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Modeling of On-Chip Biosensor for the in Vivo Diagnosis of Hypertension in Wireless Body Area Networks

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ABSTRACT High Blood Pressure (HBP) over a long period of time leads to a medical condition known as Hypertension (HTN or HT), in which the arterial blood pressure is persistently inflated. In this research, a blood pressure biosensor has been implemented that monitors the different stages of hypertension by measuring the varying blood pressure values. Further, a system design has been proposed for the theranostics (combination of diagnosis and therapy) of hypertension. The proposed sensor takes blood pressure as the input, and gives the corresponding electrical signal variations at the output, so as to detect the exact stage of hypertension. The working principle of this BP sensor is based on the electrostatic transduction mechanism. The proposed system aims to design a low-cost, easily available, implantable lab-on-chip (LoC) platform for the continuous measurement of blood pressure by keeping track of the patient history, so as to prevent chronic hypertensive disorders. Further, such an implantable LoC theranostic platform is among the best possible solutions for the e-healthcare systems, owing to its potential in a wireless body area network (WBAN) using Internet of Things (IoT) and other similar technologies.

INDEX TERMS Lab-on-chip, implantable devices, hypertension, blood pressure biosensor, IoT.

I. INTRODUCTION

Blood pressure (BP) is defined as the pressure exerted upon the blood vessels walls due to the circulation of blood. BP is generally measured in mmHg (millimetres of mercury). It is expressed in terms of the systolic (maximum) pressure over diastolic (minimum) pressure. BP is one among several vital signs of the body, along with heart rate, respiratory rate, body temperature, and oxygen saturation [1]–[3]. In adult, the normal resting blood pressure is observed to be approximately 120/80 mmHg [4].

BP varies in nature, and generally depends on the activity, disease state, situation, and other medical conditions of a person. The endocrine and nervous systems play significant roles in regulating the BP. Due to a disease state, a low BP condition is known as hypotension, while persistent high BP condition is referred to as hypertension [5]. Both of these conditions arise because of several mild or severe causes, and can persist in a person over a long duration, or may be of abrupt onset. Hypertension (HTN or HT), also known as high blood pressure (HBP), is basically defined as an abiding medical condition that can cause the insistent increase of BP in the arteries [6]. Long-term HTN may lead to several other medical complications, such as strokes, cardiovascular diseases [7], [8], and renal failure. Hypotension over a long term is less prevalent than long-term HTN.

HTN often goes uncharted, due to its asymptomatic nature and infrequent monitoring [9]. This sustained HTN over a

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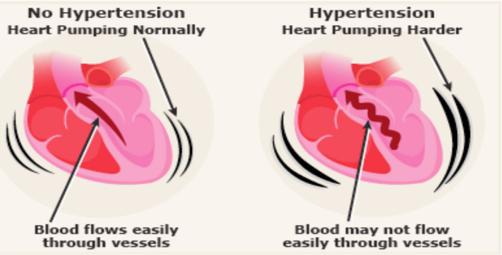


FIGURE 1. HTN effect on heart function [14].

span of time is one of the dominant risk factors for prolonged kidney disease, peripheral artery disease (PAD), aortic aneurysm, strokes, hypertensive heart disease, and coronary artery disease [10]–[12].

Essentially, arterial HTN can be an alarm for other complications, and can cause lifelong adversities. Moreover, due to arterial pressure levels, the walls of arteries experience a lot of mechanical stress, as shown in Fig. 1, and within the arterial walls, a debilitated tissue known as atheroma grows as a result of elevation in the workload of the heart, owing to higher pressure. The higher this pressure, the more stress in the heart, leading to further progress of atheroma. The consequence of all this is the thickening, weakening, and enlargement of the heart muscles over time [13].

A. *NEED FOR BP MEASUREMENT*

Monitoring the variations in the absolute values of internal pressures permits the exact diagnosis and tracing of medical intervention progress. The current medical practice in clinics allows the pressure data of a single patient pressure data point to be obtained. However, the information by this method offers only a restricted snapshot of the dynamic profile of pressure within the organ of interest. With current medical practice, it is not possible to capture trough or peak values or profile variations, despite the fact that such information is necessary, and can indicate in a timely manner the essential clues for suitable intervention strategies. Several diseases and conditions are related to the depression or elevation of internal pressures from a healthy and normal range, thus motivating the requirement for an implantable chip containing pressure sensors, in order to periodically monitor the pressure profile. Pressure in different body organs (e.g., eye, brain, bladder, and heart) is markedly regulated, and its value may be an implication of disease progression or patient health [15]. In those diseases where it is not possible to regulate these pressures, function impairment or even death may be caused. Further, at the microscopic level, these abnormal pressures may also induce the damage of cells [16].

One such example of internal pressure is blood pressure (BP). High BP is categorized into primary (essential) or secondary. The majority of the cases (almost around (90–95%)) are of primary high BP, which results from various genetic factors, or from nonspecific lifestyle factors, such as overweight or obesity, excess salt concentration, smoking, or drinking. The remaining (5–10 %) cases come under secondary high BP category, which occurs from an existing identifiable reason, like an endocrine disorder, excess use of birth-control pills, chronic renal disease, or because of the narrowing of the kidney arteries [17]. Some patients experience stress in clinical settings, which may cause perturbations in the BP measurements [18]. Therefore, advancements in sensing technology are required to support accurate, easy to use, and continuous pressure monitoring. Such sensors can be extended to the outside of clinical settings with the help of medical team collaboration, in order to empower more effective disease management by remote advisory and regular monitoring of, in particular, home-based patients.

II. BP SENSOR

A BP sensor is usually designed to monitor and record either the systolic or diastolic BP, or the mean arterial pressure, by utilizing different techniques, such as the oscillometric method [19], or auscultatory method. The pulse rate can also be reported by this sensor. Figure 2 shows the working principle of this sensor:

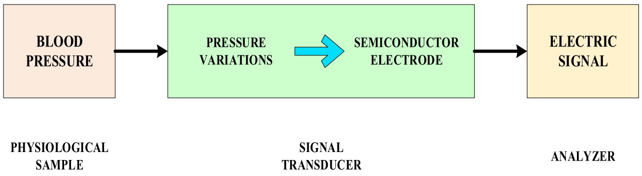


FIGURE 2. Working principle of the BP sensor.

A. *CURRENT METHODS OF BP MEASUREMENT*

In medical science, it is very common practice to observe and regulate the cardiovascular system pressure, as it indicates the overall health condition of a person [20]. Continuous and long-term BP monitoring is very much required for numerous critical applications, such as for intracardiac pressure measurement in the case of patients suffering from high risk of congestive heart failure, observing an animal's cardiovascular function in genetic and disease research, monitoring hypertensive patients, administering repaired aneurysms, or the monitoring of patients with spinal cord injury [21], [22]. The following methods are intensively used for the measurement of BP:

1) NON-INVASIVE TECHNIQUE

Non-invasive methods for measuring the BP of a person have been extensively explored [23]. Such techniques usually derive the pressure from the interaction of tissues with high-energy waves that are inflicted on the body, either as electromagnetic radiations (e.g., X-ray, light ray) or in the form of sound waves. However, this approach is not very accurate, and does not provide adequate precision [16]. Most of the techniques based on this approach employ a wrapped cuff around an extremity (commonly the arm), which is then inflated, resulting in blood flow occlusion [24]. After this, the cuff pressure is reduced, thereby allowing the return of arterial blood flow. Routine BP Non-invasive blood pressure (NIBP) methods can detect only the change in pulse pressure, and thus for correct interpretation, more appropriate information about the patients and events is required [25]. The pros and cons of this technique are as follows:

a: PROS

- Implementation of this method is easy and convenient.
- This approach is free from the difficulties associated with invasive techniques (including infections, complications, and discomfort).
- Easily transportable.

b: CONS [26]

- Reliability is a concern with this approach, as accuracy issues persist, and for accurate measurements, a pulse with a consistent rhythm and rate is required.
- The cuff used in this approach should be of appropriate size, with the capability of covering about two-thirds of the upper arm, or in the case of any other extremity (other than the arm), it should be able to cover 20 % more than the extremity diameter. If the cuff being used is too small, it will result in BP over-estimation.
- The other main issue is the hindrance in accurate BP measurement due to unintentional limb movement. The concerned limb should be aligned with the heart.
- With the non-invasive techniques, very low pressures cannot be precisely measured.

2) INVASIVE TECHNIQUE

Invasive methods involve inserting the catheters inside the patient's body. This catheterization technique not only enables the targeted probing of pressure in specific body regions but also assures the accuracy required for effective chronic monitoring, and currently serves as the gold standard for patient care in many conditions [16]. However, prolonged catheterization of bed-bound patients hinders normal and ambulatory behaviour (e.g., psychological white-coat effects that show false positives); and this catheter breaches the skin, leaving the patient more prone to infection [27].

a: PROS

- Gold standard of accuracy.
- Very useful when rapid changes in blood pressure are anticipated.
- Used when long-term measurement in sick patients is required, as it avoids the problem of repeated cuff inflation.

b: CONS [26]

- Catheter can be occluded by blood or tissue.
- Needs reposting of transducer level with change in head position.
- Transducer must be at level with the heart.
- Complications of arterial cannulation, such as:
    - Infection
    - Damage to local structures, e.g., nerves
    - Thrombosis
    - Air embolus
    - Infarction of distal limb
    - Hemorrhage
    - Inadvertent arterial injection of drugs

B. NEED FOR IMPLANTABLE BP SENSORS

As discussed above, the most common methods for blood pressure measurement are through a catheter-based system, or through the use of an external cuff [28]. The fundamental reasons why these methods fail for continuous and long-term pressure measurement are the intermittent measurement, occlusion of blood flow, discomfort, and percutaneous connections (e.g. an external cuff utilizing the oscillatory method). In addition, non-invasive BP measurement techniques are usually less stable and less accurate than invasive methods. In contrast, the methods using a catheterization procedure and a pressure transducer are very accurate, but they prohibit the person from free movement, and may be unsafe for long-term use, due to several complications, such as infection, and trauma to the arterial vessel [21]. Recent advancements in the field of implantable devices can overcome the diagnostic voids of prohibition of free movement or occlusion of blood flow, and have the capability of providing accurate and continuous data [29]. In addition, in certain cases, such as when the blood pressure at a specific area of the body needs to be monitored over an extended period of time, implantable devices prove to be the only efficient solution.

III. MATERIALS AND METHODS

BP is expressed by two measurements, the systolic and diastolic pressures, which are the maximum and minimum pressures, respectively, in the arterial system [30]. As mentioned in section II, there are many techniques for the non-invasive and *in vitro* measurement and monitoring of BP. In general, no such method provides accurate and continuous measurements; and also, *in vitro* techniques may lead to infections. The advantages of fully implantable sensors make them the best choice to overcome all of the above mentioned issues. Furthermore, there are variations in BP measurements if BP is measured at the doctor's clinic, or at home (for example, as specified in Table 1); and for the detection of HTN, many such readings are required. Table 2 describes the different stages of HTN according to the measured values of BP [31].

TABLE 1. Comparison of clinical and home BP range [30].

Type	**Systolic BP (mmHg)**	**Diastolic BP (mmHg)**
Clinical BP	140	90
Home BP	135	85

Thus, for detecting the different stages of HTN, a pressure transducer is required for measuring the BP. A pressure sensor

TABLE 2. BP classification for different stages of hypertension (HTN) [31].

Category	Systolic (mmHg)	Diastolic (mmHg)
Normal	90–119	60–79
High Normal (Pre HTN)	120–139	80–89
Stage 1 HTN	140–159	90–99
Stage 2 HTN	160–179	100–109
Stage 3 HTN (Hypertensive Emergency)	≥180	≥110

TABLE 3. Comparison of different electromechanical pressure transducers [35].

Features	Electrostatic	Piezoelectric
Accuracy	More critical than the piezoelectric pressure transducer	High Accuracy
Ageing	Age-dependent instability	Age Stability (Low Ageing)
Size	Smaller in size	Comparatively larger in size
Component Cost	Generally, has lower component cost	Generally, has higher component cost
MEMS Implementation	Easy to implement in MEMS	Difficult to integrate with MEMS
Energy Density	Energy density decreases with the decrease in separation between the capacitor plates	Higher energy density
Frequency Dependence	No dependence	Highly frequency-dependent
Issues	Requires initial polarizing charge	Possible bio-compatibility issue

measures the pressure, typically of gases or liquids [32], [33]. It usually acts as a transducer, and generates a signal (say electrical) that is proportional to the pressure imposed. For our application, we want to model an implantable electromechanical transducer, because such transducers are best suitable, since when implanted inside the body, they can not cause any hindrance, and have no biocompatible issues (unlike electromagnetic, optical sensors etc.). This electromechanical pressure transducer can be implemented in two ways [34], as:

1. Capacitive (Electrostatic) Pressure Transducer, or,
2. Piezoelectric Pressure Transducer

Table 3 describes the various features of electrostatic and piezoelectric transducers. Based on our application requirements, the electrostatic transduction method seems to be the most suitable. The main advantage of this technique is that it is easily possible to realize this as a micro-electromechanical system (MEMS). The most essential feature of implants is that they should have a small size, and this can be achieved by the electrostatic transducer structure. In piezoelectric transducers, the design parameters are mostly determined by the material properties. So keeping in consideration the small volume allocated to the implantable sensor, making a flexible piezoelectric transducer using conventional material is strenuous. Capacitive sensors have considerably advanced over the last decade [22], [36]–[41]. In 2018, Sebastián *et al.* described an integrated wireless pressure sensor based on the touch mode capacitive principle for observing ventricular pressure [39]. Mishra *et al.* implemented another capacitive pressure sensor design [41], in which the deflection of a circular diaphragm is measured in response to the blood pressure, and consequently, the capacitance is of the order of fF/bar of pressure (1 Bar = 750.062 mm Hg). In 2020, Rao *et al.* [38] presented a MEMS clamped pressure sensor based on the capacitive transduction principle with the operating pressure range of (0 to 0.16) MPa. On the application of pressure, the diaphragm deflects, and causes the change in the capacitance in fF with the maximum value of 59.6 fF for a 5 μm thick diaphragm. The following subsections describe the detection principle, design parameters, and implementation of the proposed pressure sensor.

A. DETECTION PRINCIPLE

The proposed sensor takes blood pressure as the input, and gives the corresponding electrical signal variations at the output, so as to detect the exact stage of hypertension. The working principle of this BP sensor is based on the electrostatic transduction mechanism, which consists of a variable capacitor whose capacitance is varied as a function of blood pressure variations at the input. As the blood pressure varies at the input, the distance between the two electrodes of the capacitor transducer changes; leading to the capacitance variations at the output.

It is then possible to calculate the electrostatic energy of the capacitor as a function of displacement, as shown below:

$$\mathrm{W_{electrostatic}} = (1(\mathrm{C(x).V^2}))/2$$

where,

V = capacitor voltage

C(x) is the capacitance as a function of displacement

Displacement and pressure are related through force, as:

Force = Pressure × Area

and, Force $\approx 1/\mathrm{d}^2$

where, pressure is the blood pressure given as the input, and ‘d’ is the displacement of the transducer due to the application of pressure.

Various standard topologies of the electrostatic transducer, like area-sensitive and gap-sensitive [42], [43], produce less capacitance on the deflection of electrodes. Figure 3a below therefore shows a more advanced geometry that incorporates the sensitivity of both area and gap by introducing a modified finger element with angled sidewalls, in order to maximize the obtainable capacitance variations.

B. DESIGN PARAMETERS

- x: Displacement of the mobile part of the Interdigitated comb structure
- h, j: Initial overlap length of the mobile and fixed parts of the structure
- g_o: Initial gap between the electrodes, as shown in the figure
- g(x, A): Gap between the fingers as a function of angle A and displacement x
- h(x, A): Overlap between the fingers as a function of angle A and displacement x
- ε: Permittivity of the material
- A: Angle given in the shape of the electrode
- F_t: Height or width of the electrode
- P_2, B_2, H_2: Various dimensions of the electrode

C. IMPLEMENTATION

The Finite Element (FEM) Analysis Software "COMSOL Multiphysics" is used to implement the modified on-chip biosensor design shown in Fig. 3 for the application of diagnosing the different stages of hypertension. The BP of the patient needs to be monitored regularly, so as to determine whether he or she is suffering from hypertension or not, or from which stage of hypertension Thus, to implement the sensor design for our application, the BP record (systolic and diastolic values) of the patient is provided at the input of the sensor.

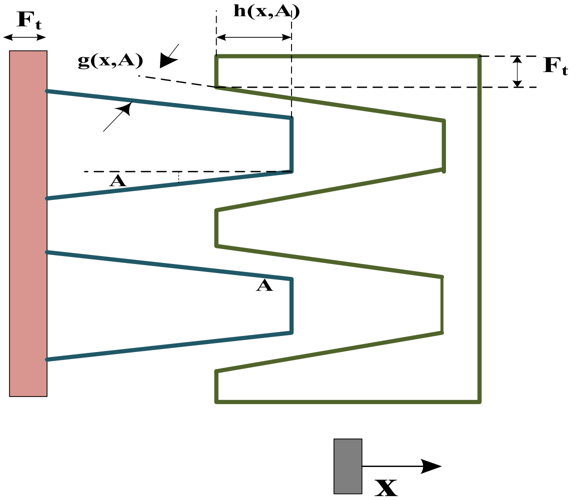


FIGURE 3. Interdigitated triangular (Area and gap sensitive) electrode geometry.

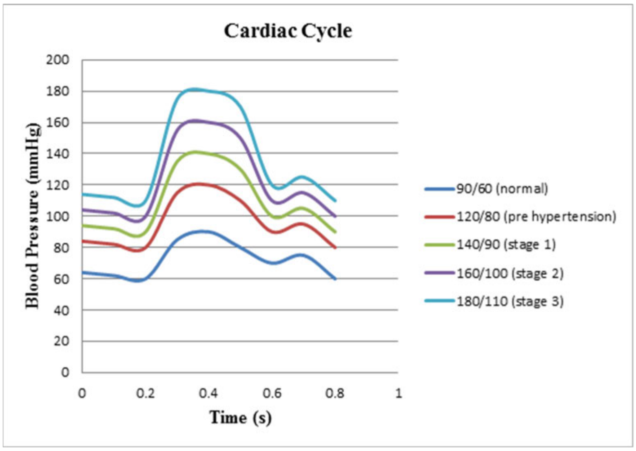


FIGURE 4. Cardiac cycle for different stages of hypertension.

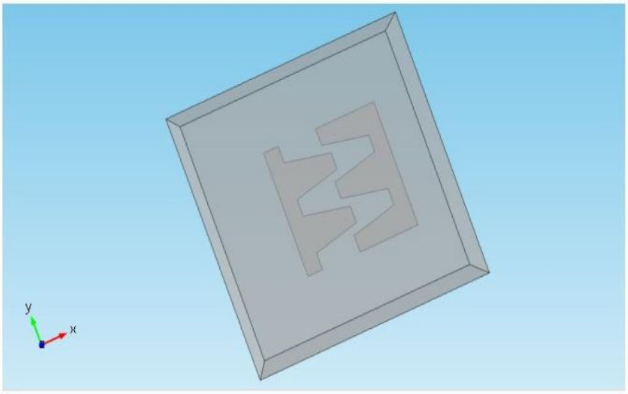


FIGURE 5. Geometry implementation.

For better estimation and convenience purposes, it is better to give a cardiac cycle at the input of the sensor, since one cardiac cycle contains both the systolic and diastolic values of BP. One cardiac cycle is of about 0.8 s, and out of this duration, systole occupies almost about 0.3 s (i.e., about 1/3 of the cardiac cycle duration), while the remaining 0.5 s (i.e. about 2/3 of the cardiac cycle duration) [44] is occupied by diastole. Figure 4 shows the cardiac cycles for different blood pressure ranges in accordance with Table 2

Figure 5 shows how the required sensor geometry is designed in COMSOL Multiphysics. The left comb drive with two comb teeth as shown in the figure has been given a fixed constraint, and is immobile. Whereas the right comb drive with three comb teeth is movable by the application of suitable load (for example, force or pressure).

The implantable sensor geometry containing two comb drives is surrounded by the environment where it needs to be implanted, and as shown in Fig. 5, this environment is shown by a box.

It has been found that the BP sensor can be implemented in the brachial artery (at the upper arm), in the femoral artery (at the thigh) [45]–[48], or at the heart near the aorta.

Based on the advantages and disadvantages of implanting the sensor at these locations, we decided to implant our sensor at the heart near the aorta to monitor hypertensive patients. This will have the advantage of measuring the central blood pressure (CBP). CBP is also known as aortic pressure, i.e., the pressure in the aorta close to the heart, and it has shown

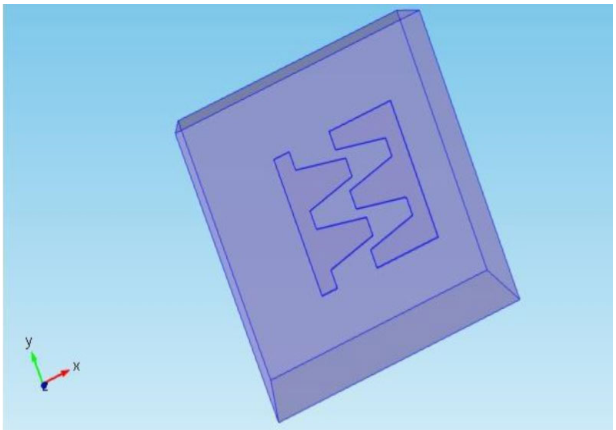


FIGURE 6. Illustration of the cardiac environment.

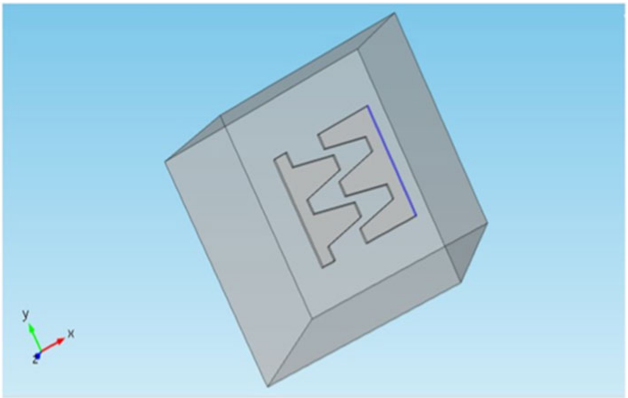


FIGURE 7. Boundary load application.

that CBP is more strongly related to vascular diseases and its consequences, than the traditional upper arm BP. The various effects of different hypertension medications can also be distinguished by the CBP, which generally cannot be attained by the upper arm BP and pulse wave velocity. Higher CBP levels imply that the heart has to work harder to do its job, and thus provide the indication of heart failure. CBP also governs the pressure in the blood vessels feeding the brain. If the CBP is too high, it may eventually lead to strokes and aneurysms [49].

The human heart is a hollow, four-chambered muscular organ, and the muscles of the heart are known as cardiac muscles. Cardiac or Heart muscle is striated and involuntary, and is one of the three major types of muscles found in the human body. So, the sensor geometry is surrounded by a box (shown blue in Fig. 6) having the properties of cardiac muscle, such as density of 1,090 kg/m^3, and Young's modulus of 6.8 kPa [50], [51].

For implantable sensors, the material used for sensor fabrication should be biocompatible, non-toxic, and should not hinder normal functions of the body. In the proposed sensor geometry, Silicon is used owing to its biocompatible and bio resorptive properties, which make it non-cytotoxic, and useful for implants. The highlighted portion in Fig. 7 shows the area where the boundary load is applied. In our application, this

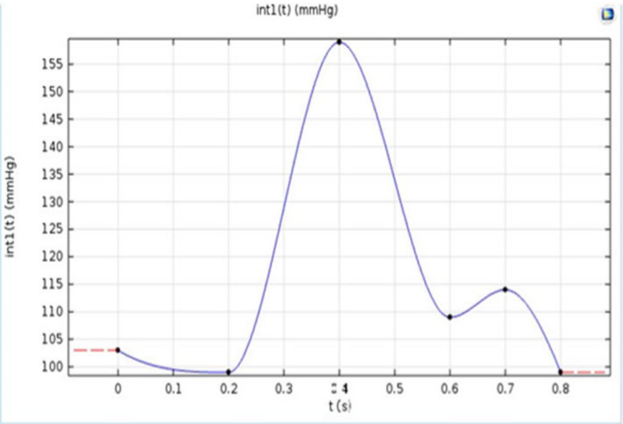


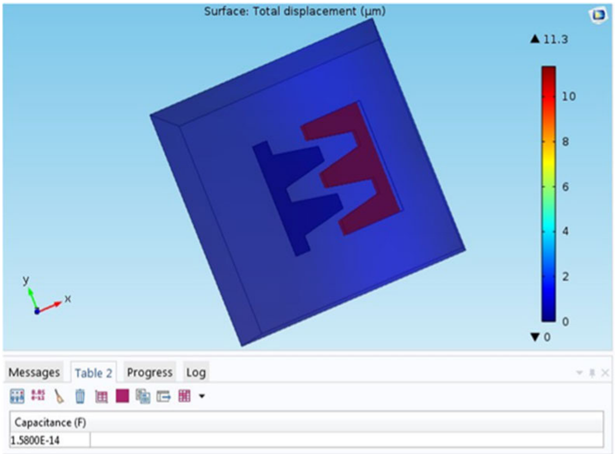
FIGURE 8. Cardiac cycle of 159/99 mmHg blood pressure as boundary load.

boundary load is the cardiac cycle constituting the systolic and diastolic values of BP, as Fig. 4 shows.

Figure 8 plots the cardiac cycle for the BP value of 159/99 mmHg, which comes under stage 1 hypertension. After applying the input, the model is simulated, in order to get the corresponding displacement and capacitance values.

IV. RESULTS AND DISCUSSION

When the cardiac cycle is applied as a boundary load to the movable comb drive shown in Fig. 8, this movable comb drive will move in the negative x- direction towards the fixed comb drive. The movable (right-side) comb drive will displace from its position according to the systolic and diastolic values of BP in the cardiac cycle. Because of this displacement, the distance and gap between the two comb drives will also change. The two comb drives when initially charged act as two electrodes of a capacitor, and according to the electrostatic principle, as the gap between the two electrodes decreases, the capacitance will increase.



Capacitance (F)
1.5800E-14

FIGURE 9. Displacement and capacitance values after simulation.

Figure 9 shows the original, as well as the displaced geometry. The displacement of the movable right-side comb drive

TABLE 4. Displacement and capacitance values corresponding to different blood pressure values.

Stages		Pressure bands (mmHg)	Displacement (μm)	Capacitance (10^{-14} F)
Normal	1	90/60	4.41	1.48
	2	119/79	7.08	1.515
High Normal (Prehypertension)	pre 1	120/80	7.63	1.548
	pre 2	139/89	8.95	1.5643
Stage 1 Hypertension	1a	140/90	9.45	1.5678
	1b	159/99	11.3	1.5800
Stage 2 Hypertension	2a	160/100	11.7	1.5927
	2b	179/109	13.3	1.6069
Stage 3 Hypertension (Hypertensive Emergency)	3a	180/110	14.8	1.6258
	3b	200/120	15.3	1.65

is observed to be 11.3 μm towards the fixed left comb drive by the application of blood pressure of 159/99 mmHg as a boundary load. Due to this displacement, the capacitance is calculated to be 1.58^{-14} Farads (F). Similarly, by applying different blood pressure values, the displacement and corresponding capacitance values can be calculated. Table 4 shows the displacement and capacitance values when various BP values are applied according to the different stages of hypertension:

For every stage, we have taken two samples, so that we will be able to find the displacement and capacitance bands for different stages of hypertension. These bands are the indications of particular stages of hypertension, and can be applied further as input to an implantable drug delivery system that will give the medicine to the patient according to the particular type of band.

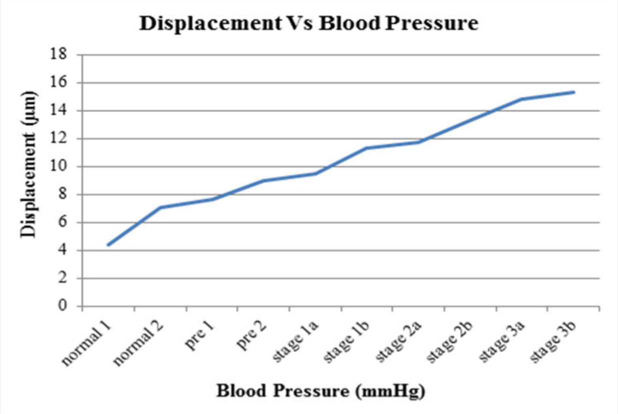


FIGURE 10. Displacement vs. blood pressure graph.

Figure 10 shows that with the increase in blood pressure from normal stage to hypertensive emergency stage (stage 3), the displacement of the movable right-side comb drive also increases non-linearly.

With the increase in displacement shown in Fig. 10, the distance and gap between the two comb drives decreases. Since the two comb drives act as electrodes when initially charged (say with a voltage of 1 V), and by the application of the electrostatic principle, the capacitance between the two electrodes (comb drives) also increases.

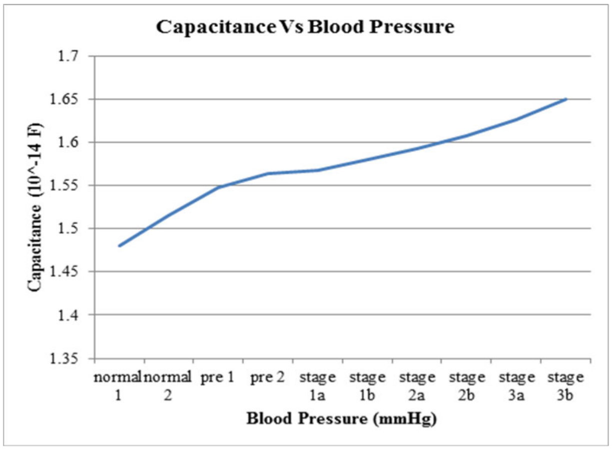


FIGURE 11. Capacitance vs. blood pressure.

Figure 11 shows the non-linear increase in capacitance with the increase in blood pressure from the normal stage to the hypertensive emergency stage (stage 3). This increase in capacitance is due to the decrease in gap between the two comb drives on the application of different values of blood pressure.

V. CONCLUSION

For the different stages of hypertension, by applying different blood pressure values as input to the modified pressure transducer geometry, as required, the corresponding capacitance bands are found whose values are of the order 10^{-14} Farads. Table 5 shown below specifies the displacement and capacitance bands for the various stages of hypertension

TABLE 5. Displacement and capacitance bands corresponding to different stages of hypertension.

Stages	Displacement (μm)	Capacitance (10^{-14} F)
Normal	4.4 – 7.1	1.4 – 1.52
High Normal (Prehypertension)	7.6 – 9.0	1.54 – 1.565
Stage 1	9.3 – 11.5	1.567 – 1.58
Stage 2	11.7 – 13.5	1.59 – 1.61
Stage 3	≥ 14	≥ 1.62

In comparison to the already existing sensor designs discussed in the literature [36]–[39], [41], the proposed sensor geometry is much more feasible for monitoring the hypertensive patients, and aids in their critical care. This is because the complete cardiac cycle indicating the systolic and diastolic values is applied as an input, rather than single pressure values. The capacitance values of this sensor are of the order 10^{-14} F, and these can be improved and optimized by using an array of such pressure transducers, leading to the more appropriate and timely sensing of the hypertension stage. Additionally, this sensor can be useful in Energy Harvesting applications, as specified in the next section. This sensor can further be implemented in the Wireless Body area network (WBAN), and can be integrated into E-healthcare platforms, owing to the advancements in digitization. Some more related literature can be studied in the references [54]–[58].

VI. FUTURE WORK/APPLICATIONS

In this study, the hypertension cases for a normal patient are considered without sensing his/her other medical conditions, such as lipid profile, cholesterol level, glucose level, and renal disorders. For future work, a new design can be proposed for a patient suffering from diabetes mellitus or any other clinical disorder, by changing the corresponding environment around the sensor. By doing so, the hypertension stage of the patient is expected to change from the standard values shown in Table 2.

A. ENERGY HARVESTING

Energy can also be harvested with the help of this model by generating voltage. By the proposed sensor geometry, the voltage of $\leq 10.348\ \mu$V has been generated under normal pressure conditions. If an array of these integrated BP sensors is used, then more voltage can be generated, which is beneficial for energy harvesting applications, such as in the case of pacemakers.

B. THERANOSTICS AND WIRELESS BODY AREA NETWORK (WBAN)

Further, owing to the emergence of lab-on-chip (LoC) technology and the expansion in digitalization practices, it has become possible to integrate several components that include biosensors, power management circuitry, and drug-delivery devices on a single-chip, leading to a completely automated point-of-care theranostic platform. Figure 12 shows one such theranostic platform model for diagnosing and monitoring the different stages of hypertension, and also to automatically provide the medicine of the corresponding hypertension stage to the patient, according to his or her condition [52]:

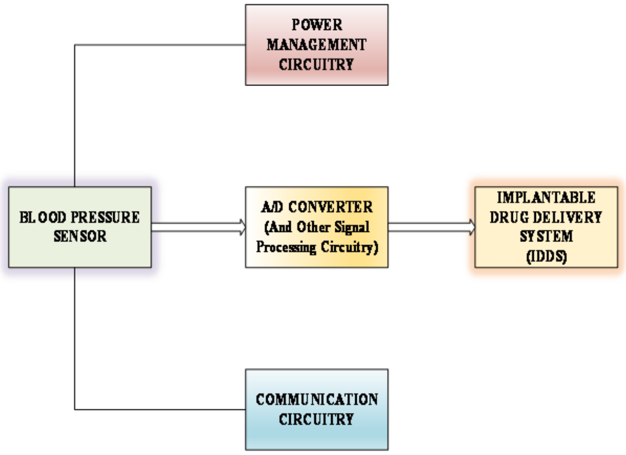


FIGURE 12. Implantable lab-on-chip (LoC) theranostic platform for HTN [52].

The implantable BP sensor geometry proposed in this study and the above-mentioned implantable LoC theranostic platform can be used in a wireless body area network (WBAN), and thus provide a solution for e-healthcare systems [53]. Additionally, the communication protocol required for integrating the proposed sensor with WBAN can also be explored as future work. Figure 13 shows the architecture of a WBAN for an e-healthcare solution using implantable sensing chips:

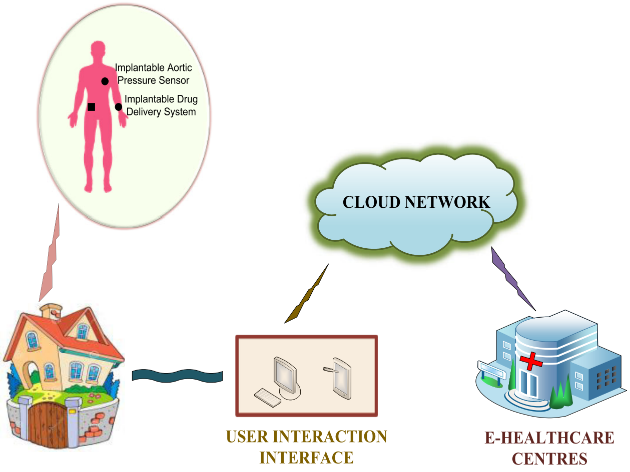


FIGURE 13. Proposed WBAN architecture for hypertension biosensor application.

DECLARATIONS

CONFLICTS OF INTEREST/COMPETING INTERESTS

The authors declare that they have no conflict of interest.

AVAILABILITY OF DATA AND MATERIAL (DATA TRANSPARENCY)

Not applicable

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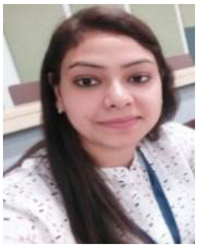

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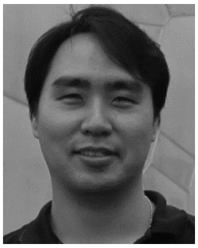

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