Novel Long-Term Implantable Blood Pressure Monitoring System

Peng Cong, Darrin J. Young, and Wen H. Ko
EECS Department, Case Western Reserve University
10900 Euclid Avenue, Cleveland, Ohio, U.S.A.
Email: pxc59@po.cwru.edu

Abstract

A novel long-term implantable blood pressure monitoring system is proposed. The system employs an instrumented elastic cuff, wound around a blood vessel, operating in a linear "diameter v.s. pressure" region of the vessel for real time blood pressure monitoring. The elastic cuff is made of soft bio-compatible rubber, filled with bio-compatible insulating fluid with an immersed MEMS pressure sensor. The MEMS sensor detects the vessel blood pressure wave form with a constant scaling factor, independent of the cuff bias pressure exerting on the vessel. This technique avoids vessel insertion and also substantially minimizes vessel restriction due to the soft cuff elasticity, thus attractive for minimizing long-term adverse biological effects. A scaled up prototype system is developed. It is used to verify and demonstrate the concept.

Keywords

Blood Pressure Sensor, Biomedical Implant, *In Vivo* Monitoring

INTRODUCTION

Long-term *in vivo* real time arterial or veinous blood pressure monitoring of small laboratory animals is critical for various biomedical and genetic research to discover new genetic functions and develop effective treatments for diseases, such as hypertension, obesity, epilepsy, and cancers. This capability will significantly impact the advanced biomedical research as well as future health care. The most common techniques used for monitoring blood pressure in small animals rely on an invasive catheter-tip transducer inserted into an artery or a tail cuff device. The implantable catheter pressure transducers require a complex surgical procedure and potentially suffer from an increased blood pressure, blood clotting, and reduced sensitivity with drift over time. Tail cuffs are inadequate for long-term monitoring due to constraining animal movement, thus resulting in a stress-induced signal distortion. Furthermore, tail cuffs can only obtain systolic and diastolic blood pressure levels instead of a continuous blood pressure waveform, which is critical for advanced biomedical research. Miniature implantable pressure sensor cuffs for tonometric blood pressure measurement have been demonstrated [1]. The technique can solve the forth-mentioned issues associated with the conventional methods but significantly deforms the blood vessel shape, which could cause adverse physiological effects to the vessel property and thus may not be suitable for a long-term monitoring. It is, therefore, highly desirable to develop a long-term implantable blood pressure monitoring system without the aforementioned concerns.

A novel long-term implantable blood pressure monitoring system is presented in this paper. The system employs an instrumented elastic cuff, wound around a blood vessel, operating in a linear "diameter v.s. pressure" region of the vessel for real time blood pressure monitoring, as shown in Figure 1. The elastic cuff is made of silicone or latex rubber, filled with low viscosity bio-compatible insulating fluid with an immersed highly sensitive MEMS pressure sensor. The MEMS sensor enclosed in the cuff measures the pressure waveform, which represents a scaled version of the blood pressure in the vessel, independent of the cuff bias pressure exerting on the vessel. This method avoids vessel insertion, bleeding, and potential blood clotting. Furthermore, since the cuff is made of soft elastic material such as latex or silicone rubber, and the stiffness of the cuff can be much smaller than that of a blood vessel, the restrictive effect on the blood vessel is thus substantially minimized while the soft cuff is in close contact with the vessel. This can reduce the sliding-motion-induced signal drift, thus attractive for tolerating long-term implant variations and minimizing adverse biological effects.

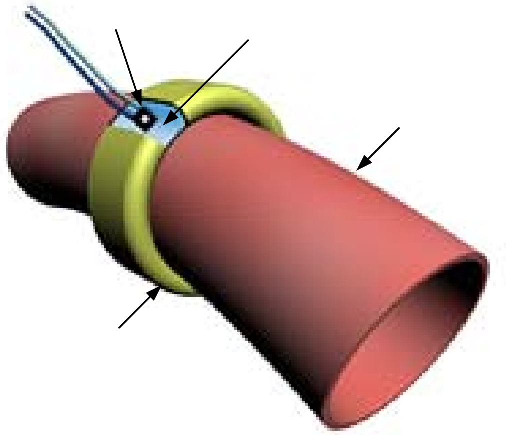


Figure 1. Implantable blood pressure monitoring system

IMPLANT SYSTEM ANALYSIS

Figure 2 shows the cross section of a blood pressure monitoring cuff wound around a blood vessel. Since the fluid in the cuff is incompressible, the volume of fluid is constant, and it is reasonable to assume that the cuff cross-sectional area is constant.

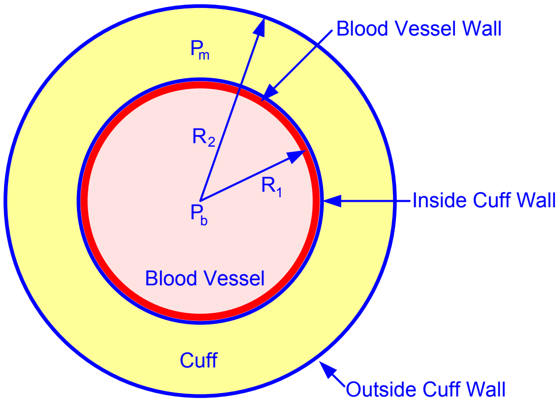


Figure 2. Cross section of cuff wound around blood vessel

The following equations can be derived from analysis.

$$\Delta P_m = \Delta P_b - \Delta P_w , \tag{1}$$

where ΔP_m, ΔP_b, and ΔP_w represent the pressure change measured by the sensor in the cuff, the blood pressure change in the blood vessel, and the pressure change exerted on the blood vessel wall and inside cuff wall, respectively. ΔP_w can be further expressed as:

$$\Delta P_w = \left[(K_{BW} + K_{InsideCW}) / K_{Total} \right] \times \Delta P_b , \tag{2}$$

where K_{BW}, $K_{InsideCW}$, and K_{Total} are the elastic modulus of the blood vessel wall, the cuff inside wall, and the total equivalent elastic modulus associated with the blood vessel wall and the cuff, respectively. Substituting (2) into (1) results in

$$\Delta P_m = (1 - \frac{K_{BW} + K_{InsideCW}}{K_{Total}}) \times \Delta P_b = \eta \times \Delta P_b , \tag{3}$$

where η is a scaling factor. Using the assumption that the cuff cross-sectional area, $\pi R_2{}^2 - \pi R_1{}^2$, is a constant, it can be shown that

$$\frac{\Delta R_2}{\Delta R_1} = \frac{R_1}{R_2} . \tag{4}$$

Thus,

$$\eta = \frac{\frac{R_1}{R_2} K_{OusideCW}}{K_{BW} + K_{InsideCW} + \frac{R_1}{R_2} K_{OutsideCW}} , \tag{5}$$

where $K_{OutsideCW}$ is the elastic modulus of the cuff outside wall.

The pressure waveform measured by the sensor would be the same as that in the blood vessel with a scaling factor. From Equation (5), it can be seen that η is a constant if the elastic modulus of the blood vessel, K_{BW}, is a constant. In a typical blood vessel, the vessel wall consists of three layers: smooth muscle, elastin, and collagen. Elastin and smooth muscle can be appropriately characterized as a Hookean material. Collagen is a protein consisting of a triple helix, which is much stiffer than elastin and smooth muscle. It is responsible for the reinforcement of the vessel wall against rupture at high pressure levels. In a certain blood pressure range, blood vessel walls exhibit a nearly constant elastic modulus as shown in Figure 3 [2][3]. Therefore, a constant scaling factor can be achieved for an accurate real time continuous monitoring of the blood pressure within the linear region.

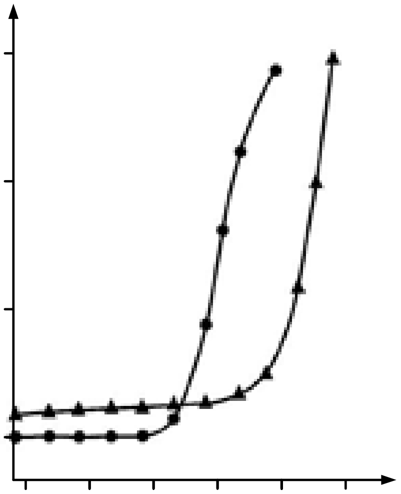


Figure 3 Elastic modulus K vs blood pressure in 8-week-old rats. ● = normotensive, ▲ = hypertensive

The blood pressure waveforms can be expressed as shown in Equation (6).

$$P_b(t) = \frac{1}{\eta} \left[P_m(t) - P_{Bias} \right] , \tag{6}$$

where $P_m(t)$ and $P_b(t)$ are the pressure measured in the cuff and blood vessel pressure as a function of time, respectively. P_{Bias} is the cuff bias pressure. η and P_{Bias} can be accurately obtained by a calibration process during the implant using either a catheter-tip transducer or tail-cuff device. In practice, η could vary over time due to the change in blood vessel elastic modulus caused by diseases and aging [4]. P_{Bias} could also vary due to system implant packaging limitation. However, the changes of η and P_{Bias} are relatively slow and thus can be effectively calibrated by using the systolic and diastolic blood pressure levels, which can be readily obtained by using a tail-cuff device or other ultrasound means [5].

EXPERIMENTAL SETUP

A prototype system with an enlarged dimension is developed for concept demonstration. A segment of latex rubber tubing with a diameter of 3/8 inch and sidewall thickness of 1/16 inch is used to emulate a blood vessel. An elastic cuff made of the similar material but with a much-reduced dimension (a diameter of 5/32 inch and sidewall thickness of 1/64 inch) is wound around the vessel-emulating tubing, as shown in Figure 4. Both tubings are filled with insulating fluid and inserted with MEMS pressure sensors. The bias pressure in the cuff can be adjusted by a clamp. A time varying pressure waveform applied to the vessel-emulating tubing can be generated by a motor shown in the figure. The pressures in the tubing and in the cuff are measured by MEMS pressure sensors simultaneously for comparision. The elastic modulus of the cuff tubing and the vessel-emulating tubing is measured as 94 kPa and 780 kPa, respectively. A scaling factor is thus estimated as 0.074 by Equation (5).

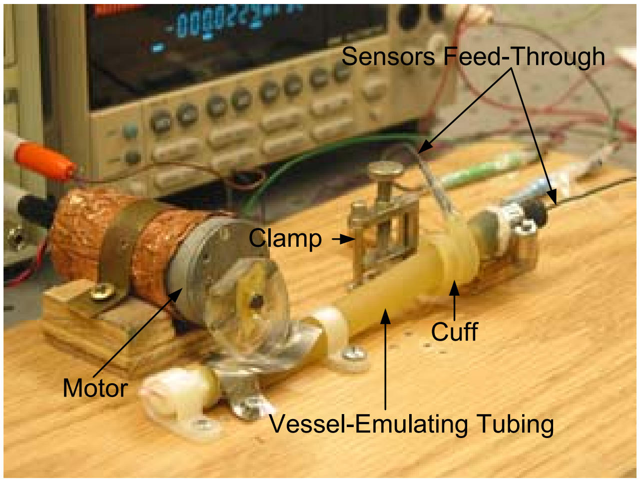


Figure 4. Prototype testing setup

MEMS piezoresistive pressure sensors with a Wheatstone bridge configuration are used for the pressure measurement. Piezoresistive devices are selected for the prototype demonstration due to a nearly constant operating temperature environment. Figure 5a presents a microscope photo of the sensor diaphragm area. The packaged device occupies an area of 1.3 mm x 3.75 mm with the sensor characteristic curve shown in Figure 5b, achieving a sensitivity of 20 µV/mm Hg and an nonlinearity of 0.4 % of full scale.

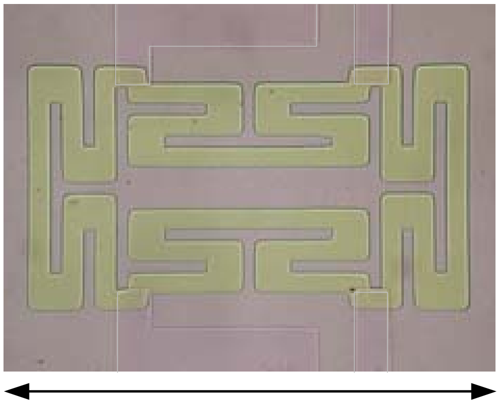


Figure 5a. Piezoresistive pressure sensor

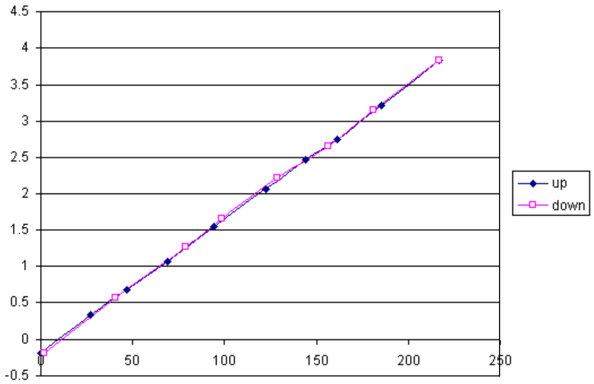
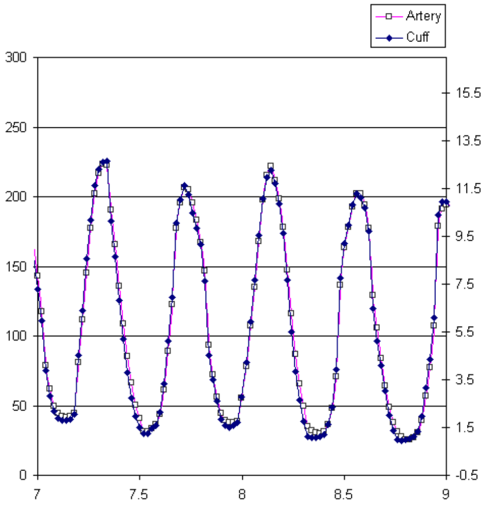


Figure 5b. Piezoresistive pressure sensor characteristics

EXPERIMENTAL RESULT

Figure 6 shows the measured pressure waveforms from the vessel-emulating tubing and cuff at different cuff bias pressures, indicating closely matched waveforms with a constant scaling factor of 0.06, which is independent of the bias pressure and is close to the estimated scaling factor.



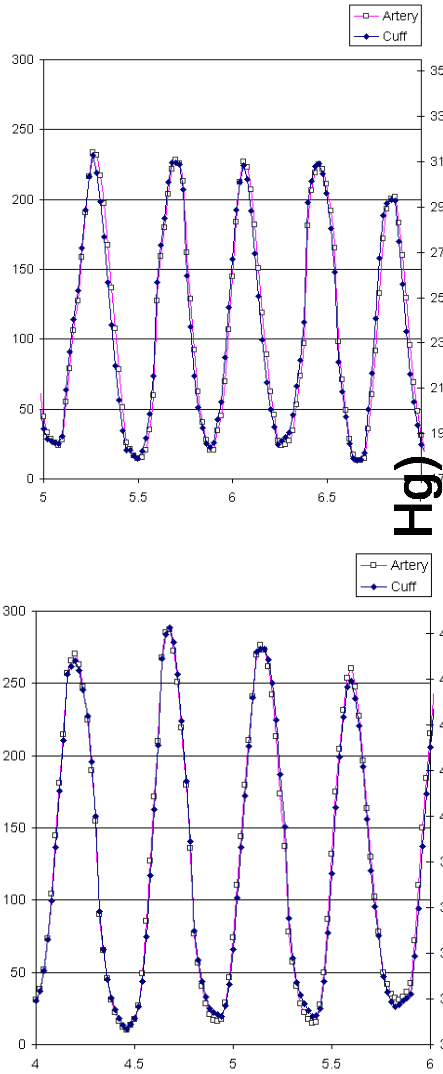


Figure 6. Pressure waveforms in vessel-emulating tubing and cuff at different bias pressures

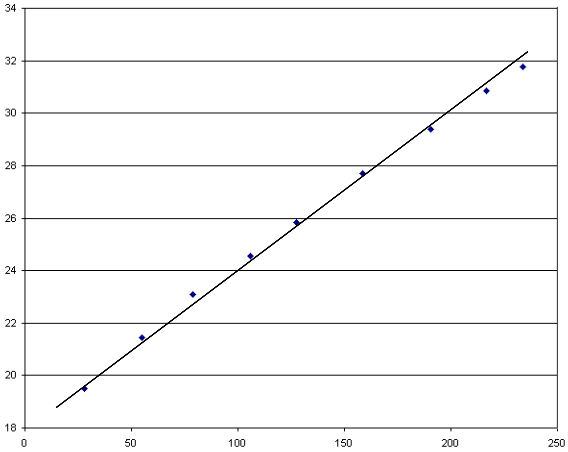


Figure 7. Pressure in cuff vs. pressure in vessel-emulating tubing at 18 mm Hg bias pressure

Figure 7 shows the pressure in the cuff vs. the pressure in the vessel-emulating tubing with a bias pressure of 18 mm Hg above 1atm. The linear characteristic with a 1.2% of full scale nonlinearity indicates a constant scaling factor over the entire cycle. A miniature *in vivo* blood pressure monitoring system based on the proposed technique is currently under development for small animal implant study.

CONCLUSION

A novel long-term implantable blood pressure monitoring system is proposed in this paper. The proposed method avoids vessel insertion, bleeding and potential blood clotting, thus is suitable for long-term implant application. A prototype system with an enlarged dimension has been developed for concept demonstration. The result shows the pressure in a vessel-emulating tubing can be measured by an MEMS pressure sensor in a monitoring cuff with a constant scaling factor independent of the cuff bias pressure.

REFERENCES

[1] B. Ziaie, T. Wu, N. Kocaman, K. Najafi, and D. J. Anderson, “An Implantable Pressure Sensor Cuff for Tonometric Blood Pressure Measurement,” *IEEE Solid-State Sensor and Actuator Workshop*, pp. 216-219, June 1998.

[2] F. L. Wuyts, V. J Vanhuyse, G. J. Langewouters, W. F. Decraemer, E. R. Raman, and S. Buyle, “Elastic Properties of Human Aortas in Relation to Age and Atherosclerosis: a Structural model,” *Phys. Med. Biol.*, Vol. 40, pp. 1577-1597, 1995, UK.

[3] R. G. Gosling and M. M. Budge, “Terminology for Describing the Elastic Behavior of Arteries,” *Hypertension*, Vol. 41, No. 6, pp. 1180-1182, June 2003.

[4] A. W. van Gorp, D. S. van Ingen Schenau, A. P.G. Hoeks, H. A.J. S. Boudier, R. S. Reneman, and J. G.R. De Mey, “Aortic wall properties in normotensive and hypertensive rats of various ages *in vivo*,” *Hypertension,* Vol. 26, pp. 363-368, 1995.

[5] C. J. Hartley, A. K. Reddy, S. Madala, M. L. Entman, L. H. Michael, and G. E. Taffet, “Noninvasive Ultrasound Measurement of Arterial Wall Motion in Mice,” *Proceeding of the 26 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 3688-3691, October 2004.

Bias pressure at 1 atm + 18 mm

P vessel (mm Hg)

Time (s)