TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

ANTTI PURANEN

IMPLANTABLE PRESSURE SENSORS

Kandidaatintyö

Tarkastajat: Yliopistonlehtori Juha Nousiainen ja tutkija Aleksi Hänninen

ABSTRACT

Antti Puranen: Implantable pressure sensors
Tampere University of Technology
Bachelor of Science Thesis, 25 pages
June 2018
Bachelor's Degree Programme in Information Technology and Electrical Engineering
Major: Biomedical Engineering
Examiners: University lecturer Juha Nousiainen and researcher Aleksi Hänninen

This bachelor's thesis presents a literature-based review of implantable pressure sensors. The focus is on the basic structure of implantable pressure sensors, and on two applications: intracranial pressure (ICP) and cardiovascular pressure (CVP). Implantable pressure sensor is a pressure sensor that is placed completely or partially inside the patient's body. The basic structure of implantable pressure sensor includes the sensing element that measures the pressure, and a way of transmitting the measured values to a monitor for doctors to analyze. This can be done either with wires or wirelessly. In wireless sensors the data transmitting is often done either with radio frequencies or with an inductive link.

Intracranial pressure is especially important to monitor after a traumatic brain injury. Monitoring with implantable pressure sensors allows more accurate and continuous data, which is important, because it allows doctors to react faster in case the pressure values inside the brain would start to increase. With cardiovascular pressure monitoring, the implantable pressure sensors are used, for example, to monitor heart functioning after placing a ventricular assist device.

Finally, the thesis discusses biodegradable implantable pressure sensors, which will be used in the future. At this point in time the biodegradable pressure sensors are undergoing in vitro and animal testing. Many of the test results are promising. The implantable biodegradable pressure sensors will decrease the risk of infections because they do not require surgery to be removed. Non-degradable pressure sensors, however, do need removal surgery and more surgeries means more risk for infection.

TIIVISTELMÄ

Antti Puranen: Implantoitavat paineanturit
Tampereen teknillinen yliopisto
Kandidaatintyö, 25 sivua
Kesäkuu 2018
Tieto- ja sähkötekniikan kandidaatin-ohjelma
Pääaine: Biolääketieteentekniikka
Tarkastajat: Yliopistonlehtori Juha Nousiainen ja tutkija Aleksi Hänninen

Tämä kandidaatintutkielma on kirjallisuustutkimus implantoitavista paineantureista. Tutkielmassa keskitytään implantoitavien paineantureiden perusrakenteeseen ja kahteen yleiseen sovellukseen: kallonsisäisen paineen ja kardiovaskulaarisen paineen mittaamiseen. Implantoitava paineanturi asetetaan osittain tai kokonaan kehon sisälle. Paineanturi rakentuu painetta mittaavasta elementistä, sekä joko johdoista tai langattomasta toteutuksesta, jolla mitatut painearvot saadaan kuljetettua monitorille, lääkäreille analysoitaviksi. Langattomassa toteutuksessa painearvot yleensä lähetetään monitorille joko radioaalloilla tai induktiivisen linkin avulla.

Kallonsisäisen paineen mittaaminen on erityisen tärkeää vakavan päähän kohdistuneen vamman jälkeen. Implantoitavilla paineantureilla saadaan tarkempia ja jatkuvia mittaustuloksia, mitkä ovat tärkeitä ominaisuuksia, sillä lääkäreiden on pystyttävä reagoimaan nopeasti mikäli painearvot alkavat kohota. Kardiovaskulaarista painetta mittaavilla implantoivilla paineantureilla tarkastellaan esimerkiksi sydämen toimintaa sydänkammion tukilaitteen asennuksen jälkeen.

Lopuksi tutkielma käsittelee biohajoavia implantoitavia paineantureita, jotka tulevat käyttöön tulevaisuudessa. Tällä hetkellä biohajoavat paineanturit ovat testattavana laboratorioissa ja eläinkokeissa. Monet testien tuloksista ovat lupaavia. Biohajoavat implantoitavat paineanturit tiputtavat tulehdusriskiä, sillä ne eivät tarvitse toista leikkausta kuten ei-hajoavat paineanturit, jotka tarvitsevat poistoleikkauksen.

TABLE OF CONTENTS

TABLE OF TERMS AND ABBREVIATIONS

ASIC	application-specific integrated circuit
BRE	Bit Rate Error
CSF	cerebrospinal fluid
CVP	cardiovascular pressure
ECG	electrocardiograph
EVD	external ventricular drainage
FDA	Food and Drug Administration
ICP	intracranial pressure
IOP	intraocular pressure
LAP	left atrial pressure
LC	coil-capacitor
LVAD	left ventricular assist device
MEMS	micro-electro-mechanical system
MRI	magnetic resonance imiging
NEMS	nano-electro-mechanical system
PCL	polycaprolactone
PLGA	plylactic-co-glycolic acid
PLA	polylactic acid
PPG	photoplethysmographic
PTT	pulse transit time
PVA	polyvinyl alcohol
RF	radio freaquency
TBI	traumatic brain injury
V	volts
WSB	Wheatstone bridge

1. INTRODUCTION

Pressure is one of the most common things to measure from the body. Different pressure measurements are important diagnostic information for doctors. Sometimes pressure is monitored for making sure that the pressure values stay within desired rates during or after the operation. Pressures are measured in numerous parts of the body, including cardiovascular pressures like blood pressures and intracranial pressures inside the skull. The location where the pressure is measured affects the results. Sometimes it is necessary to measure the pressure in locations where the pressure sensor must be inside the body, in order to be able to measure the pressure with accuracy.

Implantable pressure sensors are pressure sensors that are placed fully or partially inside the body for measurement. These pressure sensors allow doctors to measure the pressure directly where they want to. For example, with non-implantable pressure sensors, doctors can measure blood pressure, but if the doctors want to monitor the blood pressure exactly in the aorta or inside the heart chambers, they need to use implantable pressure sensors. However, the disadvantage of implantable pressure sensors is the difficulty of placing them. They always require surgeon to place them.

This thesis is about different applications, possibilities and challenges of implantable pressure sensors. The focus is on the basic structure of implantable pressure sensors, and on two applications: intracranial pressure (ICP) and cardiovascular pressure (CVP). In both of these applications the implantable pressure monitoring is important because non-implantable monitoring cannot achieve the accuracy or continuous monitoring of implantable pressure sensors. Continuous monitoring is especially important and often the reason to use implantable pressure sensors. For example, if the pressure values inside the brain start to increase, doctors need to know about it immediately in order to react fast enough.

The end of this thesis contain a glace to the future as well. It is likely that most implantable pressure sensors in the future will be biodegradable, as well as other implants and implantable devices. Implantable biodegradable pressure sensors are not yet in diagnostic use, but they are developing fast and are already showing promising results.

The structure of this thesis is the following: chapter two is about the basic structure of implantable pressure sensors and challenges that apply basically to every sensor. Chapter three discusses intracranial and cardiovascular pressure measurements, and chapter four is about biodegradable pressure sensors and where the studies are going with them.

2. IMPLANTABLE PRESSURE SENSORS

All implantable pressure sensor systems consist of at least a pressure-sensing element and a method of transmitting the data to an external unit [1]. Both of these elements can create challenges when designing an implantable pressure sensor. The sensing element must be accurate enough for potential long-term implants and transmitting unit has to get power from somewhere in order to keep sending the data forward. All this also has to be done while considering that the size of the sensor cannot grow too big for patients' comfort and the sensor must also have good biocompatibility like any implantable device. To keep the size of the sensor small enough, micro-electro-mechanical systems (MEMS) and nano-electro-mechanical systems (NEMS) are the most used techniques for manufacturing implantable pressure sensors. [2]

2.1 Basic structure of the implantable pressure sensor

Implantable pressure sensors can be categorized into wireless and non-wireless sensors. Both sensor types include the sensing element and a monitor where the results of the measurement can be observed. The difference between wireless and non-wireless pressure sensors is the method of transferring the data from inside the body to the monitor. With non-wireless sensors the sensing element is directly connected to the monitor with wires. The wires also transmit power to the sensor, as well as data from the sensor. Wireless sensors are not connected directly to the external monitor but have a transmitting unit in them which sends data wirelessly to the external monitor. For wireless sensors there are two possible power solutions. Firstly, that the system has its own power source, and secondly, that the system is remotely powered [2]. There are different sensing methods for implantable pressure sensors. The sensing systems are typically membrane-based MEMS capacitive sensors or piezoresistive sensors [3] but some of the sensors are also optical fiber pressure sensors [1]. The sensing systems are the same for wireless and non-wireless sensors.

2.1.1 Different sensing methods

The basic sensing method for membrane-based capacitive sensor is simple. The membrane of the sensing element has one of the electrodes of the capacitor, and when it is under pressure it deflects, changing the distance between electrode plates and changing the capacitance of the circuit [1], [3]. The same method is used widely on many types of pressure sensors. The simple basic structure of the circuit allows MEMS technology to make it in small enough scale for implantable sensor. The idea is presented in Figure 1.

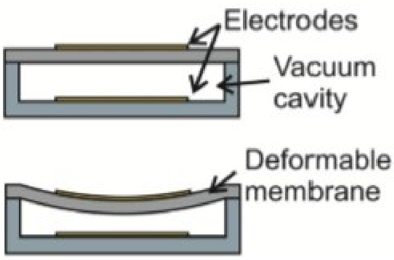

Figure 1. *Capacitive-based sensor's idea.* [1]

The piezoresistive pressure sensors are practically always silicon based. The working principle is the Piezoresistive effect, which means a change in resistivity when the conducting material gets strained. [4], [5] The design of the piezoresistive pressure sensor includes a silicon diaphragm that has piezoresistive elements mounted onto it. Most commonly, four equal piezoresistors are placed in the membrane of the silicon diaphragm and connected to a Wheatstone bridge (WSB) [6]. A Wheatstone bridge is presented in Figure 2. Any stress on the silicon diaphragm will change the resistivity of the circuit, which can be seen linearly in the output voltage. [4] When there is no pressure applied to the sensor, all of the piezoresistors have same resistance and therefore the output voltage is zero. [7]

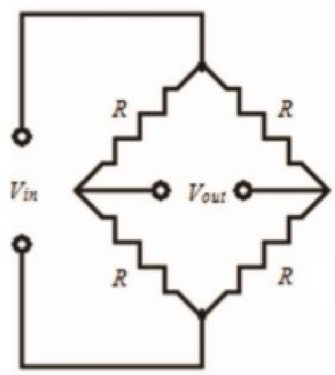

Figure 2. *Wheatstone bridge circuit.* [4] *V_{in} and V_{out} are input and output voltages and R stands for piezoresistor.*

Some pressure sensors have an optical sensing unit. An optical sensing unit includes a light emitting unit, and two optically flat mirrors which are parallel to each other. The principle is shown in Figure 3. The light enters the chamber between the mirrors, and reflects multiple times before leaving the chamber. One the mirrors are on a highly sensitive diaphragm and when the pressure is applied to the sensor, the distance between the mirrors changes, changing the intensity of optical output. [8]

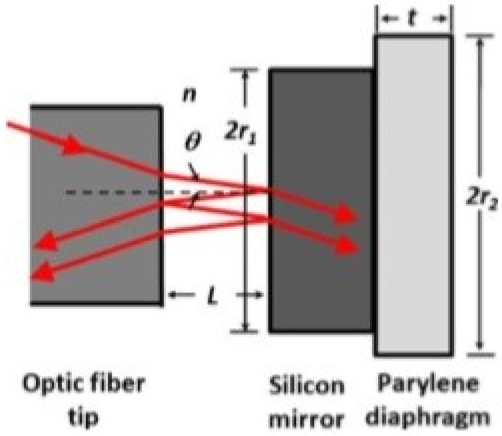

Figure 3 *The principle of optical sensing unit.* [8]

A sensor can have more than one sensing unit in it. Especially capacitive or piezoresistive sensors can have multiple sensing units in array formation, to get better sensitivity. The sensor still has only one sensing plate, but the pressure applied is measured with more than one capacitor or WSB. [9]

2.1.2 Power solutions

Receiving the data from an implanted wireless pressure sensor requires a wireless communication system, which necessitates some sort of power. The power sources for implantable pressure sensors can be divided into two different categories. In the first one the pressure sensor has its own power source. The second one is called telemetry, where the sensor itself does not include a power source of its own. Telemetry can also be divided into two categories which are called active and passive telemetry. [2] Wireless connection with a long-term pressure sensor is important for patient's safety, if the implantable sensor has wires, the risk for infection grows dramatically. Non-wireless implantable pressure sensors are used in short-term use only. [1]

In case where the pressure sensor itself includes a power source, the wireless transmission is only for data. The advantage of this is that the transmitted data can have a high bandwidth, while the obvious disadvantage is that the batteries have a limited lifetime. Also, the size of the implantable pressure sensor grows if it has power source of its own. [2]

In active telemetry the implantable pressure sensor does not have its own power source. However, it does have a transmitter and receiver for communication with an external device. The pressure sensor is powered remotely by the external device. [2] The powering can be done with inductive coupling, where an external coil is kept close to the implanted sensor, which includes a coil of its own. The external coil is powered with suitable frequency and it gives power to the internal coil through induction and the coil works as a power receiving unit of the sensor circuit. [10] After obtaining power, the sensor can transmit the data forward.

Passive telemetry differs from active telemetry by sensor itself having absolutely zero active electronics, such as microcontrollers or an amplifier. It still has an LC-circuit as a transmitting unit which can communicate with an external coil. The resonant frequency shifts of the LC tanks can be converted into pressure changes. [1]

When comparing these three power solutions with each other, it depends on the application and placement of the pressure sensors which power solution is the best for the sensor. The battery powered sensors enable continuous data collection better than other two, and the range of wireless communication is up to 10 meters, whereas with telemetry the range is tens of centimeters. However, the limited lifetime and large size makes battery power unfit for long-term applications. Passive telemetry enables the smallest size and longest lifetime for the pressure sensor, but has the smallest data bandwidth and wireless range. The pressure sensor's application and implant's location are the determining factors when choosing which power solution will be used. [2]

2.1.3 Transmitting unit

Transmitting the data from a sensor to an external unit in a wireless pressure sensor has two main options, which are inductive link and radio frequency (RF) link. Inductive link needs the external device closer to the sensor than RF link. RF link can transit also more data with minimal errors. [11] However, an inductive link can be smaller in physical size and works with less power than RF link.

The tissue around the antenna has huge impact on the impedance and the resonance frequency of the antenna [12]. That is why the design of the antenna needs to be done while considering the application of the sensor. Parameters that needs to be considered when designing antenna for implantable pressure sensor are frequency bands, safety issues, polarization and power consumption. [11]

2.2 Challenges with implantable pressure sensors

Biocompatibility is always a challenge for implantable devices, especially for electrically active circuits. Interacting with warm and saline body fluids is an environment that can cause corruption on an electric circuit. It can also cause corrosion and highly negative foreign body reaction. [1] One of the solutions for this is biocompatibility coating [11]. However, a more common solution is micropacking or using micropackaging and coating together [13]. The reason for packing being more popular is that coating materials are so thin and can unbond, creating problems again with biocompatibility [14]. Even in a case where the device is fractured, it should not contain any toxic materials that might be released into the body [2].

Polymers are the most used packaging materials. Silicone gels are used to cover the sensing element for low viscosity so that the sensing element remains sensitive. For the rest of the sensor, polymers like epoxy are used to cover them. Parylene-C is a popular coating material. [13] One of the factors for choosing packing materials is how easy it is to sterilize and if the sterilizing method works for the pressure sensor as well [14].

One of the other challenges for implantable pressure sensors are to get is accurate data in long-term measurements. Calibration is a big part of getting accurate and true results. Some non-wireless pressure sensors can be calibrated even after placing them in the body, but most of the implantable pressure sensors needs to be calibrated beforehand. The sensors' accuracy also often gets lower after being implanted. Two main reasons for drifting are changes in the environment where the sensor is implanted (and calibrated), and mechanical fatigue that can occur from ageing. [2]

Other big challenges for wireless implantable pressure sensors is are get accurate data safely to the doctors. Using radio frequency antenna includes a couple of issues. One of the issues that RF implants need to consider is the tissue absorption. It is the amount of electromagnetic energy that is reduced while the signal is coming through human tissue. [12] With higher frequency level the amount of energy absorbed by human body increases, which can be harmful for the tissue. However, with low frequency levels the amount of data transferred decreases, which can effects on the accuracy of the data. The other issue is power consumption. The power consumption is an issue for the whole implant, but normally the communication takes the most energy in implantable sensors. One reason to keep the power consumption as low as possible is that it generates heat that can be harmful for surrounding tissue. [2] Communicating with an inductive link has issues as well. The distance between sensor and external device needs to be minimum, which means that the sensor's transmitting unit needs to be in the surface of the body. There is also higher possibility of Bit Rate Error (BRE) in inductive link communication compared to RF link. [11]

3. APPLICATIONS FOR IMPLANTABLE PRESSURE SENSORS

Implantable pressure sensors have many applications. The most commonly measured pressures are intracranial pressure (ICP), cardiovascular pressure (CVP), intraocular pressure (IOP) and bladder pressure. The reasons to use internal measuring for pressure instead of external are that sometimes doctors cannot measure the desired pressure externally, and with internal measuring doctors often get more continuous and more accurate data. [1] The next section goes through the ICP and CVP sensors and couple different applications and methods of measuring them.

3.1 Intracranial pressure measurements

Intracranial pressure refers to the pressure inside the skull and brain tissue [15]. ICP monitoring is important for patients who have a traumatic brain injury (TBI) [16]. TBIs can be caused by traffic accidents, sport injuries or any kind of strong hit to the head, which assaults a strong external force on the brain. With ICP monitoring the doctors are able to see if the pressure in the brain starts to increase. Increased ICP can cause intracranial hemorrhaging, neurological problems, coma, visual impairment, stroke or even death. [15] Placing the implantable ICP sensor requires neurosurgery, which is always a risk to the patient. However, often in case of TBI monitoring ICP is critical despite the risk of the surgery. [16]

3.1.1 Measurement methods

If possible, ICP is most often measured with implantable pressure sensors in cases of TBI. Some non-invasive techniques also exist, but they are less accurate [15]. Non-invasive ICP measurement is based on studies that show that the change of ICP is associated with changes of flow velocity and arterial blood pressure, which can both be recorded with non-invasive techniques [17]. Non-invasive methods have been studied from the 1970s in order to find a replacement for invasive methods [18]. As previously stated, the results of non-invasive ICP measurements are not as accurate and are often referred to as estimated intracranial pressure [15]. However, placing the implantable pressure sensor requires a neurosurgeon, which is not available in every hospital. In these cases the non-invasive methods are used, and if the estimated intracranial pressure is high, the patient is most often transferred to another hospital with a neurosurgeon.

ICP is measured in millimeters of mercury (mmHg) [15]. The linear (and accurate) range requirement of ICP sensor is from 0 mmHg to 70 mmHg [19]. Normal ICP values are between 7-15 mmHg for adult and over 20 mmHg is already life threating [15].

3.1.2 Implantable ICP sensors

There are a couple of different ways of categorizing implantable ICP sensors. One way is that they can be divided to microtransducer devices and external ventricular drainage (EVD) -systems. EVD is different from other sensors, because it can be used also for drainage of cerebrospinal fluid (CSF). [20] ICP sensors are normally placed in either the brain tissues or the ventricles [17].

With both, EVD and microtransducer devices, it is advantageous if the monitoring system does not contain ferromagnetic components which would prevent patients from magnetic resonance imaging (MRI) [20]. MRI is currently the most used diagnostic application for brain injuries. Brain tissue is very sensitive to increased heat and even 1 °C temperature increase can be very damaging. The MRI coils can induce large voltages to some ICP sensors which could cause unnecessary heat around the sensor's transmitting unit. [21] This is one of the biggest reasons why most of the ICP sensors are not wireless or even if they are, the transmitting unit can be external. The reasons for using internal transmitting unit are that a physical connection with brain and external environment is huge risk factor for infections and limits the time of the monitoring. [22] However, in most cases, a short monitoring period is enough, and the measuring can be done with a system with a physical link to the external computer. With non-wireless system the maximum monitoring period is five to seven days, but often the monitoring time is shorter.

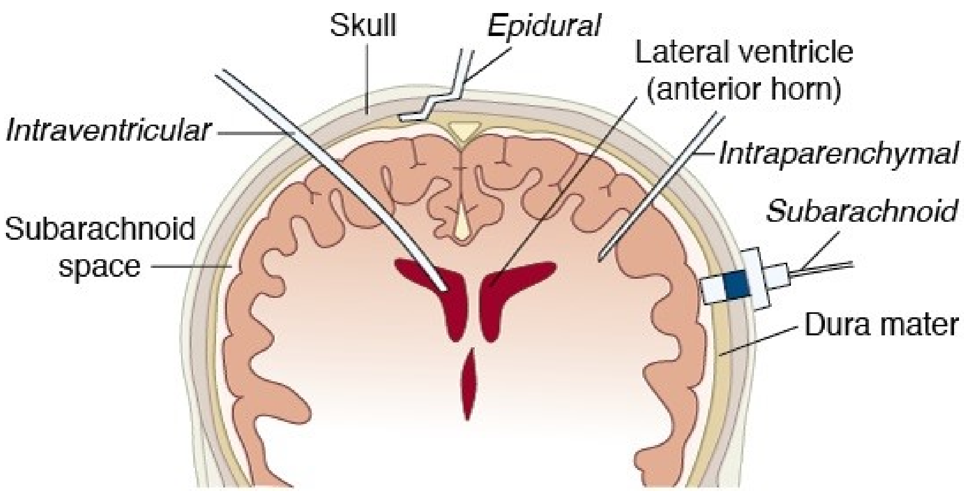

Figure 4. *Different areas of the brain where the ICP is measured.* [23]

Microtransducer ICP monitoring devices can be divided by their sensing method to fiber optic devices, strain gauge devices and pneumatic sensors. The microtransducer ICP monitoring devices are widely used to measure ICP from different intracranial locations, such as intraventricular and intraparenchymal, and in rare cases epidural, subdural and subarachonidal. [20] The locations are presented in Figure 4. Often the location where the pressure is wanted to be measured, is not on the surface of the brain. In that case the sensing unit is placed on the desired location with sensor leads. Sensor leads are wires that are coated with isolating and biocompatible material, normally with medical silicone. If the sensor's communication with a computer is wireless, the transmitting unit is placed outside the cranial bone, under the skin, so the communication distance with external device is minimal [22]. In Figure 5A is shown Raumedic's Neurovent P-tel wireless ICP sensor and in Figure 5B is shown Raumedic's wireless reading device of the ICP.

Figure 5: ***A)*** *Raumedic's wireless ICP sensor.* ***B)*** *Wireless reading of the ICP.* [24]

EVD system's catheter is traditionally placed into a ventricle through a coronal burr-hole. It measures the intraventricular pressure, and if the pressure rises too high, it drains CFS from the ventricle which lowers the ICP. EVD catheter is presented in Figure 6. As well as with the other sensors, EVD must be placed using neurosurgery. The surgery itself is considered a minor surgical procedure, but especially with younger patients placing the EVD can be difficult because of the small size of the ventricle. Ventricular size widens with age, so this problem is more common with young patients. The risks with placing the EVD are minor, but there is a risk of postoperative hemorrhage and infection. That is why the routine CT scan is important after placing EVD. [20] To avoid infection, EVD catheter can also be impregnated with antibiotics [25]. However, even with impregnated catheters infections can occur [26].

Figure 6: *Integra® Camino® Flex Ventricular Catheter.* [27]

EVD system is the most used intraventricular pressure sensor. Two main reasons make it so popular. The first one is, as already mentioned before, that it can drain CSF to lower the pressure in case the ventricular pressure is increasing too much. The second is that it can be calibrated anytime, which increases the accuracy and the reliability of the sensor.

[20] Normal sensitivity of the EVD ICP sensors are in the range of 2 µV/V/mmHg to 0.17 mV/V/mmHg [7].

At Tampere University of Technology Behfar et al. [28] studied a fully implantable passive sensor for continuous wireless subdural ICP monitoring. The sensor is capacitive and the size of it is 1.4x1.4x0.8 mm^3 and it is made minimally invasive. The transmitting of the pressure values is done by inductive link with an external reader coil on-body. The focus of the study was the accuracy of the inductive link with reader coil. The changes in the reader coil's input impedance's magnitude and phase as well as the resonance frequency were measured in 5 mmHg intervals between 0 and 70 mmHg. The results show that the most accurate and linear readout can be achieved with measuring the phase angle variations of the reader coil's input impedance instead of magnitude of input impedance or the resonance frequency. [28]

In another study Behfar et al. [29] researched an inductive passive pressure sensor for intraventricular and intraparenchymal ICP monitoring. The sensor includes a miniature pressure sensing unit, which is capacitive and placed either inside a ventricular or in the parenchymal for measurement. Besides the sensing unit, the sensor also includes a subcutaneous spiral coil and an ultra-flexible and thin coaxial cable to connect the coil to the sensing unit. An external coil with a RF antenna is coupled with the internal coil to send the pressure values forward. The study shows that frequency shift of external coil is wider with intraventricular ICP measurements than intraparenchymal ICP measurements in the range of 10 to 70 mmHg, which means that intraparenchymal ICP monitoring would require a more sensitive sensor than intraventricular ICP monitoring. However, the accurate readout resolution in this study is 5 mmHg, while in ICP measurements the ideal resolution is 1 mmHg. As Behfar et al. writes: "Therefore, further study on this topic is necessary to improve resolution, repeatability and sensitivity of the measurement." [29]

In table 1 is presented 4 different ICP sensors: Camino® Intracranial pressure monitoring catheter model 110-4L [30], Codman Microsensor ICP Transducer [31], Raumedic® ICP-TEMP-Monitoring-system [32] and Raumedic® Neurovent P-tel [33]. Camino's sensor is the only one in the table that is fiber optic. It is also smallest in size. The sensing ranges of Raumedic's two sensors are wide compared to other two. Raumedic® Neurovent P-tel is the only wireless ICP monitor in this table, which can also be seen from the lifetime of the implant. Raumedic's sensors have also low drifting during the lifetime of the sensor.

Table 1: *Technical information of different ICP sensors*

Product	Sensing method	Size	Range	Zero drift	Placement	Lifetime
Camino® Intracranial pressure monitoring catheter model 110-4L	Fiber optic	1.35mm diameter	-10 to 125 mmHg	less than ± 1 mmHg per day	Parenchymal or ventricular	5 days
Codman Microsensor ICP Transducer	Piezoresistive strain gauge	n/a	n/a	less than 5.0 per 7 days	Parenchymal, subdural, or ventricular	Surgeon discretion
Raumedic® ICP-TEMP-Monitoring-system	Piezoresistive strain gauge	1.67mm diameter	-50 to 250 mmHg	Less than 2mmHg during the first 7 days	Parenchyma or ventricle	7 days
Raumedic® Neurovent P-tel	Piezoresistive straun gauge	1.67mm diameter	-20 to 400 mmHg	±2.0 mmHg per month	Parenchyma	90 days

3.2 Cardiovascular pressure measurement

3.2.1 Reasons for cardiovascular pressure monitoring

Heart diseases, like hypertension (high blood pressure), are one of the most common causes of death in industrial countries. To get the optimal treatment, it is important to have the possibility of continuous monitoring of arterial blood pressure over extended periods of time. [34] Non-invasive methods of measuring blood pressure are not continuous or accurate enough. However, they are more commonly used, because they are much easier to use and they cause less discomfort to the patient. They also do not have the risks of infection that the operation of placing implantable sensor brings. [35] Non-wireless invasive catheter based devices are used, but they cannot offer long term monitoring, because of the increased risk of infections and thrombosis. Fully implanted wireless blood pressure system is one way of achieving continuous monitoring of cardiovascular pressure (CVP). [34]

Cardiovascular pressure is measured for different reasons and from different locations. In the Figure 7 is shown the anatomy of the heart [36]. From the figure can be found aorta, atriums and pulmonary arteries, which all are examples of locations where doctors could want to monitor the blood pressure. Table 2 shows the estimated requirements for some different applications of blood measure monitoring [2].

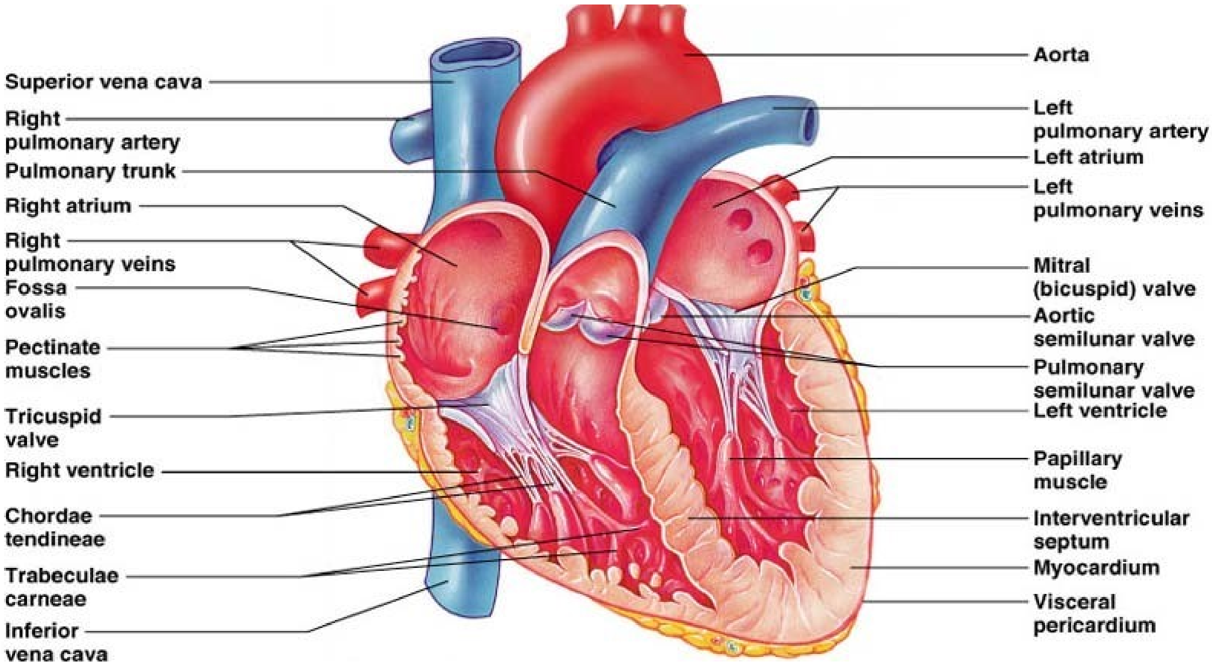

***Figure** 7 Heart anatomy.* [36]

***Table 2:** The estimated requirements for different blood pressure applications*

Aliments	**Measure location**	**Typical values** (mmHg)	**Required range** (mmHg)
Heart failure	Pulmonary artery	8 to 30	0 to 100
Coronary artery disease	Downstream of stent or blockage	60 to 150	20 to 250
Abdominal aortic aneurysm	Between graft and aneu-rysm wall	20 to 90	20 to 250
Hypertension and auto-nomic dyreflexia	Artery	60 to 150	20 to 250

3.2.2 Different implantable cardiovascular pressure sensors

Integrating medical stent with a wireless implantable cardiac sensor allows the placement of the sensor basically anywhere in the circulatory system [37]. Integrating the stent with application-specific integrated circuit (ASIC) allows the sensor to be active, which increases the communication distance of the sensor. With an active stent sensor the communication distance can be over 10 centimeters, which allows the external device to communicate with the sensor almost anywhere in circulatory system. [37] With the pressure sensor integrated to the stent it allows the doctors to see if the stent works.

Pais et al. [38] introduce an implantable blood pressure monitoring cuff that goes around the artery. The device is currently only used for rats and other small laboratory animals, but in the future it could also be used for humans. The sensor is placed around the artery and provides continuous blood pressure measurements for days. It uses a piezoresistive sensor. Figure 8A shows the computer aided design of the sensor and in Figure 8B the device has been implanted into a rat. The results with this device were highly positive. It allows for the blood measurement of the rat without stressing the rat with, for example, an invasive catheter tip which can affect the results. Also in vitro testing the device followed applied pressure accurately. [38] One of the goals for wireless implantable pressure sensors is that they would not cause any stress effect for the patient, which would affect the results of blood pressure monitoring. Some patients experience stress when visiting hospitals, which can be seen in results from a singular measurement with a non-implantable pressure sensor. Using a wireless implantable pressure sensor for continuous monitoring instead of a singular snapshot, which can be affected with stress or other possible peaks, is therefore much more accurate less affected by the environment. [1]

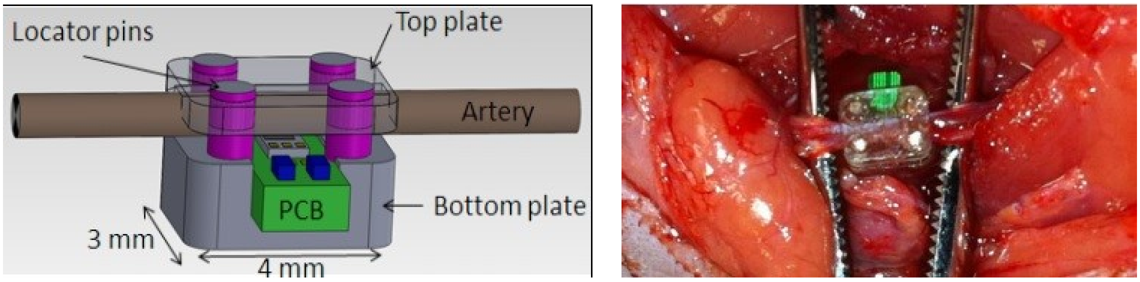

Figure 8 A) *The computer aided design of blood pressure cuff.* ***B)*** *Blood pressure cuff implanted to rat.* [38]

Fiala et al. [34] also presented a sensor that would be placed around the arteria. The sensor uses an optical sensing unit and active telemetry. The sensor acquires also other cardiovascular information than just intravascular pressure. It also measures electrocardiograph (ECG) and photoplethysmographic (PPG) and uses all these to calculate pulse transit time (PTT). The sensor is presented in Figure 9. The sensor have been tested in vivo with pigs. [34]

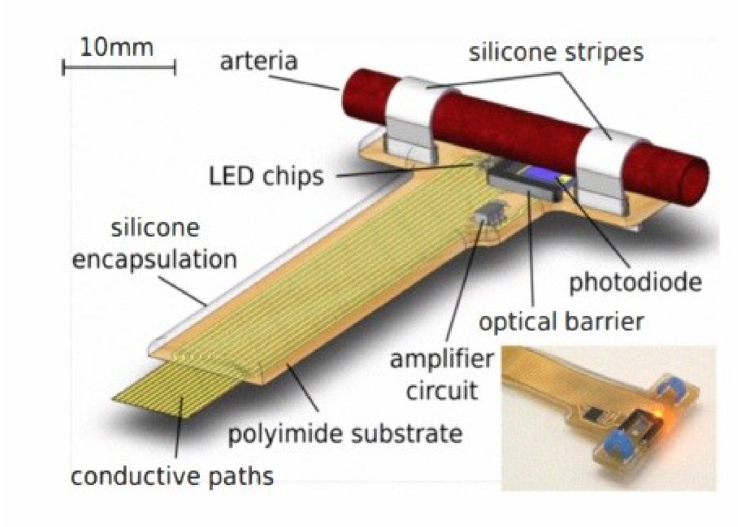

***Figure 9** Optical sensor to measure intravascular pressure and pulse transit time.* [34]

The optical sensor which Fiala et al. presented allows the blood pressure measurement without applying external pressure to the artery, which could cause artery deform and affect the blood flow inside the vessel [34]. The sensor measures also ECG, PPG and PTT so the sensor could be used as a part in implantable drug delivery system or nerve stimulation device in the future for chronic hypertension patients. The first test results for this device were positive and the PTT values were determined with invasive methods for the first time. According to Fiala et al., the results were promising for implantable blood pressure regulation systems with a drug pump or nerve simulator as a closed loop system. [34]

One of the conditions in which the doctors would need the pressure monitoring inside the heart is after implantation of a continuous-flow left ventricular assist device (LVAD) [39]. The LVAD is a device for helping the failing heart to function. Monitoring the left atrial pressure (LAP) allows the doctors to see that the LVAD is functioning correctly. LVAD can be a long-term implant and therefore LAP monitoring should be long term as well. For long term LAP monitoring Hubbert et al. [39] introduced a wireless MEMS pressure sensor called the Titan. The sensor itself is passive MEMS pressure sensor with titan package. The external device for monitoring the device is connected to the Internet, which allows the patients to do the measurements at home and the doctors are still able to get the real time data of the measurement. The sensor has been clinically tested in patients with LVAD. The longest period of The Titan sensor being implanted is 180 days. [39]

The first FDA approved fully wireless device for heart failure monitoring was CardioMEMS HF System from St. Jude Medical [1], [40]. It received FDA approval in 2014. The device measures pressure within the pulmonary artery. It is a passive sensor and the communication with external device is through LC tank's resonant frequency. The pressure sensing method of the device is capacitive. CardioMEMS HF system is presented in Figure 10. Size of the device is 3.4 x 2 x 15 mm^3. [40]

Figure 10: *CardioMEMS HF System from St. Jude's Medical. The sensor size is being compared to one dime (US 10 cents coin).* [40]

The procedure of placing the CardioMEMS™ HF system to the pulmonary artery is relatively simple. With a minimally invasive operation, a catheter is placed in pulmonary artery advantage along with the guide wire to assure that the implant will go into target vein. The delivery tool for the CardioMEMS™ follows the wire. Once the delivery tool is in the correct place, the wires that can be seen in Figure 10 are released from the delivering tool, anchoring the pressure sensor to its location. [41]

After placing the CardioMEMS™ HF system into the pulmonary artery, the readings of the pressure values can be done at home. The electronic unit that completes the measurements will automatically send the readings to the secured website, where the patient's doctor will have access. The readings are meant to be done daily for continuous monitoring. [42] The continuous data from the CardioMEMS™ HF system, which monitors the pulmonary artery pressure and heart rate, allows doctors to diagnose possible heart failure and act on it by making changes to the treatments even before the patient notices any symptoms. The CardioMEMS™ HF system is placed in patients with either a history of heart failure or patients that are considered to have increased risk for heart failure, due some other heart disease. [43]

4. BIODEGRADABLE PRESSURE SENSORS

Advantages of implantable biodegradable pressure sensors compared to regular pressure sensors are mostly the same as the advantages with any biodegradable implants. The most obvious one is that there is no need for the second surgery, which lowers the risk for infection and other issues that are always present with operations. Secondly biodegradable materials have often good biocompatibility and the sensors themselves are less likely to cause negative foreign body reaction. Biodegradable implants are also environmental friendly, because they do not create any electronic waste [44]. It is easy to see that in the future biodegradable pressure sensors will become more common. Biodegradable pressure sensors are not yet in diagnostic use, but there are a lot of different sensors that are being tested in vitro and in vivo for animals.

4.1 Materials and structure

The basic idea of biodegradable pressure sensor is that after it has fulfilled its purpose as diagnostic device, it will safely be absorbed by the body [44]. The dissolve time depends on the materials. Polymers such as polylactic-co-glycolic acid (PLGA), polyvinyl alcohol (PVA), polylactic acid (PLA) [45] and polycaprolactone (PCL) [46] are for example used. Different polymers have different degradation rates, and by using co-polymers or blends of these materials can be achieved the wanted degradation time. The conducting materials needs to be biodegradable as well, or at least dissolve into so small molecules, that the body is able to get rid of them. Zinc, iron and magnesium and their alloys are for example used. In the sensing unit silicon and silicon oxide are common materials [19]. The size of the sensor does not necessary effect on the degradation time. The same stages and percentage weight losses can be found from two different sized pressure sensors made from same material [45]. The functional lifetime of the pressure sensor can be just a small fraction of the degradation lifetime. For example, PLGA/PVA -based sensor has functional lifetime of 24 hours and degradation lifetime of 25 days. [45]

The basic structure of the biodegradable pressure sensor remains the same as regular implantable pressure sensor. There is still sensing unit and transmitting unit. The sensing unit is most often piezoresistive or capacitive as in non-degradable sensors. Radio frequency powered electronics are used in biodegradable pressure sensors as well. Majority of biodegradable pressure sensors use passive telemetry to communicate. However there are research about bio-battery systems that could be used in the future to create active and fully biodegradable pressure sensors as well. [44]

4.2 Comparing biodegradable to non-degradable implantable pressure sensors

As already said before, the advantages of biodegradable pressure sensors to non-degradable ones are the same as any biodegradable implant. But there are some disadvantages as well. Calibration is often harder for biodegradable sensor and the functional lifetime varies always a little bit with every individual case. It can be hard to know when the accurate functional lifetime is over.

The sensitivity results of the biodegradable cardiovascular sensor presented by Boutry et al. [47] are really similar to non-degradable pressure sensor with similar design. The sensing unit of the sensor is capacitive with 4 x 5 array formation. The sensing array is shown in Figure 11. [47] The array formation increases the sensitivity but can also cause higher error with multiple capacitors. However, often in cardiovascular monitoring the biggest interest is in the shape of the pulse wave, not in the absolute pressure value.

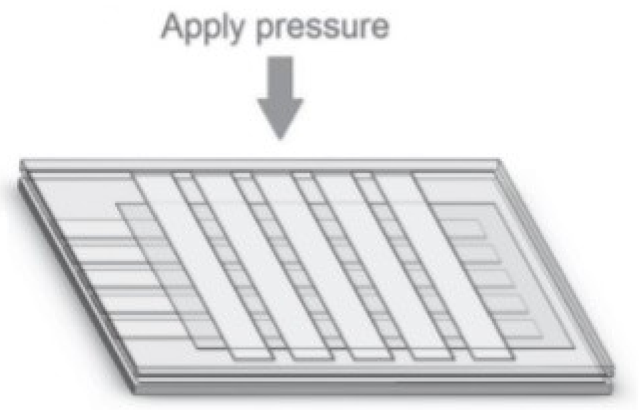

Figure 11 *Capacitive sensing array* [47]

Boutry et al. [48] introduced also an entirely biodegradable sensor that can measure both pressure and strain. This sensor is designed to monitor the progress of tendon repair after surgery. The pressure sensing unit is capacitive and uses the same array formation that is presented in Figure 11. [48] Using the biodegradable sensors to monitor the healing after surgery makes more sense than using non-degradable sensor, since non-degradable sensor would need another surgery to remove the sensor.

One of the applications already presented in this thesis for cardiovascular pressure monitoring was integrating medical stent with MEMS pressure sensor. There are also stents that are made from biodegradable materials, so it is logical to have biodegradable sensor on those as well. One of the biggest problems with biodegradable stent sensor is that while they are passive, the communication distance with external device cannot be too long. Finding the suitable operating frequency is also a challenge. High frequencies can deliver high energy but also increases the amount of energy absorbed by human body and with low frequencies the sensitivity of the sensor gets weaker. [49]

There are already many biodegradable pressure sensors under studies that show promising results. They have good sensitivity and multiple applications where they can be used. Monitoring the healing of surgery is a good example of application that benefits from the biodegradability of the sensor. There are still issues with biodegradable sensors, but the research is ongoing and have taken massive steps during the last five years. Comparing to the non-degradable sensors, the biodegradable sensors have many good qualities, but non-degradable sensors have longer history and the doctors are used to them.

5. CONCLUSIONS

This thesis has discussed implantable pressure sensors, which are a diagnostic tool for doctors to measure pressure inside the body. Compared to non-implantable pressure sensors, the advantages of implantable sensors are that pressure can be measured more directly from a desired location and the monitoring is continuous and more accurate. Disadvantages include the difficult placing of the sensor, which always requires a surgical operation. Operations always include risks for infections.

When designing implantable pressure sensors there are multiple things to take in to account, such as choosing the sensing method, the method of data transfer, and power solutions. For sensing methods, the most commonly used are piezoresistive and capasitive sensing elements, but other techniques are also used. For data transfer and power solutions, it is important to first choose if the implantable pressure sensor is going to be wireless or not. This is an important decision, because it makes significant difference in the monitoring time of the sensor. All these decisions are made based on the desired application of the implantable pressure sensor.

For long-term wireless pressure sensors, the data transferring, long-term accuracy and receiving power are challenges that need to be adressed. The most used techniques for data transferring are using radiofrequencies or an inductive link. Choosing the data transferring method is highly related to power solutions as well as the accuracy of the sensor. The size of the sensor cannot grow too much for the comfort of the patient and the safety of the device needs to be number one priority.

Intracranial and cardiovascular pressures are two instances in which implantable pressure sensors are used. Intracranial pressure is often monitored after traumatic brain injury, because it can increase slowly after a major hit in the head. Increased intracranial pressure can have even lethal consequences, so if the intracranial pressure starts to increase, doctors need to be able to react quickly. This is why an external ventricular drainage -system is the most popular system for monitoring intracranial pressure, because it can drain the cerebrospinal fluid from ventricles in case the pressure starts to increase.

Cardiovascular pressure is measured from many different locations in the circulatory system. Blood pressure values are key element in diagnosing different heart diseases. With implantable pressure sensors the blood pressure can be monitored from different veins or even inside the heart chambers. Besides using the implantable pressure sensors for diagnostic purposes, they can be used for monitoring that the medication or heart assisting devices are working properly.

Biodegradable pressure sensors are the future of implantable pressure sensors. There are many promising models which are now being tested in animals, and in a couple of years they will most likely be undergoing diagnostic tests. The main advantage of biodegradable pressure sensors is that there is no need for removing the sensor, so there is no need for a second surgery that non-degradable pressure sensors require. This lowers the risks for infection and other possible risk factors that every surgical operation has.

This thesis has explored different kinds of implantable pressure sensors for different applications. The importance of continuous pressure monitoring for health of many different types of patients keeps the developing of implantable sensors going in the future as well. There are still only few fully wireless long-term monitoring devices available for doctors. When the patients are able to measure the values at home and send them to the doctors for analysis, it increases the value of the sensor for the patients as well as for the doctors. With the biodegradable pressure sensors the applications will increase as well, which will increase the use of wireless implantable pressure sensors in the future.

REFERENCES

[1] L. Yu, B. J. Kim, and E. Meng, “Chronically implanted pressure sensors: Challenges and state of the field,” *Sensors (Switzerland)*, vol. 14, no. 11, pp. 20620–20644, 2014.

[2] J. A. Potkay, “Long term, implantable blood pressure monitoring systems,” *Biomedical Microdevices*, vol. 10, no. 3. pp. 379–392, 2008.

[3] S. Oh *et al.*, “A dual-slope capacitance-to-digital converter integrated in an implantable pressure-sensing system,” *IEEE J. Solid-State Circuits*, vol. 50, no. 7, pp. 1581–1591, 2015.

[4] R. S. Jakati, K. B. Balavalad, and B. G. Sheeparamatti, “Comparative analysis of different micro-pressure sensors using comsol multiphysics,” *2016 Int. Conf. Electr. Electron. Commun. Comput. Optim. Tech.*, pp. 355–360, 2016.

[5] S. S. Maflin and J. a Vimala, “A comparative analysis on nanowire based MEMS pressure sensor,” *IJCSE_Indian J. Comput. Sci. Eng.*, vol. 3, no. 2, pp. 349–353, 2012.

[6] K. V. Meena, R. Mathew, J. Leelavathi, and A. Ravi Sankar, “Performance comparison of a single element piezoresistor with a half-active Wheatstone bridge for miniaturized pressure sensors,” *Meas. J. Int. Meas. Confed.*, vol. 111, no. April 2016, pp. 340–350, 2017.

[7] M. Mohamad, N. Soin, and F. Ibrahim, “Design of a high sensitivity MEMS piezoresistive intracranial pressure sensor using three turns meander shaped piezoresistors,” *2016 Int. Conf. Bio-Engineering Smart Technol. BioSMART 2016*, vol. 8, 2017.

[8] M. Da Zhou, C. Yang, Z. Liu, J. P. Cysyk, and S. Y. Zheng, “An implantable Fabry-Pérot pressure sensor fabricated on left ventricular assist device for heart failure,” *Biomed. Microdevices*, vol. 14, no. 1, pp. 235–245, 2012.

[9] S. C. B. Mannsfeld *et al.*, “Highly sensitive flexible pressure sensors with microstructured rubber dielectric layers,” *Nat. Mater.*, vol. 9, no. 10, pp. 859–864, 2010.

[10] K. Van Schuylenbergh, R. Puers, F. Rodes, F. Bumy, M. Donkerwolcke, and F. Moulart, “Monitoring orthopaedic implants using active telemetry,” *Eng. Med. Biol. Soc. 1992 14th Annu. Int. Conf. IEEE*, vol. 6, pp. 2672–2673, 1992.

[11] A. Valanarasi and R. Dhanasekaran, “A review on design considerations of implantable antennas,” *Proc. 2016 Int. Conf. Adv. Commun. Control Comput. Technol. ICACCCT 2016*, no. 978, pp. 207–211, 2017.

[12] E. Y. Chow, M. M. Morris, and P. P. Irazoqui, “Implantable RF medical devices: The benefits of high-speed communication and much greater communication

distances in biomedical applications," *IEEE Microw. Mag.*, vol. 14, no. 4, pp. 64–73, 2013.

[13] P. Wang *et al.*, "Long-term evaluation of a non-hermetic micropackage technology for MEMS-based, implantable pressure sensors," *2015 Transducers - 2015 18th Int. Conf. Solid-State Sensors, Actuators Microsystems, TRANSDUCERS 2015*, pp. 484–487, 2015.

[14] G. Kotzar *et al.*, "Evaluation of MEMS materials of construction for implantable medical devices," *Biomaterials*, vol. 23, no. 13, pp. 2737–2750, 2002.

[15] A. Raghunathan and J. K. Antony, "MEMS based intracranial pressure monitoring sensor," *2017 2nd IEEE Int. Conf. Recent Trends Electron. Inf. Commun. Technol.*, pp. 451–456, 2017.

[16] J. A. Hughes, E. C. Jackson, and M. Daley, "Modelling intracranial pressure with noninvasive physiological measures," *2017 IEEE Conf. Comput. Intell. Bioinforma. Comput. Biol. CIBCB 2017*, 2017.

[17] S. Wu, P. Xu, S. Asgari, M. Bergsneider, and X. Hu, "Time series mining approach for noninvasive intracranial pressure assessment: An investigation of different regularization techniques," *2009 WRI World Congr. Comput. Sci. Inf. Eng. CSIE 2009*, vol. 5, pp. 382–386, 2009.

[18] M. N. Khan, H. Shallwaini, M. U. Khan, and M. S. Shamim, "Noninvasive monitoring intracranial pressure – A review of available modalities," *Surg. Neurol. Int.*, vol. 8, pp. 1–7, 2017.

[19] S. K. Kang *et al.*, "Bioresorbable silicon electronic sensors for the brain," *Nature*, vol. 530, no. 7588, pp. 71–76, 2016.

[20] P. H. Raboel, J. Bartek, M. Andresen, B. M. Bellander, and B. Romner, "Intracranial pressure monitoring: Invasive versus non-invasive methods-A review," *Crit. Care Res. Pract.*, vol. 2012, pp. 3–7, 2012.

[21] A. T. Mobashsher and A. Abbosh, "Implantable Intracranial Pressure Monitoring Sensing Antenna with Magnetic Resonance Compatibility," in *Antennas and Propagation (ISAP), 2017 International Symposium*, 2017, vol. 1, pp. 5–6.

[22] M. Frischholz, L. Sarmento, M. Wenzel, K. Aquilina, R. Edwards, and H. B. Coakham, "Telemetric Implantable Pressure Sensor for Short- and Long-Term Monitoring of Intracranial Pressure," *2007 29th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, pp. 514–514, 2007.

[23] A. Atchbahian and R. Gupta, "The Anasthesia Guide." [Online]. Available: https://accessmedicine.mhmedical.com/content.aspx?bookid=1340&sectionid=80036194&jumpsectionID=80036282. [Accessed: 30-Mar-2018].

[24] S. Welschehold *et al.*, "First clinical results with a new telemetric icp monitoring system," *Neurosurgery*, vol. 70, no. MARCH 2012, pp. 44–49, 2011.

[25] A. A. Konstantelias, K. Z. Vardakas, K. A. Polyzos, G. S. Tansarli, and M. E.

Falagas, "Antimicrobial-impregnated and -coated shunt catheters for prevention of infections in patients with hydrocephalus: a systematic review and meta-analysis," *J. Neurosurg.*, vol. 122, no. 5, pp. 1096–1112, 2015.

[26] R. Beer, P. Lackner, B. Pfausler, and E. Schmutzhard, "Nosocomial ventriculitis and meningitis in neurocritical care patients," *J. Neurol.*, vol. 255, no. 11, pp. 1617–1624, 2008.

[27] Integra® and Camino®, "Integra® Camino® Flex Ventricular Catheter Kit (VTUN)," 2016. [Online]. Available: http://occ.integralife.com/index.aspx?redir=detailproduct&Product=755&ProductName=Integra%AE Camino%AE Flex Ventricular Catheter Kit %28VTUN%29&ProductLineName=ICP Monitoring&ProductLineID=11&PA=neurosurgeon. [Accessed: 30-Mar-2018].

[28] M. H. Behfar, E. Moradi, T. Björninen, L. Sydanheimo, and L. Ukkonen, "Design and Technical Evaluation of an Implantable Passive Sensor for Minimally Invasive Wireless Intracranial Pressure Monitoring," *World Congr. Med. Phys. Biomed. Eng. Toronto, Canada*, vol. 51, no. L, pp. 1301–1304, 2015.

[29] M. H. Behfar *et al.*, "Inductive passive sensor for intraparenchymal and intraventricular monitoring of intracranial pressure," *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. EMBS*, vol. 2016–Octob, pp. 1950–1954, 2016.

[30] Integra® and Camino®, "PRESSURE MONITORING CATHETER Model 110-4L," 2010. [Online]. Available: http://occ.integralife.com/products%2FPDFs%2FCamino%2F110-4L.pdf. [Accessed: 02-Apr-2018].

[31] CODMAN & Shurtleff, "Value Analysis Brief : CODMAN ® MICROSENSOR ® ICP Transducer for Intracranial Pressure Monitoring," 2012. [Online]. Available: http://synthes.vo.llnwd.net/o16/LLNWMB8/US Mobile/Synthes North America/Product Support Materials/Brochures/ICP Express and Monitoring VAB MON-43-000.pdf. [Accessed: 02-Apr-2018].

[32] RAUMEDIC, "Raumedic 510k," 2013. [Online]. Available: https://www.accessdata.fda.gov/cdrh_docs/pdf13/K130529.pdf. [Accessed: 02-Apr-2018].

[33] S. Antes, C. A. Tschan, M. Heckelmann, D. Breuskin, and J. Oertel, "Telemetric Intracranial Pressure Monitoring with the Raumedic Neurovent P-tel," *World Neurosurg.*, vol. 91, pp. 133–148, 2016.

[34] J. Fiala *et al.*, "Implantable sensor for blood pressure determination via pulse transit time," *Proc. IEEE Sensors*, pp. 1226–1229, 2010.

[35] N. Gayapersad, S. Rocke, Z. Ramsaroop, A. Singh, and C. Ramlal, "Beyond Blood Pressure and Heart Rate Monitoring: Towards a Device for Continuous Sensing and Automatic Feature Extraction of Cardiovascular Data," *2016 8th Int. Conf. Comput. Intell. Commun. Networks*, pp. 261–265, 2016.

[36] Nour Health, "LET'S PREVENT BEFORE IT'S TOO LATE," 2017. [Online].

Available: https://nourhealth.sg/cardiovascular-disease.html. [Accessed: 02-Apr-2018].

[37] E. Y. Chow, A. L. Chlebowski, S. Chakraborty, W. J. Chappell, and P. P. Irazoqui, “Fully wireless implantable cardiovascular pressure monitor integrated with a medical stent,” *IEEE Trans. Biomed. Eng.*, vol. 57, no. 6, pp. 1487–1496, 2010.

[38] R. Pais, A. Duttaroy, M. Dobbs, E. Pastalkova, and J. Wolever, “Implantable Blood Pressure Monitoring Cuff for Small Laboratory Animal,” in *Microsystems for Measurement and Instrumentation (MAMNA)*, 2012, pp. 1–3.

[39] L. Hubbert, J. Baranowski, B. Delshad, and H. Ahn, “Left Atrial Pressure Monitoring with an Implantable Wireless Pressure Sensor after Implantation of a Left Ventricular Assist Device,” *ASAIO J.*, vol. 63, no. 5, pp. e60–e65, 2017.

[40] E. Y. Chow, S. P. Sanghani, and V. Ramesh, *Emerging research in wireless and MEMS for medical applications*. Elsevier Ltd., 2016.

[41] Abbot, “CARDIOMEMS™ HF SYSTEM: IMPLANT PROCEDURE VIDEO,” *September 07*, 2017. [Online]. Available: https://www.sjm.com/professionals/resources-and-reimbursement/video-and-media/hf-cardiomems-hf-system-implant?halert=show&clset=af584191-45c9-4201-8740-5409f4cf8bdd%3Ab20716c1-c2a6-4e4c-844b-d0dd6899eb3a#header. [Accessed: 31-May-2018].

[42] Abbot, “HOW THE CARDIOMEMS™ HF SYSTEM WORKS VIDEO,” *August 15*, 2017. [Online]. Available: https://www.sjm.com/en/patients/heart-failure/our-solutions/pulmonary-artery-pressure-monitoring/cardiomems-hf-system/how-it-works. [Accessed: 31-May-2018].

[43] Abbot, “CARDIOMEMS™ HF SYSTEM,” *August 22*, 2016. [Online]. Available: https://www.sjm.com/en/patients/heart-failure/our-solutions/pulmonary-artery-pressure-monitoring/cardiomems-hf-system. [Accessed: 31-May-2018].

[44] R. Li, L. Wang, D. Kong, and L. Yin, “Recent progress on biodegradable materials and transient electronics,” *Bioact. Mater.*, pp. 1–12, 2017.

[45] M. Luo, W. Shen, and M. G. Allen, “MICROFABRICATED PLGA / PVA-BASED COMPLETELY BIODEGRADABLE PASSIVE RF PRESSURE SENSORS Georgia Institute of Technology , Atlanta , GA , USA University of Pennsylvania , Philadelphia , PA , USA,” pp. 101–104, 2015.

[46] V. F. Annese, D. De Venuto, C. Martin, and D. R. S. Cumming, “Biodegradable pressure sensor for health-care,” *2014 21st IEEE Int. Conf. Electron. Circuits Syst. ICECS 2014*, pp. 598–601, 2015.

[47] C. M. Boutry, A. Nguyen, Q. O. Lawal, A. Chortos, S. Rondeau-Gagné, and Z. Bao, “A Sensitive and Biodegradable Pressure Sensor Array for Cardiovascular Monitoring,” *Adv. Mater.*, vol. 27, no. 43, pp. 6954–6961, 2015.

[48] C. M. Boutry, B. C. Schroeder, Z. Bao, A. Legrand, and P. Fox, “A sensor measuring deformation and pressure, entirely biodegradable, for orthopedic

applications," *Proc. - 2016 IEEE Biomed. Circuits Syst. Conf. BioCAS 2016*, no. 622362, pp. 144–147, 2017.

[49] J. Park, J. K. Kim, S. J. Patil, J. K. Park, S. A. Park, and D. W. Lee, "A wireless pressure sensor integrated with a biodegradable polymer stent for biomedical applications," *Sensors (Switzerland)*, vol. 16, no. 6, 2016.