ELSEVIER

Journal of Biomechanics 36 (2003) 283–287

JOURNAL
OF
BIOMECHANICS

www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Performance characteristics of a pressure microsensor

Kenton R. Kaufman[a,*], Tom Wavering[b], Duane Morrow[a], Jennifer Davis[c], Richard L. Lieber[c]

[a] *Biomechanics Laboratory, Division of Orthopedic Research, Mayo Clinic, 200 First street, SW, Rochester, MN 55905, USA*
[b] *Luna Innovations, 2851 Commerce St. SE, Blacksburg, VA 24060, USA*
[c] *Departments of Orthopedics and Bioengineering, University of California-San Diego, San Diego, CA 92161, USA*

Accepted 18 September 2002

Abstract

A new fiber optic microsensor has been developed for pressure measurement. The pressure microsensor is extremely small (360 μm). Performance characteristics of the microsensor were evaluated over a pressure range from 0 to 250 mm Hg. Five sensors were compared to a National Institute of Standards and Technology traceable reference pressure. The microsensor had an accuracy, repeatability, and linearity better than 2% full-scale output (FSO) and a hysteresis of 4.5% FSO.

Keywords: Pressure; Fiber optic sensor; Extrinsic Fabry–Perot interferometer

1. Introduction

Since the first reported measurement of interstitial fluid pressure by Landerer in 1884 (Landerer, 1884) many different measurement techniques have been used. Pressure measurement systems can be classified as either fluid filled or solid state. A comprehensive review of techniques to measure interstitial fluid pressure has been performed previously (Aukland and Reed, 1993; Wiig, 1990).

Fluid-filled methods consist of the needle manometer, wick technique, and micropipette technique. The needle manometer (Burch and Sodeman, 1937; Landerer, 1884) is a fluid-filled system which uses a slow, continuous infusion to keep the needle patent. The wick technique for pressure measurement consists of a cotton wick inserted into a 1.5 mm Teflon tube and introduced into the tissue through a needle (Scholander et al., 1968). Hargens (Hargens et al., 1977) later modified the technique to become the wick catheter technique. A third type of system uses a glass micropipette with a 5 μm tip diameter, making this the least traumatic method and also resulting in the least tissue distortion (Wiederhielm et al., 1964). However, micropipette measurements require tissue immobilization. Fluid-filled pressure recording systems are sensitive to hydrostatic artifacts (Matsen et al., 1976; Rorabeck et al., 1981; Styf, 1989). Thus, fluid-filled systems may be used only with limited movements that do not involve position changes relative to the horizontal plane rendering this technology inappropriate for measurements during dynamic activities.

In contrast, a fiber optic transducer is not sensitive to hydrostatic artifact (Crenshaw et al., 1990) and is effective for measuring intramuscular pressure during exercise (Crenshaw et al., 1992). Recently, Willy et al. (1999) introduced an accurate self-calibrating, battery powered electronic transducer-tipped catheter. However, the catheter tip is quite large (0.99 mm). Commercially available fiber optic pressure transducers are also too large for optimum comfort (0.55 mm) and may themselves induce pressure artifacts based on their large size.

A new microsensor has been developed for measuring interstitial fluid pressure. The purpose of this technical note is to evaluate the accuracy, repeatability, linearity, and hysteresis of this electronic fiber optic measurement system.

---

*Corresponding author. Tel.: +1-507-284-2262; fax: +1-507-284-2227.

E-mail address: kaufman.kenton@mayo.edu (K.R. Kaufman).

0021-9290/03/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S0021-9290(02)00321-4

2. Methods

The pressure microsensor has a 360 μm diameter (Fig. 1). The measurement method is based on an extrinsic Fabry–Perot interferometric (EFPI) technique (Murphy et al., 1991). EFPI technology is a distance measurement technique based on the formation of a low-finesse Fabry–Perot cavity between the polished end of a fiber and a reflective surface, which is the undersurface of a diaphragm (Fig. 2). Light is passed through the fiber, where a portion of the light is reflected off the fiber/air interface (R1). The remaining light propagates through the air gap between the fiber and the reflective surface and is reflected back into the fiber (R2). R1 is the reference reflection while R2 is the sensing reflection. Fluid pressure causes displacement of the diaphragm. These two light waves interfere constructively or destructively based on the path length difference traversed by the sensing reflection relative to the reference reflection, and travel back through the single mode fiber to the demodulation unit. A broadband source is used to address the sensor head, while the returned signal is analyzed with a miniature spectrometer (Fig. 2). The plots in Fig. 2 show the returned raw signal at two different sensor air gaps. Absolute gap information is contained in the frequency content of the signal (Wavering et al., 2000).

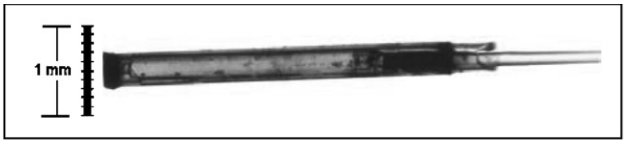

Fig. 1. Microscopic view of the pressure microsensor.

A calibration chamber was used to test the microsensor performance (Fig. 3). The pressure in the calibration chamber could be adjusted from 0 to 250 mm Hg. The microsensor was placed in the pressure chamber and subjected to a dynamic pressure signal that slowly increased to the maximum pressure and then decreased to ambient pressure over 120 s. The chamber pressure was measured with a pressure transducer (Model PX5500, Omega Engineering Inc., Stanford, CT) traceable to the National Institute of Standards and Technology (NIST) and accurate to 0.2% full scale. The chamber pressure and microsensor pressure were collected simultaneously at 20 Hz using a data acquisition board (PCI-MIO-16E-4 A/D National Instruments, Austin, TX) and a Labview application.

Testing was performed to determine the transducer performance characteristics of accuracy, repeatability, linearity, and hysteresis. The output of the pressure microsensor was compared to the NIST traceable reference pressure. The algebraic difference between the indicated value and the true value of the measurand was the transducer's error. Accuracy was defined as the ratio of the mean error to the full-scale output (FSO). Repeatability of the transducer was defined as the ability

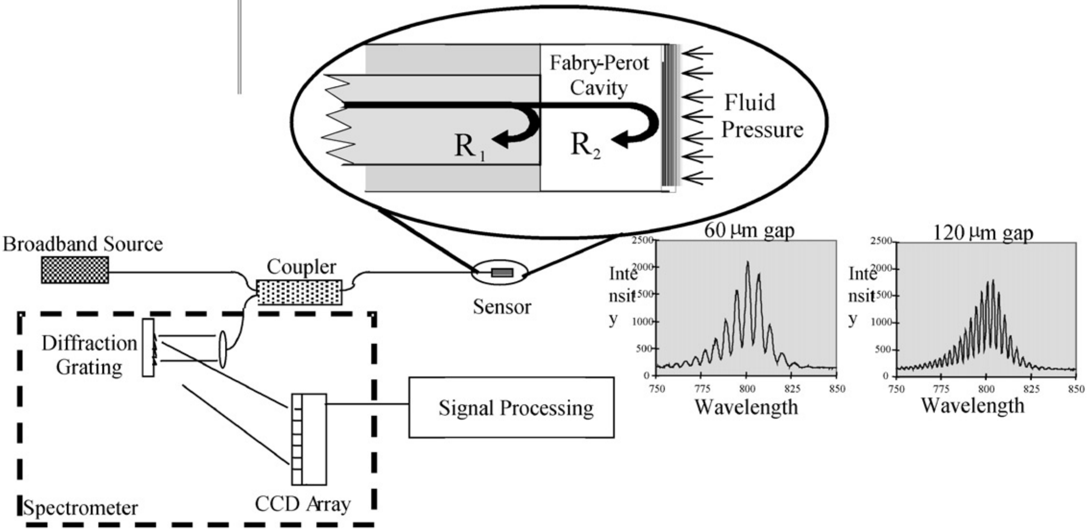

Fig. 2. Block diagram of the low-frequency, high resolution, fiber optic pressure measurement system. Light is conveyed via a fiber optic cable to the sensor. Fluid pressure causes a diaphragm to deflect. The light is reflected back at the fiber optic interface and the sensor diaphragm. The returned light is analyzed with a miniature spectrometer to determine the relative displacement of the diaphragm. The graphs represent the light spectrum that is returned from the sensor before it is processed to determine the gap measurement.

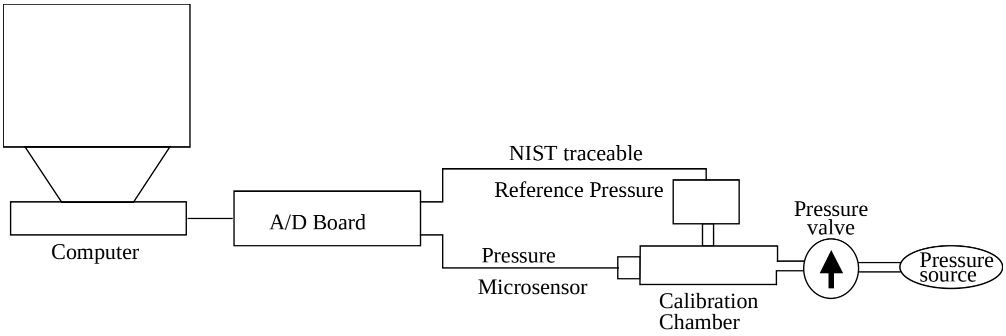

Fig. 3. Schematic diagram of the calibration setup. The pressure microsensor and a NIST traceable reference pressure transducer were co-located in a 20 mm^3 calibration chamber. A pressure source increased and decreased the chamber pressure which was measured with a NIST traceable reference.

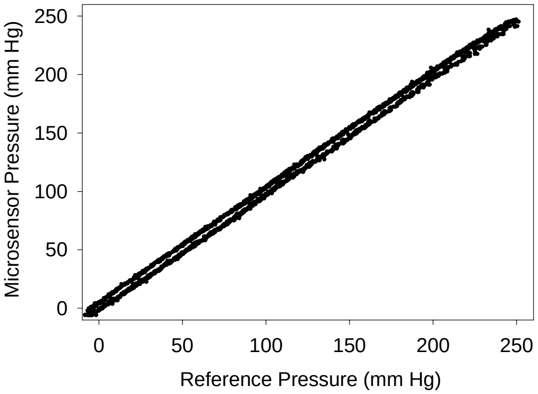

Fig. 4. A comparison of the pressure recorded by microsensor to that measured by a NIST traceable reference. The pressure is increased to a maximum of 250 mm Hg and then decreased. The microsensor provides an accurate, linear response with minimal hysteresis.

of the transducer to reproduce an output reading when the same measurand value was applied to it consecutively, under the same conditions, and in the same direction. Five calibration cycles were used to determine the repeatability. The closeness of the transducer calibration curve to a least-squares straight line was defined as the linearity of the transducer. Linearity was expressed as the maximum deviation of any calibration point to the corresponding point of the least-squares calibration straight line. Hysteresis was defined as the maximum difference between any pair of output readings obtained during a calibration cycle of the transducer when the measurand level was first increased and then decreased throughout the entire pressure range of the transducer. All performance characteristics were specified as a percentage of FSO. Five sensors were tested.

3. Results

The pressure microsensor displayed excellent accuracy, repeatability, linearity, and hysteresis. There was close correlation between the reference pressure and the pressure reported by the microsensor (Fig. 4). Accuracy, repeatability, and linearity were better than 2% FSO (Table 1). Hysteresis was slightly higher at 4.5% FSO. The low standard deviation of all measurements demonstrated that all transducers displayed similar operating characteristics.

Table 1
Pressure microsensor performance ($n = 5$)

	Mean[a]	Standard deviation
Accuracy	1.45	0.32
Repeatability	1.50	0.81
Linearity	1.61	0.20
Hysteresis	4.52	0.84

[a] Values are reported as a percentage of full-scale output (FSO).

4. Discussion

This study demonstrates that the fiber optic pressure microsensor accurately measures fluid pressure. The microsensor is based on extrinsic Fabry–Perot interferometric techniques. The basic physics governing the sensor make it immune to high electromagnetic interference environments. These sensors are very small, and therefore ideal for in vivo applications where minimal invasiveness is an important consideration. The sensor is easy to use. Because the signal conditioning unit is fully self referencing, calibration procedures that are typically required with conventional strain-gauge techniques are not required with this fiber optic sensor. The instrumentation requires only one connection per sensor and the sensor may be disconnected at any time with no loss of measurement reference. The signal conditioning unit is designed for up to 8 sensor channels at a sampling rate of 66 Hz.

Several studies have measured the accuracy of fluid-filled and solid-state transducer systems. The accuracy of fluid-filled systems have ranged from 1% to 18% (Hargens et al., 1977; Henkes et al., 1999; Mubarak et al., 1976; Reed, 1979; Rorabeck et al., 1981; Shakespeare et al., 1982; Styf, 1989; Wiig et al., 1981). The accuracy of electronic solid-state systems have a similar range of variability from 0.2% for a piezoelectric system (Willy et al., 1999) to 17% for a solid-state system (Mubarak et al., 1976). The accuracy of the microsensor is comparable to the piezoelectric system and better than other systems that are frequently used. While the accuracy of the piezoelectric system is slightly better, it is also much larger at 990 μm as compared to 360 μm for the microsensor. The linearity for fluid-filled systems ranged from 2% to 15% (Mubarak et al., 1976; Shakespeare et al., 1982). The linearity of the electronic systems was better, ranging from 0.3% for the piezoelectric system (Willy et al., 1999) to 4% for the solid-state system (Mubarak et al., 1976). Once again, the microsensor had better performance characteristics than all other pressure measurement systems with the exception of the piezoelectric system. The repeatability and the hysteresis of other measurement systems has not been reported.

Acquiring accurate interstitial fluid pressure has always pushed the limits of available sensor technology. The pressure microsensor described in this technical note is smaller than other sensors. The advantage of this small size is evident when comparing the size of the microsensor to a muscle fiber. In normal human muscle, the adult muscle fiber diameter is reached at 12–15 years of age and varies over a narrow range (Oertel, 1988). Adult muscle fibers range in diameter from 50 to 100 μm (Kirkeby and Garbarsch, 2000; Trappe et al., 2000). The microsensor is approximately the same diameter as a muscle fiber. This small size will permit minimally traumatic measurement of intramuscular pressure.

In summary, a pressure microsensor has been developed that is smaller than other pressure measurement systems and provides extremely accurate and repeatable measurements. Future work will be undertaken to evaluate the sensor biocompatibility. This will be necessary before this sensor can be used for in vivo human testing.

Acknowledgements

This work was supported by NIH Grant HD 31476. The authors thank Barbara Iverson-Literski for careful manuscript preparation.

References

Aukland, K., Reed, R.K., 1993. Interstitial-lymphatic mechanisms in the control of extracellular fluid volume. Physiological Reviews 73 (1), 1–78.

Burch, G.E., Sodeman, W.A., 1937. The estimation of the subcutaneous tissue pressure by a direct method. Journal of Clinical Investigation 16, 845–850.

Crenshaw, A.G., Styf, J.R., Mubarak, S.J., Hargens, A.R., 1990. A new "transducer tipped" fiber optic catheter for measuring intramuscular pressures. Journal of Orthopaedic Research 8, 464–468.

Crenshaw, A.G., Styf, J.R., Hargens, A.R., 1992. Intramuscular pressures during exercise: an evaluation of a fiberoptic transducer-tipped catheter system. European Journal of Applied Physiology 65, 178–182.

Hargens, A.R., Mubarak, S.J., Owen, C.A., Garetto, L.P., Akeson, W.H., 1977. Interstitial fluid pressure in muscle and compartment syndromes in man. Microvascular Research 14, 1–10.

Henkes, H., Felber, S.R., Wentz, K.U., Czerwinski, F., Monstadt, H., Weber, W., Kuhne, D., 1999. Accuracy of intravascular microcatheter pressure measurements: an experimental study. British Journal of Radiology 72, 448–451.

Kirkeby, S., Garbarsch, C., 2000. Aging affects different human muscles in various ways. An image analysis of the histomorphometric characteristics of fiber types in human masseter and vastus lateralis muscles from young adults and the very old. Histology and Histopathology 15 (1), 31–71.

Landerer, A.S., 1884. Die Gewebesspannung in ihrem Einfluss auf die ortlich Blut-und-Lymphbewegung [Tissue Contraction and its Influence on Local Blood and Lymph Flow]. Vogel, Leipzig, Germany.

Matsen, F.A., Mayo, K.A., Sheridan, G.W., Krugmire Jr., R.B., 1976. Monitoring of intramuscular pressure. Surgery 79, 702–709.

Mubarak, S.J., Hargens, A.R., Owen, C.A., Garetto, L.P., Akeson, W.H., 1976. The wick catheter technique for measurement of intramuscular pressure: a new research and clinical tool. Journal of Bone and Joint Surgery. American Volume 58A (7), 1016–1020.

Murphy, K.A., Gunther, M.F., Vengsarkar, A.M., Claus, R.O., 1991. Quadrature phase-shifted, extrinsic Fabry–Perot optical fiber sensors. Optics Letters 16 (4), 273.

Oertel, G., 1988. Morphometric analysis of normal skeletal muscles in infancy, childhood and adolescence. An autopsy study. Journal of the Neurological Sciences 88 (1–3), 303–313.

Reed, R.K., 1979. An implantable colloid osmometer. Measurements in subcutis and skeletal muscle of rats. Microvascular Research 18 (1), 83–94.

Rorabeck, C.H., Castle, G.S.P., Hardie, R., Logan, J., 1981. Compartmental pressure measurements: an experimental investigation using the slit catheter. Journal of Trauma 21, 446–449.

Scholander, P.F., Hargens, A.R., Miller, S.L., 1968. Negative pressure in the interstitial fluid of animals. Science 161 (3839), 321–328.

Shakespeare, D.T., Henderson, M.J., Clough, G., 1982. The slit catheter: a comparison with the wick catheter in the measurement of compartment pressure. Injury 13, 404–408.

Styf, J.R., 1989. Evaluation of injection techniques in recording of intramuscular pressure. Journal of Orthopaedic Research 7, 812–816.

Trappe, S., Williamson, D., Godard, M., Porter, D., Rowden, G., Costill, D., 2000. Effect of resistance training on single muscle fiber contractile function in older men. Journal of Applied Physiology 89 (1), 143–152.

Wavering, T., Meller, S., Evans, M., Pennington, C., Jones, M., Murphy, K., VanTassel, R., Velander, W., Valdes, E., 2000. Interferometric optical fiber microcantilever beam biosensor. Proceedings SPIE Biochemical and Biomolecular Sensing. 5–8 November, 2000, Boston, MA.

Wiederhielm, C.A., Woodbury, J.W., Kirk, S., Rushmer, R.F., 1964. Positile pressures in microcirculation of frogs mesentery. American Journal of Physiology 207, 173.

Wiig, H., 1990. Evaluation of methodologies for measurement of interstitial fluid pressure (P_i): physiological implications of recent pi data. Critical Reviews in Biomedical Engineering 18 (1), 27–17354.

Wiig, H., Reed, R.K., Aukland, K., 1981. Micropuncture measurement of interstitial fluid pressure in rat subcutis and skeletal muscle: comparison to wick-in-needle technique. Microvascular Research 21 (3), 308–319.

Willy, C., Gerngross, H., Sterk, J.C., 1999. Measurement of intracompartmental pressure with use of a new electronic transducer-tipped catheter system. Journal of Bone and Joint Surgery. American Volume 81A, 158–168.