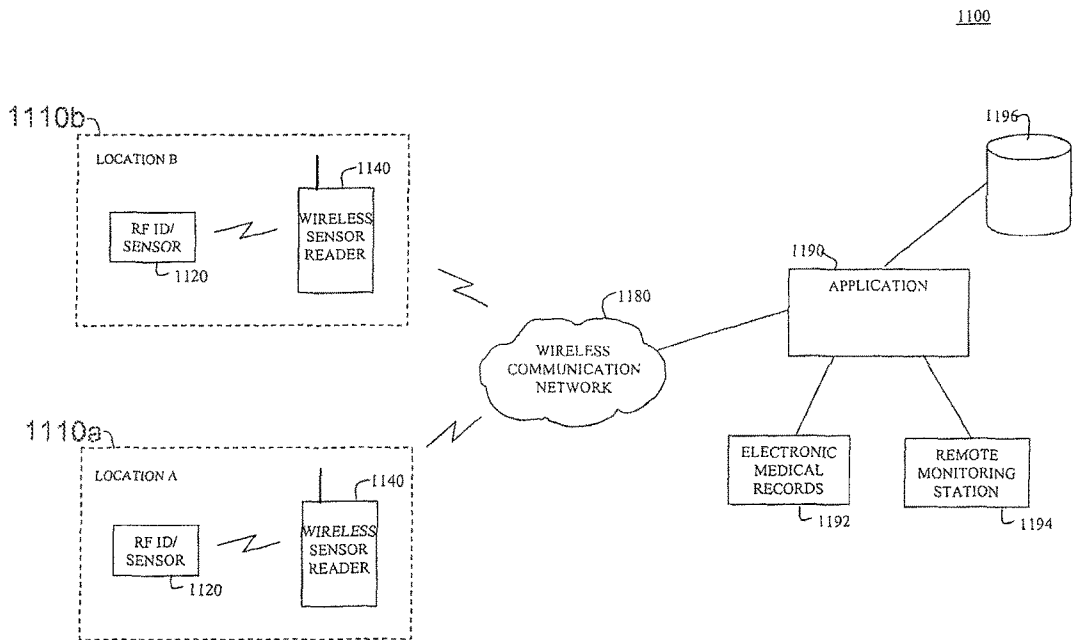


FIG. 11

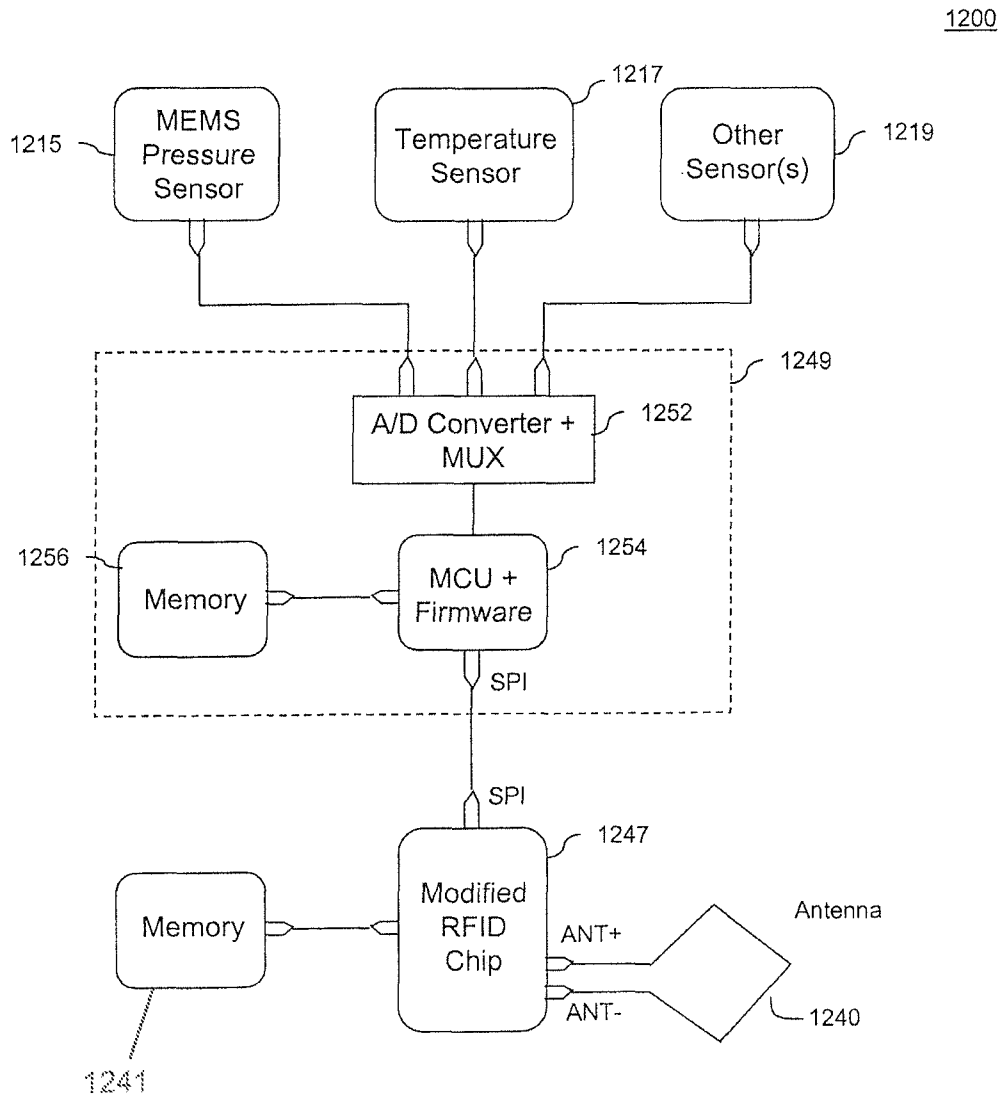


FIG. 12

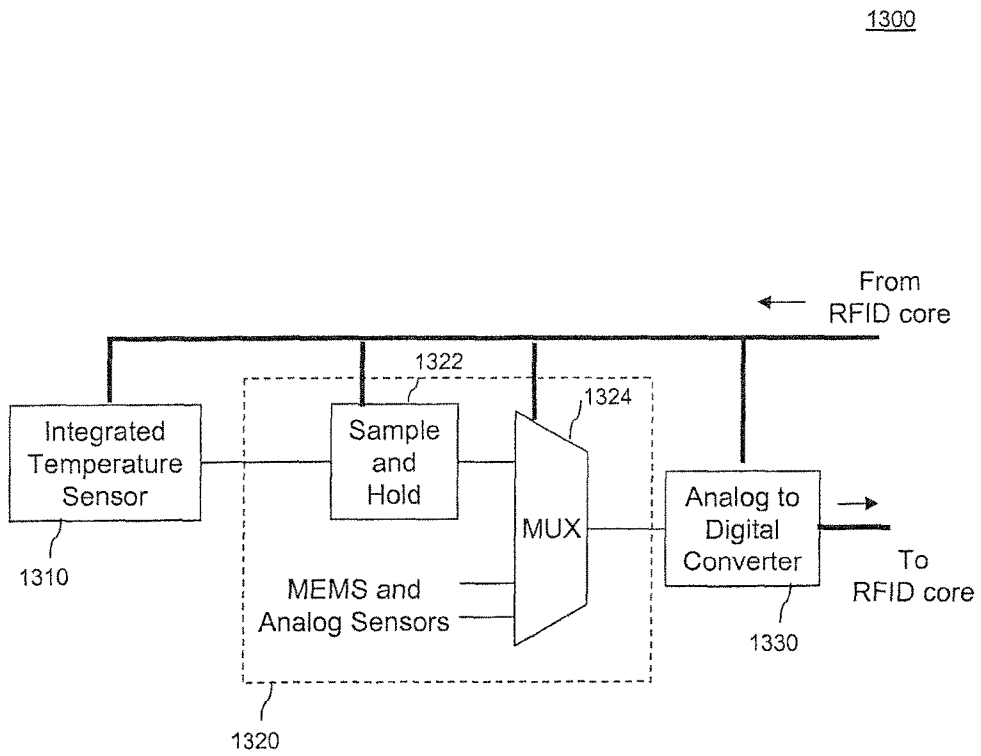


FIG. 13

1400

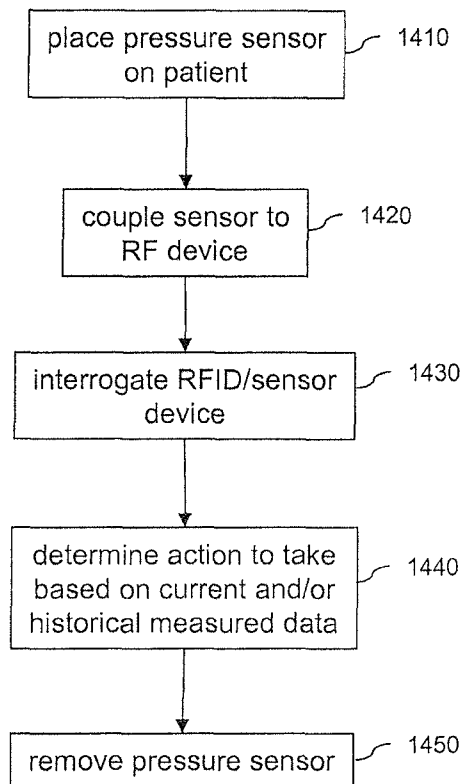


FIG. 14

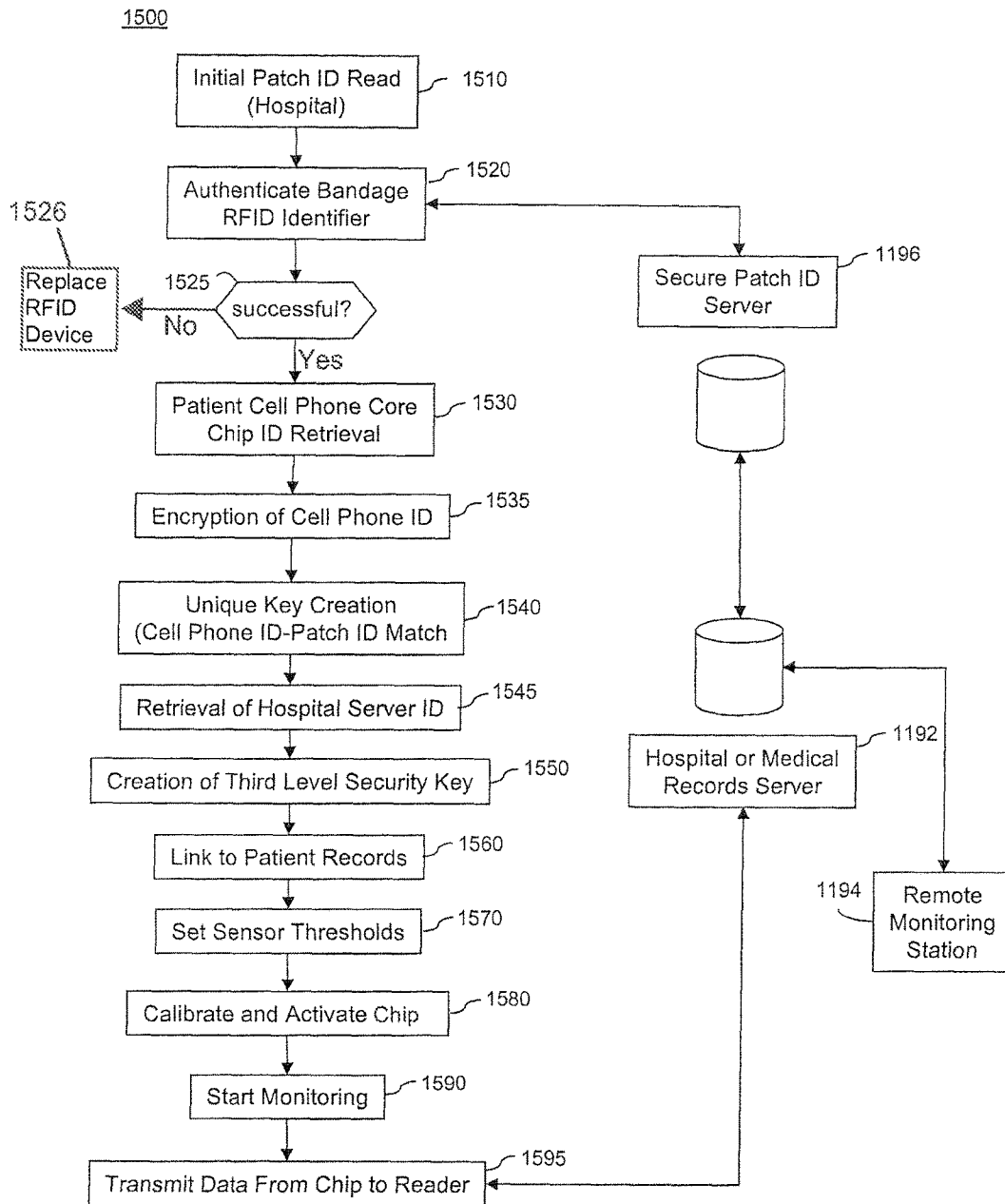


FIG. 15

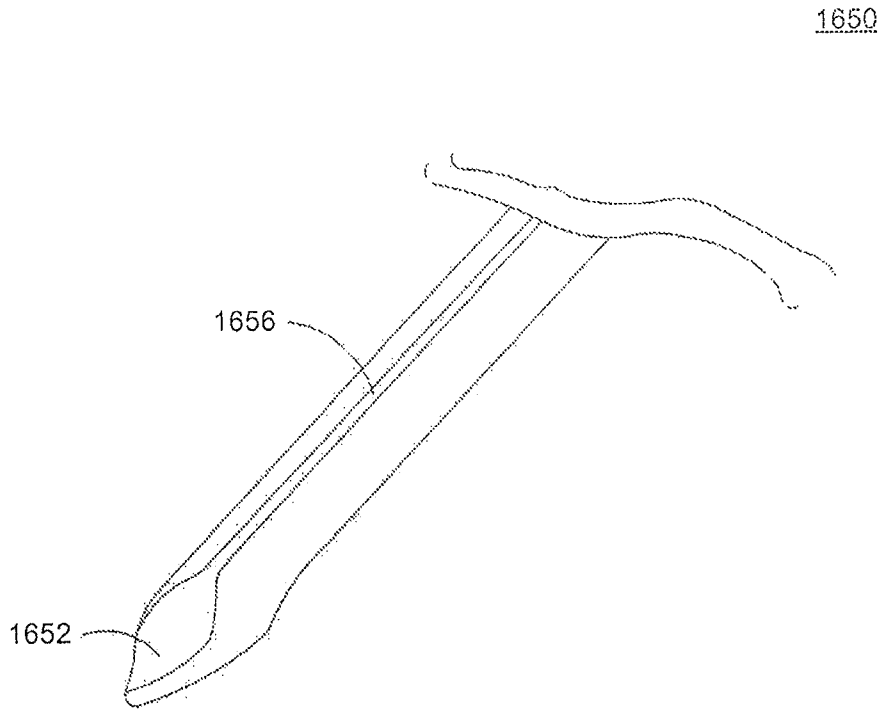


FIG. 16

1710

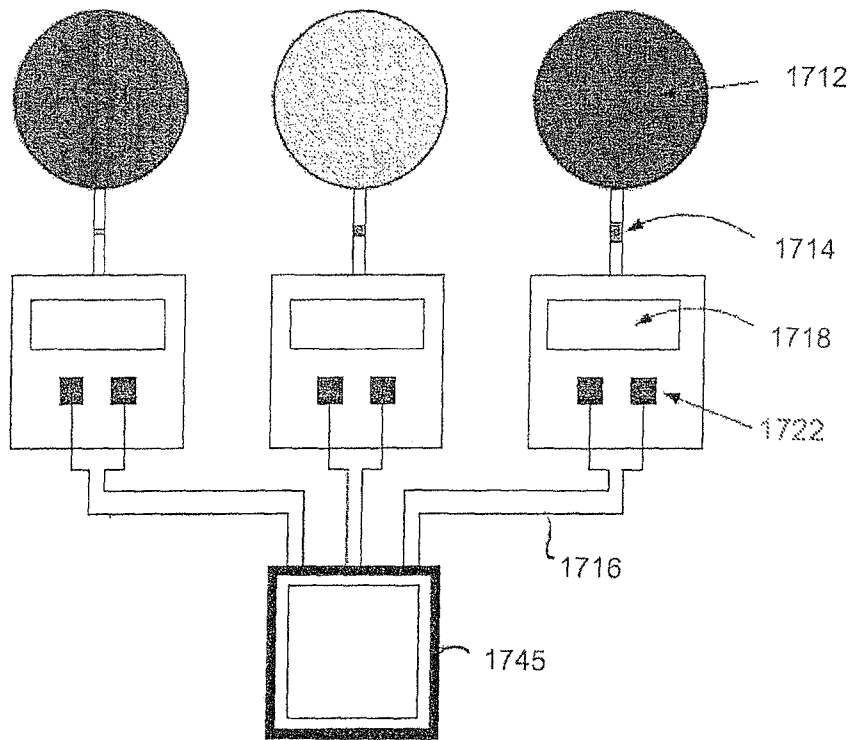


FIG. 17

COMPARTMENT SYNDROME MONITORING SYSTEMS AND METHODS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. application Ser. No. 12/832,767, which has a filing date of Jul. 8, 2010, the disclosure of which is hereby incorporated by reference in its entirety.

FIELD

The present invention is related to systems and methods for diagnosing compartment syndrome. More specifically, the present invention is related to a partially implantable wireless compartment syndrome monitor.

BACKGROUND

Compartment syndrome is a medical condition where the pressure inside a compartment (i.e., muscle group surrounded by inelastic fascia) rises higher than the pressure in the capillaries of the tissue. Compartment syndrome leads to limited or lost circulation to the region. Compartment syndrome usually occurs after a trauma or injury to the tissues contained within the compartment. Because the fascia does not expand, bleeding or swelling that results from the trauma or injury causes increased pressure within the compartment. Venous pathways in the compartment are then restricted from draining blood and fluid from the injured area, and the pressure within the compartment continues to rise. Continued pressure increases further restrict circulation and eventually lead to the death of the affected tissue (i.e., necrosis). Necrosis will often lead to the loss of limb, and possibly loss of life in severe cases. The most common site for compartment syndrome occurs in the lower leg; specifically, in regions adjacent to the tibia and fibula.

There are four compartments in the lower human leg: the anterior (front), lateral (side next to the fibula), deep posterior (back), and the superficial posterior (back). Any one of these four compartments can yield a compartment syndrome when bleeding or swelling occurs within the compartment. Compartment syndrome can also result from a cast that is too tight, constrictive dressings, pneumatic anti-shock garments, and closure of fascial defects. The clinical conditions that may be associated with compartment syndrome include the management of fractures, soft tissue injuries, arterial injuries, drug overdoses, limb compression situations, burns, post-ischemic swelling, constrictive dressings, aggressive fluid resuscitation, and tight casts.

FIG. 1 illustrates a human leg **100** with fractured bones of the tibia **105** and fibula **110**, which can lead to one or more compartment syndromes in the muscles **115** surrounding the bones. The tibia **105** and fibula **110** usually bleed in regions proximate to the physical break regions **120**. This bleeding can form a large pool of stagnant blood (i.e., a hematoma). The hematoma can start pressing upon muscles **115**, which may be proximate to physical break regions **120**. The pressure caused by the hematoma can restrict or stop blood flow into the muscles **115** of a compartment, which leads to compartment syndrome. Normal compartment pressures are under 20 mm Hg. Concern is raised when pressures rise above 20 to 30 mm Hg, and critical intervention is often required above 30 mm Hg.

Traditional methods for diagnosing compartment syndrome include highly invasive and challenging direct pres-

sure-measurement procedures. A needle or trocar is used to access the compartment to conduct an intra-compartmental pressure measurement. Currently, such intra-compartmental pressure measurements are the only objective and reliable diagnostic tool. The diagnosis and treatment of compartment syndrome, however, can cause significant morbidity and increase the risk for infection. Therefore, inaccurate and elevated pressure readings are a very difficult and potentially dangerous pitfall.

Current needle-based pressure measuring methods are also undesirable because they only provide a snap-shot of data at an instant of time. In other words, the needle-based pressure measuring method only provides the medical practitioner with one data point for a particular time. Once pressure is read by the medical practitioner, he or she usually removes the needle from the patient. The data obtained from a single measurement in time gives no information concerning the pressure trend, and the direction the intra-compartmental pressure is moving. The collection of single data points over long periods of time is usually not very helpful because pressures within a compartment, as well as the patient's blood pressure, can change abruptly (e.g., within minutes). Further, the pain associated with the needle-based pressure measuring method restricts the medical practitioner from taking a pressure reading within a few minutes of a previous reading.

The diagnosis of compartment syndrome before the situation becomes critical is difficult, and a missed diagnosis or false positive diagnosis can have significant consequences for the patient. Treatment of compartment syndrome typically requires a fasciotomy, which is invasive, painful, complicated, and increases risk of infection and morbidity. Therefore, it is desirable to monitor the pressure in the compartment to properly and continuously assess when surgical intervention becomes absolutely necessary.

Furthermore, these traditional methods require the patient to remain in the treatment facility if continuous monitoring of compartment pressure is required. This increases the cost of treatment for the facility and the cost and inconvenience to the patient. Therefore, methods for accurately monitoring and tracking compartment pressure remotely, for example at a patient's home, are desirable.

For more information on compartment syndrome, and diagnostic and treatment methods, reference is made to the following U.S. patent and U.S. published applications, all of which are incorporated herein by reference in their entirety: U.S. Pat. Nos. 4,711,248; 4,817,629; 4,858,620; 6,942,634; and 2008/0208011. Further, reference is made to the following U.S. patents and/or publications, all of which are incorporated herein by reference in their entirety, and the subject matter of which may be related to the present invention: U.S. Pat. Nos. 6,980,852; 7,148,803; 7,256,708; 7,461,972; and 2006/0290496.

BRIEF DESCRIPTION OF THE FIGURES

The accompanying drawings, which are incorporated herein, form part of the specification and illustrate embodiments of compartment syndrome monitoring and diagnostic systems, sensors, and methods. Together with the description, the drawings further serve to explain the principles of, and to enable a person skilled in the relevant art(s) to make and use, the systems and methods described herein. In the drawings, like reference numbers indicate identical or functionally similar elements.

FIG. 1 illustrates a human leg with fractured bones of the tibia and fibula.

FIG. 2 illustrates a cross-sectional view of a human leg, illustrating the four major compartments, and schematically depicting four compartment monitors, according to one embodiment presented herein.

FIG. 3 is a schematic view of a compartment monitor in accordance with one embodiment presented herein.

FIG. 4 is a schematic view of a compartment monitor in accordance with an alternative embodiment presented herein.

FIG. 5 is a schematic view of a compartment monitor in accordance with an alternative embodiment presented herein.

FIG. 6 is a schematic view of a compartment monitor in accordance with an alternative embodiment presented herein.

FIG. 7 is a schematic view of a compartment monitor in accordance with an alternative embodiment presented herein.

FIG. 8 is a top view of a bandage incorporating a compartment monitor, in accordance with an one embodiment presented herein.

FIG. 9 is a top view of an alternate embodiment of a bandage incorporating a compartment monitor in accordance with an alternative embodiment presented herein.

FIG. 10 is a system for monitoring compartment pressure, according to an embodiment of the present invention.

FIG. 11 is a block diagram of an illustrative network 1100 for remotely monitoring one or more orthopedic sensors integrated with RFID devices, according to an embodiment of the present invention.

FIG. 12 depicts an exemplary system having a modified RFID chip, according to embodiments of the present invention.

FIG. 13 is a block diagram illustrating a portion of an RFID device in accordance with an embodiment presented herein.

FIG. 14 is a flowchart illustrating a method of monitoring compartment pressure, according to embodiments of the present invention.

FIG. 15 is a flowchart showing a method for linking identifiers to create transparent and secure wireless monitoring of compartment syndrome in a patient, according to embodiments of the present invention.

FIG. 16 is an exemplary embodiment of a needle used in accordance with an embodiment of the present invention.

FIG. 17 is a schematic view of an opto-electronic compartment monitor in accordance with an alternative embodiment presented herein.

DETAILED DESCRIPTION

The following detailed description of compartment syndrome monitoring and diagnostic systems, sensors, and methods refers to the accompanying drawings that illustrate exemplary embodiments. Unless otherwise noted, all embodiments and examples should be considered prophetic examples. Other embodiments are possible. Modifications can be made to the embodiments described herein without departing from the spirit and scope of the present invention. Therefore, the following detailed description is not meant to be limiting. Further, it would be apparent to one of skill in the art that the systems and methods described below can be implemented in many different embodiments of hardware, software, and/or firmware. Any actual hardware, software, and/or firmware described are not meant to be limiting.

Presented herein are embodiments of a compartment monitor that can be implanted and left in situ to continuously

(or semi-continuously) measure compartment pressures. These monitors can be used to measure compartment pressure for extended time periods, for example, over 24-48 hours. The monitors are also configured to transmit measured pressure data to a networkable device (e.g., a laptop computer, personal digital assistant (PDA), or cell phone) over a communication link such as a wireless link. The networkable device can then communicate the patient's status and condition to a healthcare provider (e.g., nurses, doctors, and other hospital personnel) through a local area network (LAN) or wide area network (WAN). This communication allows the healthcare provider to remotely monitor a patient. The networkable device, or associated computing system, can record and display trends in the pressure data over time, and log the data to the patient's electronic health records. The networkable device, or associated computing system, can also compare the pressure data to the patient's diastolic blood pressure, and calculate clinically important gradients in real time.

In addition to monitoring compartment pressure, the monitors presented herein can also be useful for monitoring intracranial pressure after closed head injury, brain infection, etc. or the pressure within any lumen or enclosed area of the body.

The compartment pressure monitors described herein include at least one pressure sensor. In one embodiment, the pressure sensor is tied directly to a device that includes a signal conditioner and a processor for direct read-out on the sensing device. In another embodiment the pressure sensor is integrated with a radio-frequency identification (RFID) device that has the capability of transmitting the measured pressure data to an interrogating device. The RFID device may be passive, pass-active (battery assisted), or fully active (battery dependent) depending upon the frequency of desired reads, the estimated distance of the interrogating device from the RFID device, and the power consumption needs of the RFID device. In alternative embodiments, the pressure sensor is integrated with Bluetooth® radio technology, ZigBee® radio technology, or other radios compatible with wireless devices such as cell phones.

In an embodiment, the pressure sensor of the compartment monitor resides outside the body, while being in fluid communication with a flexible bulb inside of the compartment. An example of this embodiment is depicted in FIG. 2. FIG. 2 illustrates a cross-sectional view of a human leg 100, illustrating the four major compartments 200A, 200B, 200C, and 200D, and schematically depicting four compartment monitors 210A, 210B, 210C, and 210D. As illustrated, compartment monitors 210A-D include a flexible, fluid-filled bulb 215A-D implanted into each compartment 200A-D. In this embodiment, the small flexible bulb 215A-D, sac, balloon, or a similar vessel is filled with an incompressible fluid and is connected to a thin tube 220A-D. The thin tube 220A-D is inelastic and is filled with an incompressible fluid. The thin tube 220A-D is in fluid communication with the pressure sensor, which resides outside the body and is preferably built into a skin patch that contains a radio-frequency (RF) device.

The bulb 215 may be manufactured from any flexible medical grade plastic or composite such as silicone, rubber, latex, nitrile, or similar material. The tube 220 may be composed of a similar but stiffer material (Polyethylene, TEFLON, DELRIN, etc.) which can be covered in a braided metal layer if necessary to increase resistance to deformation when the pressure changes, or to ensure the tube is strong enough to withstand tugging when the implant is removed. In one embodiment, the bulb-tube system is prepared as a

sealed unit that is assembled at the manufacturing facility; instead of at a hospital. Controlled manufacturing and preparation prevents air bubbles in the bulb-tube fluid communication system, and thus ensures accurate relaying of the pressure to the external pressure sensor.

The bulb **215**, and attached tube **220**, can be inserted into the muscle compartment such that the bulb **215** resides in the area of interest for pressure monitoring and the thin tube **220** exits the skin and attaches to the pressure sensor. A change in compartment pressure will increase pressure on the walls of the bulb and thereby force fluid out into the tube. As such, the fluid in the closed bulb-tube system contacts the pressure sensor directly, and thereby communicates changes in pressure occurring on the bulb inside the compartment. Since the tube is inelastic, and the fluid inside the tube is incompressible, the corresponding pressure change at the bulb will be seen at the pressure sensor. As such, changes in pressure in the compartment are registered at the pressure sensor on the surface of the patient's skin.

A correction factor can be introduced to account for factors such as: the volume of fluid in the flexible bulb, the diameter of the tube through which the pressure will be sensed, the location or position on the body, and the temperature of the system, patient, or ambient temperature. The bulb-tube system has several advantages including: reduction in cost because the pressure sensor and associated electronics need not be miniaturized for direct implantation; and simplification of the pressure sensor because the sensor itself is not implanted within the body, the sensor is not submerged within an aqueous environment and the electronics are not subject to Food and Drug Administration (FDA) guidelines for an implantable device.

At the surface of leg **100**, the pressure sensor is coupled to a device such as an RFID device or other similar wireless device. The device can be used to record and/or transmit the measured pressure data to an external reader. The device may additionally include an integrated or external temperature sensor or additional sensors to measure or determine one or more correction factors.

FIG. **2** is presented for illustrative purposes only. Any of the compartment monitors disclosed herein can be exchanged for the monitors **210A-D** shown in FIG. **2**.

FIG. **3** is a schematic view of an exemplary compartment monitor **210**, in accordance with one embodiment presented herein. As shown in FIG. **3**, flexible fluid-filled bulb **215** is implanted into compartment **200**. Inelastic tube **220** is attached between flexible bulb **215** and a fluid-pressure sensor **360**, which is external to the compartment **200**. Pressure changes within compartment **200** affect the volume of fluid within bulb **215**. When the pressure within compartment **200** increases, fluid within bulb **215** is pushed up into tube **220**. Because tube **220** is inelastic, and the fluid within bulb **215** and tube **220** is incompressible, the pressure change within compartment **200** is registered at pressure sensor **360**. In the embodiment shown, the pressure data is then communicated to an RFID device coupled to the pressure sensor. In the embodiment shown, pressure sensor **360** and RFID device are powered by flexible battery **370**. As would be appreciated by persons of skill in the art, RFID device and/or pressure sensor may be powered by other techniques. A substrate **330** (e.g., a layer of an adhesive bandage) is used to house and maintain the RFID device, flexible battery **370**, and fluid-pressure sensor **360**. Additional external sensors may further be included in the adhesive bandage material. Sterile gauze **350** may be present in between substrate **330** and the surface of the skin.

In a further embodiment, a pressure sensor is inserted into a muscle compartment, neurocranium, or other closed bodily space, via a needle or trocar. FIG. **4** is a schematic view of a compartment monitor **410** having a pressure monitor inserted into a compartment, according to embodiments of the present invention. In the embodiment shown in FIG. **4**, an implantable in-dwelling pressure sensor is implanted into the compartment **200**.

In one embodiment, the pressure sensor is a microelectromechanical system (MEMS) sensor on the order of 1 mm. The relatively small size of a MEMS pressure sensor allows easy insertion into the tissue. Such MEMS sensors use a change in resistance, change in capacitance, change in voltage, or a piezoelectric effect to convert changes in pressure on a sensing membrane to a voltage, current, or frequency change in the output signal. The pressure sensor can remain in the body for a prescribed period of time (generally 24-48 hours for compartment syndrome monitoring, but possibly longer for intracranial pressure monitoring).

The pressure sensor is coupled to a wire **416** that exits the compartment and skin and is coupled to an RF device **340** on a surface patch or bandage. In embodiments, a battery **370** is coupled to the RF device **340** to provide power. The RF device **340** powers the sensor **415**, and interprets or relays the data from the pressure sensor to an interrogating reader. The pressure sensor can be removed by pulling the lead wire away from the skin.

A substrate **330** is used to maintain the RF device **340** and battery **370** on the surface of the skin or tissue of the patient. Sterile gauze **350** is used between the electronic components and the surface of the skin or tissue. For example, the substrate **330** may be used on the surface of a limb or cranium of a patient.

FIG. **5** is a schematic view of a compartment monitor **510** in accordance with an alternative embodiment presented herein. Like the embodiment shown in FIG. **4**, compartment monitor **510** includes an implantable in-dwelling MEMS pressure sensor **415**. A wire or tether **416** electrically couples the MEMS pressure sensor **415** to a RF device **545**. RF device **545** is described in further detail below. Unlike the device **340** of FIG. **3**, the RF device **545** of FIG. **5** includes both RFID circuitry **547** and a pressure sensor interface **549**. The pressure sensor interface **549** receives pressure data from the MEMS pressure sensor **415** and processes that data for the RFID circuitry **547**. RF device **545** may be powered by flexible battery **370**. As would be appreciated by persons of skill in the art, RFID device and/or pressure sensor may be powered by other techniques. Compartment pressure data is transmitted to an external RFID reader (not illustrated) through an RF antenna **540**. The RF device **545**, flexible battery **370**, and antenna, are coupled to or integrated into an adhesive bandage or substrate **330**.

FIG. **6** is a schematic view of a compartment monitor **610** in accordance with an alternative embodiment presented herein. Similar to the embodiment shown in FIG. **5**, compartment monitor **610** includes an implantable in-dwelling MEMS pressure sensor **415** that is electrically coupled to an RF device **645** through a wire or tether **416** via a pressure sensor interface **649**. The RF device **645** includes an RFID chip **647**. However, compartment monitor **610** further includes an auxiliary sensor **617** that is also implanted within the compartment. Auxiliary sensor **617** is coupled to the RF device **645** through a wire or tether **616**. The auxiliary sensor **617** can be used to measure alternative parameters other than pressure in the compartment. For example, auxiliary sensor **617** can be a temperature sensor.

Alternatively, auxiliary sensor **617** can be a pH sensor. Alternatively there can be multiple auxiliary sensors taking additional measurements, as required. The pressure sensor **415** and one or more auxiliary sensors **617** are coupled to the RFID chip **647**. RF device **645** is discussed in further detail below. These systems may be powered by a flexible battery **370**. As would be appreciated by persons of skill in the art, RFID device and/or pressure sensor may be powered by other techniques. The data collected is transmitted to an external wireless receiver via RE antenna **640**. The RE device **645**, battery **370**, and antenna **640** all rest on an adhesive bandage or substrate **330**.

FIG. **7** is a schematic view of a compartment monitor **710** in accordance with an alternative embodiment presented herein. In the embodiment shown in FIG. **7**, the compartment monitor does not include an implantable pressure sensor. Instead the compartment monitor includes an external pressure sensor **715** which rests on the surface of the leg of the patient. As such, compartment monitor **710** can be used and placed in between the leg of a patient and a cast and can be used to determine whether the pressure inside of a cast has exceeded a certain amount. The compartment monitor **710** of FIG. **7** further includes an RF device **745** coupled to the pressure sensor. RF device **745** may further include a sensor interface **749** and an RFID chip **747**. Data is communicated from the pressure sensor **715** to the RFID chip **747** through wire or tether **716** and sensor interface **749**. RF Device **745** further includes an RF antenna **740**. The systems may be powered by flexible battery **370**. As would be appreciated by persons of skill in the art, RF device and/or pressure sensor may be powered by other techniques.

FIG. **8** is a top view of a bandage **800** incorporating a compartment monitor, in accordance with an embodiment presented herein. Bandage **800** includes a substrate **330**. The RF devices (and associated antennae) described above may be coupled to the surface of substrate **330**. Substrate **330** may include an adhesive material on one surface for affixing the bandage to the skin of the patient. Substrate **330** may further include multiple layers. In this embodiment, the RF device **845** and antenna **840** may be integrated within layers of the substrate **330**.

In the embodiment illustrated in FIG. **8**, the RF device is placed on top of the substrate **330**. In FIG. **8** the bandage is an oval shape, of course the bandage could be any other type of shape. Bandage **800** may be used with any of the compartment monitors described above.

FIG. **9** is a top view of an alternate embodiment of a bandage incorporating a compartment monitor in accordance with an alternative embodiment presented herein. Bandage **900** has a substrate **930** in a circular shape. Resting on the substrate **930** is a flexible battery **970**. Resting on top of the flexible battery is an RF device **945** and antenna **940**.

In the embodiments of FIGS. **8** and **9**, the compartment pressure monitor is not illustrated. However, the embodiments of FIGS. **8** and **9** may include one or more compartment pressure monitors such as the compartment pressure monitors described herein.

FIG. **10** is a system **1000** for monitoring compartment pressure, according to an embodiment of the present invention. System **1000** includes an RF device **1010** coupled to one or more external sensors **1090**. RF device **1010** includes an RF core **1020**, an analog to digital converter (ADC) **1030**, and one or more antennas **1016**. These components are mounted or formed on a substrate. Additionally, the RF core **1020** and/or ADC **1030** may be included in an integrated circuit. RF device **1010** may also include one or more sensor elements **1095**, such as sensor elements **1095a-n**. Sensor

elements **1095** may be included in the integrated circuit, on the substrate, external to substrate, or in any combination of the above. As shown in FIG. **10**, sensor elements **1095** are included on the substrate. Any compatible sensor element can be used as sensor element **1095**.

Sensor elements **1090a-n** are external to the RF device **1010**. External sensors include the sensors (e.g., MEMS sensor) described above for measuring compartment pressure. These external pressure sensors may be coupled to a pressure probe through a wire connector as illustrated in FIGS. **4-6** or an inelastic fluid filled tube as illustrated in FIGS. **2-3**. In an alternate embodiment, a fiber optic connection may be used.

Various types of sensor elements can be implemented as integrated sensors **1095** or external sensors **1090**. For example, an integrated or external sensor may include a temperature sensor element that generates information indicating ambient temperature, a pH sensor element, or other biological or chemical sensors. The system may include other types of sensor elements or combinations thereof, as would be apparent to persons skilled in the relevant art(s).

FIG. **11** is a block diagram of an illustrative network **1100** for remotely monitoring one or more orthopedic sensors integrated with RFID devices, according to an embodiment of the present invention. Network **1100** includes a plurality of remote locations **1110**, such as remote locations **1110a** and **1110b**. Each remote location **1110** includes an RFID/sensor readers **1140** and one or more RFID device and integrated sensors (RFID/sensor device) **1120**. RFID/sensor device **1120** may have one or more devices integrated into the RFID device and one or more external sensors. The wireless RFID/sensor readers **1140** are coupled to a backend application via a communications network **1180**. In an embodiment of the present invention, communications network **1180** is a publicly accessible communications network. In another embodiment, communications network **1180** is a private network or a hybrid network including public and private portions. Persons skilled in the relevant art(s) will recognize that various network architectures could be used for communication network **1180**.

Wireless RFID/sensor reader **1140** includes logic to read sensor data and RFID tag data transmitted by RFID/sensor device **1120**. In an embodiment, wireless RFID/sensor reader **1140** also includes logic to process the received sensor data. Wireless RFID/sensor reader **1140** can be any wireless device capable of communicating via an air interface protocol with RFID/sensor devices **1120**. In embodiments of the present invention, wireless RFID/sensor reader **1140** could be a wireless phone, a personal digital assistant (PDA), a computer having wireless communications capabilities, or other type of mobile, handheld, and/or computing device (e.g., an iPad® tablet computer). In further embodiments, wireless RFID/sensor reader **1140** may include global positioning system (GPS) or similar technology to identify the location of the RFID/sensor reader **1140**.

In embodiments, wireless RFID/sensor readers **1140** are deployed at different locations. For example, a patient released from a healthcare facility may be given an RFID/sensor reader for monitoring an implanted (or surface) compartment pressure sensor. In this manner, patients can leave the healthcare facility yet receive continuous monitoring to detect any changes in this condition.

According to the present invention, signals are exchanged between the wireless RFID/sensor reader **1140** and RFID/sensor device **1120** according to one or more protocols. In an embodiment of the present invention, reader **1140** and the RFID/sensor devices **1120** communicate via a single proto-

col for both RFID tag communications and sensor communications. In an alternate embodiment, reader **1140** and RFID/sensor devices **1120** communicate via a first protocol for RFID tag communications and via a second protocol for sensor communications. Examples of protocols used for RFID tag communications include binary tree traversal, HF ISO 15693 and EPC global Gen 2. The present invention is also applicable to any other types of communication protocols between tags and readers otherwise known or yet to be developed.

In an embodiment of the present invention, signals are exchanged between the wireless RFID/sensor reader **1140** and communication network **1180** according to one or more protocols. As can be appreciated by a person skilled in the relevant art(s), the communications protocol used between reader **1140** and communications network **1180** can be any wireless air interface protocol, such as used in IS-41 or GSM wireless communications networks, for example. Additionally, or alternatively, the communications may also be using a standard data communications protocol.

Application **1190** receives sensor data over network **1180**, and processes the data. In an embodiment, application **1190** also receives location information for the RFID/sensor reader **1140** (e.g., GPS position data). Furthermore, in an embodiment, the application **1190** may transmit data back over network **1180** to reader **1140**. For example, application **1190** may signal a reader **1140** if any changes to pressure are detected. Alternatively, application **1190** may send messages to trigger reader **1140** to interrogate RFID/sensor **1120** for a measurement.

Application **1190** may be coupled to a database of RFID identification numbers **1196**. When data is received from an RFID chip (via a reader), the application **1190** must associate the received identifier with a patient. Records in database **1196** may provide this mapping. For example, when a patient leaves a healthcare facility, the identifier of his or her RFID chip is associated with the patient name in database **1196**.

Application **1190** may further be coupled to an electronic medical records database **1192**. When patient data is processed by application **1190**, application **1190** may forward the processed data to electronic medical records database **1192** via a protocol such as HL7.

Application **1190** may be further integrated with a remote patient monitoring station **1194**. A healthcare provider monitors the data received from remote compartment monitoring devices to determine if additional medical intervention is necessary. When available, application **1190** provides patient monitoring station **1194** with location information. Application **1190** may display historical data or trends for monitoring station **1194**.

Extensive testing has shown that the current RFID reader chips made for cell phones (for example, Near Field Communication (“NFC”) chips based on ISO 15693 standards) are not well suited to read complex RFID sensors due to timing and/or power issues. The readers are essentially meant to read identification (ID) numbers and have a very short interrogation/response cycle time. Furthermore when the technology is passive (as is the case for most RFID) substantial power fluctuations occur on the RFID chip and this affects sensor accuracy.

Therefore medical grade sensors that require complex processing, power or accuracy will not work reliably with current RFID cell phones combined with standard passive RFID chip technology. In order to resolve this and to allow RFID cell phones to read the orthopedics skin patch comprising a complex MEMS sensor a modified RFID chip is

required. This modified chip includes a serial peripheral interface (SPI) port and allows pre-processed sensor data to be stored in memory directly linked to the ID interrogation process of the RFID tag. This type of RFID tag therefore serves as a low cost “pass-through” radio. This design and method allows any sensor to be connected to common RFID technology and be read directly with current RFID enabled cell phones. The technology can be adapted to ISO 15693 tags for example and is directly compatible with multiprotocol 13.56 MHz RFID reader chips for cell phones such as the PN 544 C2 reader chip made by NXP.

Different circuit designs and options are possible for the pass through method. FIG. **12** depicts an exemplary system **1200** having a modified RFID chip, according to embodiments of the present invention. FIG. **12** illustrates how complex sensors can be handled using a passive modified RFID radio, where the processed sensor data is passed through the RFID part as part of the standard interrogation—transmission of RFID data. The system **1200** includes a plurality of external sensors, including temperature sensor **1217** and other sensor(s) **1219**. In embodiments, the plurality of external sensors includes a complex calibrated external MEMS sensor **1215** and an ultra precise external thermistor to allow medical grade combined pressure and temperature sensor measurements.

Each of the plurality of external sensors is coupled to a sensor interface **1249**. Sensor interface **1249** includes an analog to digital converter (ADC) and multiplexer **1252**, an external microprocessor (MCU) and firmware **1254**, and memory **1256**. Using an external microprocessor and firmware allows compression of complex sensor data and extremely fast passage of information via the RFID chip, well within the limits of current standard RFID reader chips. Sensor interface **1249** further includes an external power source (e.g. battery, energy harvesting, solar, chemical, motion, etc.) that also can include a reference voltage calibration circuit. In an embodiment, sensor interface **1249** is included in a separate chip.

Sensor interface **1249** antenna **1240**, and memory **1241** are coupled to modified RFID chip **1247**. The command set for the external MCU and firmware **1254** is passed through the RFID tag **1247**. The memory on the RFID chip is cleared either when full or bumped with each new interrogation or sensor data download or by external command from the RFID interrogator (cell phone).

The RFID chip **1247** and sensor interface **1249** of FIG. **12** can be integrated into a single hybrid chip, whereby the packaged sensor data is placed in memory and where the main processor would be powered by the external power source and the communication part built to handle the constraints imposed by current RFID interrogators. Alternatively, the components of sensor interface **1249** may be included in a separate integrated circuit chip.

Various designs are possible for the fully integrated chip. The system of FIG. **12** illustrates the combination of external temperature sensor **1217** and external MEMS sensor **1215**. For temperature on chip a single calibration point digital sensor is preferred. Such sensor technology is described in U.S. Pat. No. 7,461,972 that is included by reference in its entirety.

FIG. **13** is a block diagram illustrating a portion **1300** of an RFID device in accordance with an embodiment presented herein. Portion **1300** illustrates an integrated temperature sensor **1310**, sensor interface **1320**, and an analog to digital converter (ADC) **1330**. Sensor interface **1320** receives data from integrated sensor **1310** and one or more external sensors. In an embodiment, integrated sensor data is

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fed into a sample and hold circuit **1322**. The output of the sample and hold circuit **1322** and data from external sensors are fed into a multiplexer **1324**. The output of multiplexer **1324** is fed into ADC converter **1330**. The output of ADC **1330** is communicated to RFID core (not shown). RFID core

may also communicate commands to the integrated sensor **1310**, sensor interface **1320**, and/or ADC **1330**. Additionally, power may be provided to these components by RFID core. FIG. **14** is a flowchart **1400** illustrating a method of monitoring compartment pressure, according to embodiments of the present invention. Flowchart **1400** is discussed with reference to the embodiments of FIGS. **1** through **13**. However, flowchart **1400** is not limited to those embodiments.

In step **1410**, a pressure sensor is placed on a patient. In an embodiment, the pressure sensor is loaded on a needle or trocar. The needle or trocar is then inserted into the compartment. The needle or trocar is then removed leaving the sensor implanted in the compartment. In an alternate embodiment, a vessel such as the bulb or sac of FIG. **2** is placed into a compartment and coupled to a pressure sensor on the surface of the skin of the patient.

In step **1420**, the pressure sensor is coupled to an RF device including an RFID chip. As described in the embodiments above, the RF device may be integrated in a patient bandage.

In step **1430**, the RF device is interrogated by an RFID/sensor reader. In response to the interrogation signal, the RF device communicates the measured sensor (pressure) data to the RFID/sensor reader. RFID/sensor reader may process the received data or simply pass through the received data to an external application such as an application at a healthcare provider.

In step **1440**, the RFID/sensor reader or application determines an action to take based on the current and/or historical measured pressure data. Example actions include generating and displaying a graph of the pressure over time, writing pressure information to medical records, and/or paging a healthcare provider if the current measured pressure is out of range or the pressure trend indicates pressure trending in an adverse direction.

In step **1450**, after the period for monitoring has ended, the pressure sensor is removed. If the sensor was inserted into a compartment of the patient, the sensor is removed by pulling on the wire tether. If a vessel was inserted into the compartment (as described in FIG. **2**), the vessel is removed by a healthcare provider.

FIG. **15** is a flowchart **1500** showing a method for linking identifiers to create transparent and secure wireless monitoring of compartment syndrome in a patient, according to embodiments of the present invention. Flowchart **1500** is described with reference to the embodiments described above. However, flowchart **1500** is not limited to those embodiments.

Prior to step **1510**, a pressure sensor and associated RFID device is affixed via a bandage to a patient. In step **1510**, an RFID reader at the healthcare provider performs an initial read of the RFID device.

In step **1520**, the identifier of the bandage RFID is authenticated against a list of known bandage RFID identifiers stored in a local database. In an embodiment, the bandage RFID identifier is authenticated against a database of valid identifiers. The bandage RFID identifier, for example, may be validated against a list of identifiers for a given manufacturer, a medical facility (e.g., hospital), a unit within a medical facility, or a system level basis (e.g., a collection of hospital).

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In step **1525**, a determination is made whether the authentication is successful. If the authentication was not successful, the RFID device is replaced (step **1526**). If authentication is successful, the process continues to step **1530**.

In step **1530**, the identifier of the RFID reader of the patient is retrieved. For example, the patient may have a cell phone with an integrated RFID reader. Alternatively, the healthcare facility may provide the patient with an RFID reader.

In step **1535**, the identifier of the RFID reader is encrypted.

In step **1540**, a second level cryptographic key is generated using the RFID reader identifier and the identifier of the bandage RFID chip.

In step **1545**, the identifier of the healthcare facility is retrieved.

In step **1550**, a third level security key is generated using the retrieved identifier of the healthcare facility.

In step **1560**, the bandage RFID chip identifier and RFID reader identifier is linked to the patient and the patient record.

In step **1570**, sensor thresholds within the RFID chip and associated pressure sensor are set.

In step **1580**, the RFID chip is calibrated and activated.

In step **1590**, compartment pressure monitoring begins.

In step **1595**, data is transmitted from the RFID chip via RFID reader to an application. The transmitted data may be encrypted with one of the security keys created in step **1540** or **1550**. For example, data may be transmitted to a records server and/or monitoring application at the medical facility. The medical facility can then detect changes to the status of the patient and intervene when necessary.

FIG. **16** is an exemplary embodiment of a needle **1650** used in accordance with an embodiment of the present invention. The needle will break in half lengthwise to assist with insertion of the device **1652** into the skin. The needle has a very fine cut completely through its mid diameter—longitudinally. The two halves of the needle are held together by a plastic endcap (not shown) for attachment to a syringe. The plastic endcap is scored, and once the device **1652** placed into the tissue and the needle pulled out of the skin, the needle can be split in half to remove it from the lead wire (or tube) **1656** that is left in the tissue. This configuration allows for the sensor to be placed as an assembled unit, without requiring the skin patch or some fitting on the tether to pass through the insertion needle once the sensor is secured in the tissue.

FIG. **17** is a schematic view of a low cost digital opto-electronic compartment monitor in accordance with an alternative embodiment presented herein. The opto-electronic compartment monitor of FIG. **17** may be used in applications where wireless devices or RFID readers are not available such as military or field applications.

Opto-electronic compartment monitor **1710** includes a plurality of color coded fluid cells **1712**. In one embodiment, fluid cells are color coded, in other embodiments color is optional. Each color coded fluid cell **1712** is coupled through a pressure sensitive valve **1714** to a digital sensor **1722**. When the pressure within the color coded fluid cell **1712** exceeds that of the pressure sensitive valve **1714** fluid flows into a digital sensor **1722** making the component conductive. The digital sensor **1722** thus acts as an on/off switch to send information through wires **1716** from device **1745**. An optical window **1718** can be used optionally. A healthcare provider can then visually inspect the monitor to determine the status of the compartment pressure.

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The breadth and scope of the present invention should not be limited by any of the above-described exemplary embodiments or examples, but should be defined only in accordance with the following claims and their equivalents.

What is claimed is:

1. A method for monitoring pressure within a muscle fascia compartment of a patient, comprising:

inserting a fluid-filled bulb through the patient's skin into an interior of the muscle fascia compartment of the patient,

wherein the fluid-filled bulb is fluidly coupled by a fluid-filled tube extending through the patient's skin to a pressure sensor, and wherein the pressure sensor is coupled to a skin patch removably attached to the patient's skin by an adhesive;

measuring pressure data within the muscle fascia compartment by the pressure sensor; and

receiving and storing the measured muscle fascia compartment pressure data from the pressure sensor by a radio-frequency identification (RFID) device coupled to the pressure sensor and the skin patch.

2. The method of claim 1, wherein inserting the fluid-filled bulb into the muscle fascia compartment comprises inserting the fluid-filled bulb into a leg of the patient.

3. The method of claim 2, wherein inserting the fluid-filled bulb into the leg of the patient comprises inserting the fluid-filled bulb into one of the anterior, lateral, deep posterior, and superficial posterior lower leg compartment of the patient.

4. The method of claim 1, wherein inserting the fluid-filled bulb into the muscle fascia compartment comprises inserting the fluid-filled bulb through a needle penetrating through the patient's skin and into the muscle fascia compartment.

5. The method of claim 1, further comprising interrogating the RFID device with a wireless RFID reader and communicating the measured muscle fascia compartment pressure data to the wireless RFID reader.

6. The method of claim 1, wherein measuring the pressure data within the muscle fascia compartment comprises continuously measuring the pressure data within the muscle fascia compartment.

7. The method of claim 1, wherein measuring the pressure data within the muscle fascia compartment comprises measuring the pressure data within the muscle fascia compartment for more than twenty-four hours.

8. The method of claim 1, further comprising transferring the measured muscle fascia compartment pressure data to a computing system.

9. The method of claim 8, further comprising the computing system calculating trends in the measured muscle fascia compartment pressure data over time.

10. The method of claim 9, further comprising alerting a healthcare provider in response to a determination that the measured muscle fascia compartment pressure data is outside a predetermined range or in response to a determination that the pressure trend indicates pressure trending in an adverse direction.

11. The method of claim 1, further comprising removing the fluid-filled bulb from the muscle fascia compartment through the patient's skin.

12. A system for monitoring pressure within a muscle fascia compartment of a patient, the system comprising:

a skin patch comprising an adhesive substrate configured to removably affix the skin patch to the patient's skin;

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a fluid pressure sensor housed within the skin patch and configured to measure muscle fascia compartment pressure data;

a radio-frequency identification (RFID) device housed within the skin patch and coupled to the pressure sensor, wherein the RFID device is configured to receive and store the muscle fascia compartment pressure data;

a fluid-fillable bulb configured to be inserted through the patient's skin and into the muscle fascia compartment; and

a fluid-fillable tube configured to penetrate through the patient's skin to fluidly couple the fluid-filled bulb implanted within the muscle fascia compartment with the pressure sensor housed within the skin patch.

13. The system of claim 12, wherein the muscle fascia compartment is in a leg of the patient.

14. The system of claim 12, wherein the bulb, tube, and pressure sensor of the system are configured such that an increase in pressure on the bulb within the muscle fascia compartment forces fluid into the tube and is registered at the pressure sensor housed within the skin patch.

15. The system of claim 12, further comprising a wireless RFID reader, wherein the RFID device is configured to transmit the stored muscle fascia compartment pressure data to the wireless RFID reader upon interrogation by the wireless RFID reader.

16. The system of claim 15, wherein the wireless RFID reader comprises one of a cell phone, a personal digital assistant, and a laptop computer.

17. The system of claim 15, wherein the wireless RFID reader is configured to process the muscle fascia compartment pressure data.

18. The system of claim 15, wherein the wireless RFID reader is configured to transfer the muscle fascia compartment pressure data to a computing system, wherein the computing system is configured to process the muscle fascia compartment pressure data, and wherein the computing system is configured to record and display trends in the muscle fascia compartment pressure data over time.

19. The system of claim 12, wherein the fluid pressure sensor and the RFID device are housed between an upper layer and the adhesive substrate of the skin patch.

20. A compartment syndrome monitoring system, comprising:

a fluid-fillable bulb configured to be implanted within a compartment of a muscle group in a leg surrounded by fascia;

a fluid-fillable tube coupled to the implantable fluid-fillable bulb and configured to penetrate through the skin of the leg to an exterior of the leg;

a fluid pressure sensor configured to be disposed exterior to the skin of the leg and coupled to the fluid-fillable bulb by the fluid-fillable tube;

an adhesive bandage configured to be coupled to the skin of the leg and the fluid pressure sensor;

a radio-frequency identification (RFID) device coupled to the fluid pressure sensor and the adhesive bandage and configured to record fluid pressure data measured by the fluid pressure sensor from the fluid-fillable bulb within the compartment of the muscle group in the leg; an RFID reader configured to interrogate the RFID device to receive the recorded fluid pressure data from the RFID device; and

a computer system configured to:

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receive from the RFID reader the recorded fluid pressure data measured by the fluid pressure sensor from the fluid-fillable bulb within the compartment of the muscle group in the leg;
record and display trends in the recorded fluid pressure data over time; and
alert a healthcare provider in response to a determination that the recorded fluid pressure data is outside of predetermined range.

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