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Measurement of Intracompartmental Pressure with Use of a New Electronic Transducer-Tipped Catheter System*

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Investigation performed at the Department of Surgery, Military Hospital Ulm, Ulm

ABSTRACT: Laboratory and clinical tests were carried out to determine the clinical usefulness, validity, and safety of a new self-calibrating, battery-powered monitoring system for the measurement of intramuscular pressure with use of an electronic transducer-tipped catheter. The eight probes accurately recorded applied pressures ranging from zero to 160 millimeters of mercury (zero to 21.33 kilopascals). The system registered little temperature-induced drift (maximum, 1.25 millimeters of mercury [0.17 kilopascal]) between dry room temperature and 40 degrees Celsius. There were also minimum variations (range, -0.14 to 0.81 millimeter of mercury [0.02 to 0.11 kilopascal]) in the pressures recorded during a twenty-four-hour period.

The resting pressure in the tibialis anterior muscle of twenty volunteers who had normal limbs was a mean (and standard deviation) of 13.1 ± 8.3 millimeters of mercury (1.75 ± 1.11 kilopascals). There was a good correlation between externally applied pressures (zero, twenty, forty, sixty, eighty, and 100 millimeters of mercury [zero, 2.67, 5.33, 8.00, 10.66, and 13.33 kilopascals] applied with use of antishock trousers) and the pressures measured in the tibialis anterior muscle of four volunteers ($r = 0.997$ to 0.999). The injection of sterile saline solution into the tibialis anterior muscle of a volunteer and the use of high-frequency recording during muscular activity showed a high degree of responsiveness and sensitivity to changes in intramuscular pressure. We also prospectively evaluated the clinical usefulness of the system and found it to be easy to assemble, calibrate, and use. Thus, this reusable, electronic transducer-tipped catheter system, which is based on a noninfusion technique, is simple, minimally traumatic, and highly precise. It is free of hydrostatic pressure artifacts and provides dynamic responses to changes in intramuscular pressure.

An acute compartment syndrome is an operative emergency. The most frequently affected site is the anterior compartment of the leg after a tibial fracture.

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Although there is some controversy with regard to the pathophysiology of the increased intramuscular pressure, there is little dispute as to the need for prompt fasciotomy of the involved compartment^{1,8,12,15,19,27,28}. If left to its natural course, an acute compartment syndrome results in tissue necrosis, muscle contracture, and a neurological deficit. If the elevated compartmental pressure is recognized and is treated in time with fasciotomy, these deleterious sequelae can usually be avoided^{1,11,14,19}.

In most patients, an early diagnosis of an acute compartment syndrome can be made on the basis of a clinical evaluation, provided that the physician is aware of the possibility of the syndrome. The symptoms include burning, deep-seated pain, weakness, pain on passive stretching of the muscles, hypoesthesia, swelling, and tense fascial boundaries^{15,19,20,27,28}. Physical examination is very important, but objective data are often useful or essential to confirm the diagnosis, particularly in an unconscious patient. Thus, measurement of the intracompartmental pressure is recommended^{1,4,15,19}. Ideally, the method for such measurement should be quick, accurate, and reliable, and the system should be relatively easy to use and cost-effective.

Several methods to measure intracompartmental pressure have been designed. The systems that are currently used, such as the slit^{17,19,20} and the wick catheter¹³⁻¹⁵, consist of a fluid-filled catheter attached to an extracorporeal transducer¹³. These systems are routinely calibrated with respect to the level of the tip of the catheter and usually require flushing or infusion to maintain accuracy for measurements over a prolonged period of time. Similarly, the solid-state transducer intracompartmental catheter (STIC catheter) must be attached to a pressurized constant-infusion system¹⁰. With all of these systems, the results of the measurement of intracompartmental pressure depend on the position of the limb and the height of the pressure transducer above the tip of the catheter^{10,13-15,17,19,20,23,24}. Another method, the transducer-tipped fiber-optic system, offers distinct advantages over the conventional fluid-filled systems as it does not produce hydrostatic pressure artifacts and does not require injections of fluid for long-term measurement⁴. However, the fiber-optic transducer is relatively large and must be attached to an intracath sheath (outer diameter, 2.1 millimeters), which causes discomfort to the patient, for the measurement of intramuscular pressure.

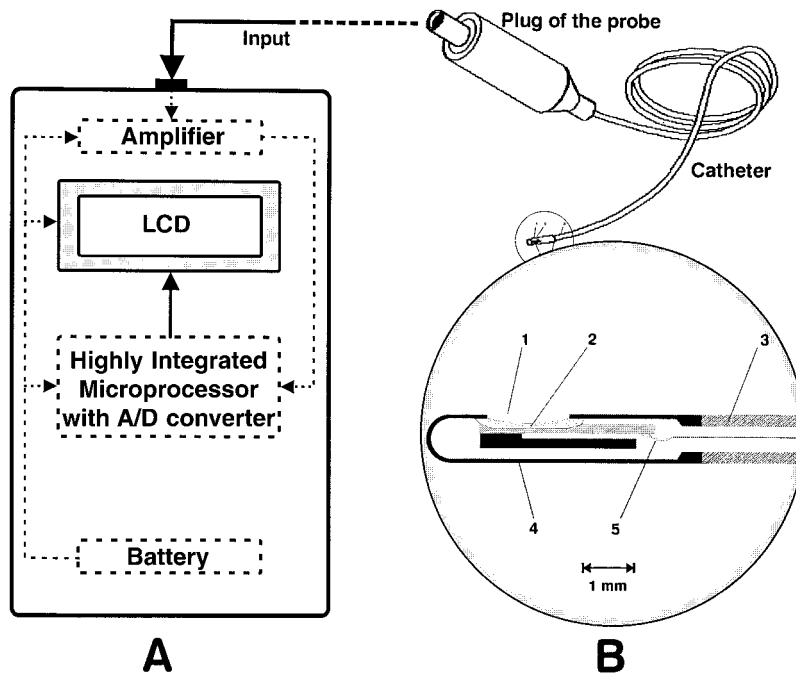


FIG. 1

Diagram showing the components of the handheld device and the electronic transducer-tipped catheter (French size 3 or 4) measuring system. *A*: The handheld device consists of an amplifier, a highly integrated microprocessor with an analog-to-digital (A/D) converter, a nine-volt battery supply, and a liquid-crystal display (LCD). *B*: The magnified detail of the electronic transducer-tipped catheter (side view) shows the pressure-sensing mechanics of the catheter tip (outer diameter, French size 3 [0.99 millimeter] or 4 [1.32 millimeters]). An increase in the tissue pressure causes a rise in the pressure on the surface of the piezoelectric crystal, resulting in changes in the electrical resistance. After amplification and conversion to digital signals, the pressure is immediately displayed on a liquid-crystal-display monitor. 1 = small measuring window (0.6 by 1.5 millimeters for French size 3 or 0.9 by 1.8 millimeters for French size 4) in the steel case without any membrane, 2 = uniaxial piezo semiconductor with a chip, 3 = tip of the sixty-centimeter polyurethane catheter, 4 = stainless-steel housing, and 5 = wires to the connector.

An electronic transducer-tipped catheter system has recently been developed and used to monitor intracranial pressure, thereby avoiding problems commonly associated with fluid-filled systems. Because this catheter technique does not require any additional manipulation, the catheter is readily available for measurements of intracompartmental pressure in patients who have a suspected compartment syndrome. The purpose of the present study was to evaluate the accuracy, safety, and clinical usefulness of this electronic transducer-tipped system for the measurement of intracompartmental pressure.

Materials and Methods

The New Technology of Intramuscular Pressure Recording

The equipment consists of a reusable probe (PiCo; Mammendorfer Institute for Physics and Medicine GmbH, Hattenhofen, Germany) that is sixty centimeters long and a separate, portable, battery-powered (nine-volt-block), handheld device (HANDY; Mammendorfer Institute for Physics and Medicine GmbH) that weighs 200 grams (Fig. 1). Technically, the monitoring system is based on the piezoresistive principle that semiconductors change their electrical resistance as a function of applied pressure. Our system uses a chip with a uniaxial piezo semiconductor, which is incorporated in

a steel case with an outer diameter of either 0.99 or 1.32 millimeters (French size 3 or 4) located at the tip of the probe (Fig. 1). The probe can be sterilized in an autoclave or by gas.

The connection of the probe with the compact device automatically starts the software-controlled self-test and offset; there is no need for keys or knobs on the instrument (Fig. 2). The self-test takes approximately eight seconds and consists of several consecutive steps: (1) activation of the memory, the ports, and the analog-to-digital converter; (2) a check of the display; (3) a check of the battery; and (4) a check of the probe to verify that it is functioning correctly, which is necessary to ensure the quality of the probe after the sterilization procedure. Sensors based on every kind of electronic bridge circuit, especially a Wheatstone-bridge circuit, always have a difference between the pressure zero and the electrical zero. This difference is called zero variation or offset, and it influences the complete pressure measurement. To ensure the accuracy of the measurement, this offset has to be checked. The check of the probe, in turn, consists of several steps: (1) a check of the initial offset value, which should be between clearly defined limits; (2) a control of the drift; and (3) storage of the actual offset, which equates the measured surrounding pressure with zero millimeters of mercury (self-calibration).

After a short audible signal, the system is operational

and the liquid-crystal display indicates zero millimeters of mercury. In the case of a failure, a clearly defined error message appears on the display and measurement is not possible. Immediately after the probe is inserted into a compartment, the display indicates the intracompartmental pressure at the point of measurement.

The system is safe in that there are no electrical connections to the patient. It was tested by the National Institute of Trade of Germany and complies with the medical product safety regulations of the European Community with the CE-Mark (93/42/EWG,II,4).

Validation of the Method

The use of the electronic transducer-tipped catheter method was validated in two different experimental settings in which pressure was elevated to known values: a laboratory model involving use of a water column and a model in which pressure was externally applied to the lower limbs of human subjects. Furthermore, intracompartmental pressure was measured in healthy volunteers at rest, after the injection of saline solution, and during exercise.

Laboratory Studies

Under direct vision, eight probes (French size 4) were inserted into a filled water column, with a temperature of 33 degrees Celsius, at different water depths (zero, 13.6, 27.2, 40.8, and 54.4 centimeters, which corresponded to zero, ten, twenty, thirty, and forty millimeters of mercury [zero, 1.33, 2.67, 4.00, and 5.33 kilopascals]). To test the probes at higher pressures, the eight probes were inserted into a calibrated pressure chamber at fifty,

eighty, 120, and 160 millimeters of mercury (6.67, 10.66, 16.0, and 21.33 kilopascals).

We had found that the temperature in resting muscle is 33 or 34 degrees Celsius and increases during exercise to as much as 40 or 41 degrees Celsius. We investigated a possible dependence of the measurement system on variations in temperature. First, after calibration at dry room temperature (19, 20, or 21 degrees Celsius), the eight probes were dipped, at depths of zero, ten, twenty, thirty, forty, fifty, eighty, 120, and 160 millimeters of mercury (zero, 1.33, 2.67, 4.00, 5.33, 6.67, 10.66, 16.00, and 21.33 kilopascals), for ten minutes in the water column with a temperature of 33 degrees Celsius. Second, after calibration at dry room temperature, the probes were dipped, at the same depths, for ten minutes in the water column with a temperature of 40 degrees Celsius. Then, to assess whether the measurement drift was affected by a possible difference between calibration in water and a dry calibration, the probes were calibrated at 20 degrees Celsius in water and then dipped into the water column with a temperature of 40 degrees Celsius. To test stability as a function of time, the eight probes were tested in the range of zero to forty millimeters of mercury (zero to 5.33 kilopascals) for zero to twenty-four hours (zero, 0.5, 1.0, 3.0, 6.0, 12.0, and 24.0 hours) in the water column at 33 degrees Celsius.

Clinical Studies of Pressure in the Tibialis Anterior Muscle

Healthy Volunteers

Normal pressure at rest: Normal resting values for pressure in the tibialis anterior muscle were determined

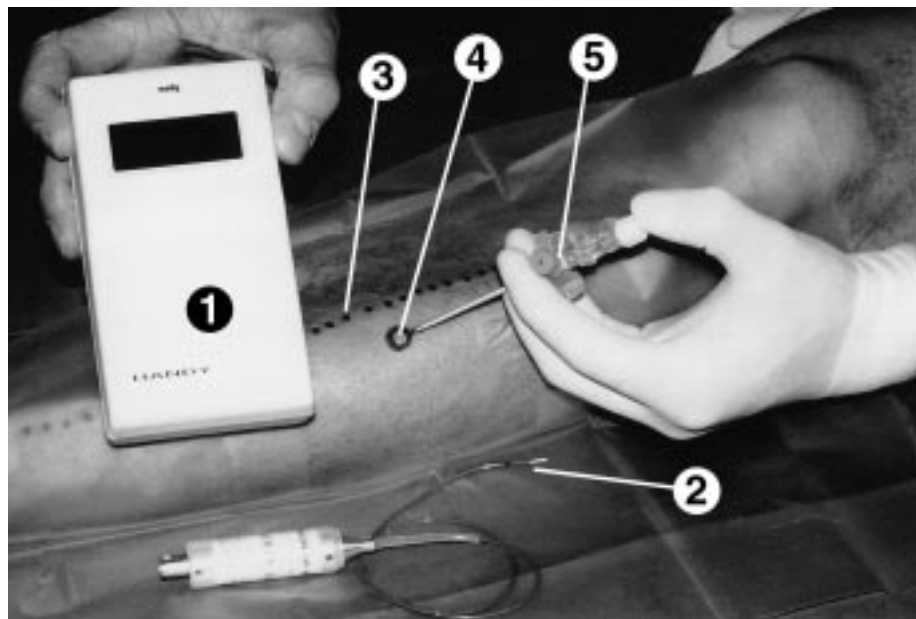


FIG. 2

Photograph of the equipment for the measurement of intramuscular pressure. 1 = compact device, which weighs 200 grams; 2 = reusable and resterilizable electronic transducer-tipped catheter; 3 = anterior ridge of the tibia; 4 = site of insertion; and 5 = 14-gauge (2.1-millimeter) intravenous cannula. The compact device performs a self-test and self-calibration immediately after it is connected to the electronic transducer-tipped catheter.

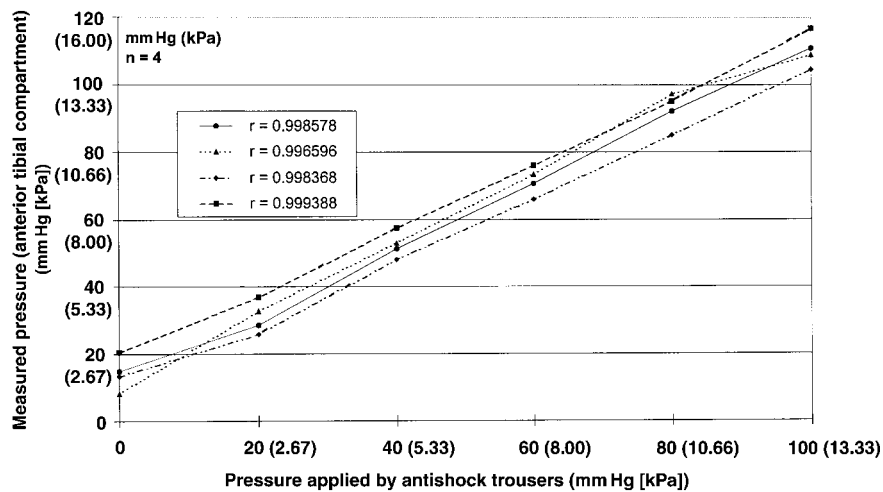


FIG. 3

Plot of the linear regression lines, showing the data from the catheter (y axis) versus the superimposed pressure induced by the antishock trousers (x axis) in four limbs that were compressed from zero to 100 millimeters of mercury (zero to 13.33 kilopascals). The total measured pressure is almost exactly equal to the sum of the intracompartmental pressure and the externally applied pressure.

for twenty male volunteers (age range, twenty to thirty-nine years) who were in a supine, relaxed position. After preparation of a sterile field, the skin and the subcutaneous tissue were anesthetized with an injection of one milliliter of 1 percent Xylocaine (lidocaine) placed 1.5 centimeters lateral to the anterior ridge of the tibia. Without a skin incision, a 14-gauge (2.1-millimeter) intravenous cannula then was introduced into the anterior compartment of the leg. The fascia was penetrated at an angle of approximately 45 degrees in a distal direction (Fig. 2). The trocar was then removed, and the French-size-4 probe was connected to the handheld device. After the self-test of the measurement system, the probe was inserted through the cannula and bluntly introduced two centimeters beyond the tip of the cannula parallel to the muscle fibers between the overlying fascia and the centrally located intramuscular tendon at a depth of approximately 1.5 centimeters from the fascia. The cannula was then removed.

Externally applied pressure: In four healthy volunteers, which included the three of us, the probe was inserted into the anterior compartment of the left leg as already described. External pressure was superimposed on the internal pressure with use of antishock trousers (LSP 600; Life Support Products, St. Louis, Missouri). With use of the calibrated manometer of the antishock trousers, a known pneumatic pressure was uniformly applied over the lower extremity. The external pressure was increased in twenty-millimeter (2.67-kilopascal) increments from zero to 100 millimeters of mercury (zero to 13.33 kilopascals) for ten minutes at each pressure. Linear regression analysis was performed to evaluate the relationship between these externally applied pressures and the measured intracompartmental pressures.

Injection of fluid into the muscle: To study the responsiveness of the pressure-monitoring method, two

probes (P1 and P2) were inserted into the middle third of the tibialis anterior muscle of one of us. The probes were placed five centimeters apart and 1.5 centimeters lateral to the anterior ridge of the tibia. In the first step, ten milliliters of sterile saline solution was injected three times at a site 2.5 centimeters distal to the distally inserted probe (P1) and 7.5 centimeters distal to the proximally inserted probe (P2). In the second step, ten milliliters of saline solution was injected twice between the two transducer-tipped catheters (2.5 centimeters from P1 and 2.5 centimeters from P2). The measured pressures were recorded continuously at a frequency of one hertz.

High-frequency recording during exercise: To evaluate the ability of the catheter to record intramuscular pressure during exercise, three electronic transducer-tipped catheters were inserted into the tibialis anterior muscle of one of us to a depth of 1.5 centimeters. The catheters were placed five centimeters apart and were connected to a measurement system that included a three-channel analog-to-digital converter and a personal computer. The probes were fixed to the skin to prevent dislocation during the exercise, and they were calibrated. The pressure course was measured with use of a software program (ARGUS; Mammendorfer Institute for Physics and Medicine GmbH) that was developed to analyze pressure measurements in patients who have suspected exertional compartment syndrome; it permitted data-recording at a frequency that ranged from one to 200 hertz. The volunteer then performed four ten-minute exercises on a treadmill: walking at six kilometers per hour on a level surface, walking at six kilometers per hour on a gradient of 10 percent, walking at eight kilometers per hour on a gradient of 10 percent, and running at ten kilometers per hour on a gradient of 10 percent. A recording frequency of ten hertz was chosen for the experiment.

TABLE I
ACCURACY AND TEMPERATURE-INDUCED DRIFT OF THE ELECTRONIC TRANSDUCER-TIPPED PROBE

Applied Pressure (mm Hg [kPa])	Method for Applying Pressure	Accuracy (Measured Pressure)* (mm Hg [kPa])	Temperature-Induced Drift*† (mm Hg [kPa])		
			Dry Room Temperature to 33 Degrees Celsius	Dry Room Temperature to 40 Degrees Celsius	20 to 40 Degrees Celsius
0	Water column	0.00 ± 0.00 (0.00 ± 0.00)	1.25 ± 0.46 (0.17 ± 0.06)	1.25 ± 0.46 (0.17 ± 0.06)	1.00 ± 0.00 (0.13 ± 0.00)
10 (1.33)	Water column	10.13 ± 0.35 (1.35 ± 0.05)	0.88 ± 0.83 (0.12 ± 0.11)	1.13 ± 0.64 (0.15 ± 0.09)	0.50 ± 0.53 (0.07 ± 0.07)
20 (2.67)	Water column	20.13 ± 0.35 (2.68 ± 0.05)	0.88 ± 0.83 (0.12 ± 0.11)	1.13 ± 0.64 (0.15 ± 0.09)	0.43 ± 0.53 (0.06 ± 0.07)
30 (4.00)	Water column	30.38 ± 0.52 (4.05 ± 0.07)	0.88 ± 0.83 (0.12 ± 0.11)	1.13 ± 0.64 (0.15 ± 0.09)	0.50 ± 0.53 (0.07 ± 0.07)
40 (5.33)	Water column	40.33 ± 0.52 (5.38 ± 0.07)	1.25 ± 0.46 (0.17 ± 0.06)	1.25 ± 0.46 (0.17 ± 0.06)	1.00 ± 0.00 (0.13 ± 0.00)
50 (6.67)	Pressure chamber	50.25 ± 0.46 (6.70 ± 0.06)	0.88 ± 0.83 (0.12 ± 0.11)	1.25 ± 0.46 (0.17 ± 0.06)	0.50 ± 0.53 (0.07 ± 0.07)
80 (10.66)	Pressure chamber	80.63 ± 0.52 (10.75 ± 0.07)	0.00 ± 1.00 (0.00 ± 0.13)	-0.33 ± 0.58 (-0.04 ± 0.08)	-0.33 ± 0.58 (-0.04 ± 0.08)
120 (16.00)	Pressure chamber	120.75 ± 0.71 (16.10 ± 0.09)	0.00 ± 1.00 (0.00 ± 0.13)	-0.33 ± 0.58 (-0.04 ± 0.08)	-0.33 ± 0.58 (-0.04 ± 0.08)
160 (21.33)	Pressure chamber	161.00 ± 0.76 (21.46 ± 0.10)	0.00 ± 1.00 (0.00 ± 0.13)	1.00 ± 1.00 (0.13 ± 0.13)	-0.33 ± 1.58 (-0.04 ± 0.21)

*The values are given as the mean and standard deviation for the eight probes.

†The time-period for each test was ten minutes.

Patients with Suspected Compartment Syndrome

From March 1994 to December 1996, intramuscular pressure in the tibialis anterior muscle was recorded prospectively in twenty-five patients who had suspected compartment syndrome. When a patient was unconscious, the cannula was introduced without any anesthesia. We included patients who had painful, swollen limbs and palpably tense compartments. No patient had a motor or sensory deficit.

Sixteen patients had a tibial fracture. The eleven men and five women had a mean age of thirty-seven years (range, nineteen to sixty-seven years). For four of these patients, the intramuscular pressure was monitored for six to twenty hours after admission. Seven patients, who were included because of soft-tissue injury with tense compartments, were artificially ventilated and unconscious. Measurement was performed in the emergency room or the operating room.

In two men (twenty and thirty-two years old) who had severe soft-tissue injury, the intramuscular pressure was recorded during intramedullary nailing of the tibia without reaming and at every half hour for the next twelve and eight hours, respectively.

Six patients (two men and four women), with a mean age of fifty-three years (range, forty-two to sixty-eight years), had an elective corrective osteotomy of the proximal part of the tibia. The intramuscular pressure was recorded during the operation and at every half hour for the next seventeen to twenty-one hours.

In addition, one patient had an acute exertional

compartment syndrome of the tibialis anterior muscle. The intramuscular pressure was measured before the performance of a fasciotomy. The correct diagnosis had been delayed because the pain was misinterpreted as resulting from acute muscular tetanic spasm induced by hyperventilation. Therefore, the fasciotomy was performed eighteen hours after the development of the acute exertional compartment syndrome.

Informed Consent

Written informed consent was obtained from all volunteers and conscious patients who did not need emergency management. Measurement of intracompartmental pressure was considered to be an essential part of the management of the twenty-five conscious and unconscious patients who were suspected of having an acute compartment syndrome. The study was approved by our local Institutional Review Board.

Statistical Analysis

The Kruskal-Wallis test was used to analyze the differences in the pressure in the experimental investigations of temperature-induced drift and the stability of the measurements as a function of time. Values are given as the mean and standard deviation. A p value of less than 0.05 was considered to be significant.

Results

Laboratory Studies

When pressures ranging from zero to 160 millimeters of mercury (zero to 21.33 kilopascals) were ap-

TABLE II
LONG-TERM STABILITY OF THE ELECTRONIC TRANSDUCER-TIPPED PROBE

Applied Pressure (mm Hg [kPa])	Measured Pressures* (mm Hg [kPa])						
	0 Hrs.	0.5 Hr.	1.0 Hr.	3.0 Hrs.	6.0 Hrs.	12.0 Hrs.	24.0 Hrs.
0	0.01 ± 0.04 (0.00 ± 0.01)	0.39 ± 0.50 (0.05 ± 0.07)	0.39 ± 0.52 (0.05 ± 0.07)	0.26 ± 0.45 (0.03 ± 0.06)	0.39 ± 0.50 (0.05 ± 0.07)	0.26 ± 0.47 (0.03 ± 0.06)	0.14 ± 0.34 (0.02 ± 0.05)
10 (1.33)	10.15 ± 0.35 (1.35 ± 0.05)	10.28 ± 0.26 (1.37 ± 0.03)	10.53 ± 0.63 (1.40 ± 0.08)	10.28 ± 0.48 (1.37 ± 0.06)	10.40 ± 0.24 (1.39 ± 0.03)	9.86 ± 0.55 (1.31 ± 0.07)	10.40 ± 0.31 (1.39 ± 0.04)
20 (2.67)	20.16 ± 0.37 (2.69 ± 0.05)	20.54 ± 0.58 (2.73 ± 0.08)	20.54 ± 0.63 (2.74 ± 0.08)	20.29 ± 0.51 (2.70 ± 0.07)	20.41 ± 0.75 (2.72 ± 0.10)	19.91 ± 0.76 (2.65 ± 0.10)	20.29 ± 0.65 (2.70 ± 0.09)
30 (4.00)	30.31 ± 0.70 (4.04 ± 0.09)	30.68 ± 0.75 (4.09 ± 0.10)	30.81 ± 0.71 (4.11 ± 0.09)	30.71 ± 0.75 (4.09 ± 0.10)	30.68 ± 0.94 (4.09 ± 0.13)	30.44 ± 0.91 (4.06 ± 0.12)	30.60 ± 0.88 (4.08 ± 0.12)
40 (5.33)	40.11 ± 0.54 (5.35 ± 0.07)	40.78 ± 0.72 (5.44 ± 0.10)	40.61 ± 0.88 (5.41 ± 0.12)	40.44 ± 0.85 (5.39 ± 0.11)	40.40 ± 0.75 (5.39 ± 0.10)	39.94 ± 0.67 (5.32 ± 0.09)	40.44 ± 0.90 (5.39 ± 0.12)

*The values are given as the mean and standard deviation for the eight probes.

plied to the eight probes with use of a water column or a pressure chamber, the electronic transducer-tipped catheter system measured pressure equal to that at the depth of the tip in the water column and equal to the applied pressure in the calibrated pressure chamber (Table I). The correlation coefficient (r) was 0.999, and the linear regression equation for catheter pressure (y) with respect to water pressure (x) was $y = 0.994x + 0.058$ (in the range of zero to 160 millimeters of mercury [zero to 21.33 kilopascals]). After the eight probes were exposed to dry room temperature and then dipped into the water column for ten minutes at 33 or 40 degrees Celsius, the mean temperature-induced drift ranged from -0.33 ± 0.58 millimeter of mercury (0.04 ± 0.08 kilopascal) to 1.25 ± 0.46 millimeters of mercury (0.17 ± 0.06 kilopascal). No significant difference could be detected between the measurements in the water columns and those at dry room temperature. This high degree of stability could be observed at all applied pressures (Ta-

ble I). After calibration of the transducer-tipped catheters in water at 20 degrees Celsius and then dipping into the water column for ten minutes at 40 degrees Celsius, the temperature-induced drift ranged from -0.33 ± 1.58 millimeters of mercury (-0.04 ± 0.21 kilopascal) to 1.0 ± 0.0 millimeter of mercury (0.13 ± 0.00 kilopascal).

Analysis over a twenty-four-hour period revealed minimum variation (range, -0.14 to 0.81 millimeter of mercury [0.02 to 0.11 kilopascal]) and no significant differences ($p > 0.05$) between the pressures in the 33-degree water column at zero hours and the pressures measured by the catheters at any of the selected times (0.5, 1.0, 3.0, 6.0, 12.0, and 24.0 hours); this was the case at all of the applied pressures (zero to forty millimeters of mercury [zero to 5.33 kilopascals]). Even twenty-four hours after insertion of the probes into the water column, we could not detect any significant changes in the pressure measurement as a function of time, with the numbers available (Table II).

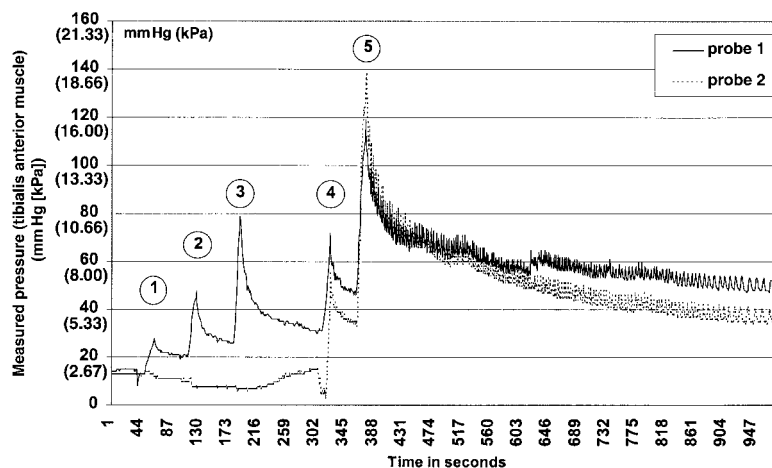


FIG. 4

Plot of the intramuscular pressure in the tibialis anterior muscle of one individual after five successive injections of ten milliliters of sterile saline solution into the muscle, demonstrating the high sensitivity and responsiveness of the pressure-monitoring system. The fluid was injected three times (injections 1, 2, and 3) at a site 2.5 centimeters distal to the distally inserted probe (probe 1) and 7.5 centimeters distal to the proximally inserted probe (probe 2). In a second step, the fluid was injected twice (injections 4 and 5) between the two probes, with a distance from each probe of 2.5 centimeters. After the two peaks (after injection 5), the plot shows an oscillation synchronous to the arterial pulse, indicating the high responsiveness of the two probes.

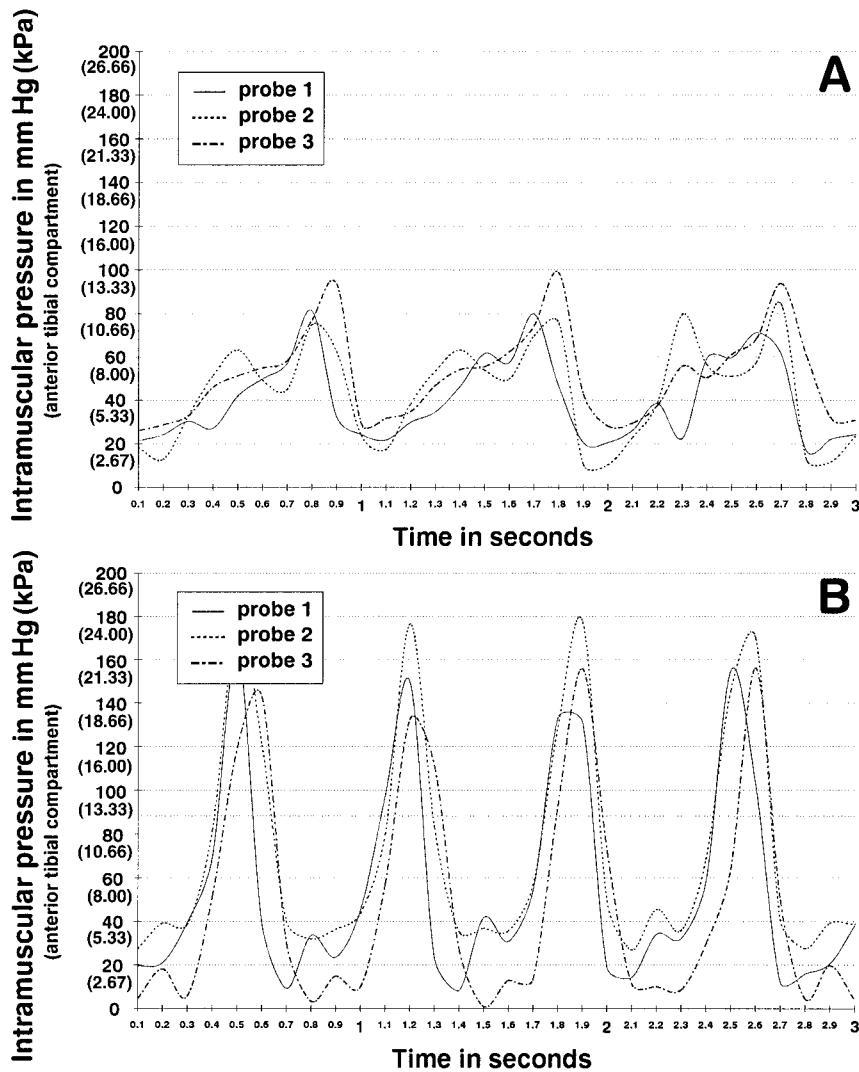


FIG. 5

Graphs of the intramuscular pressures recorded at ten hertz during muscular activity in one individual. Excerpts of three seconds' duration from recording periods of ten minutes are shown. *A*: Walking on a treadmill (six kilometers per hour, 0 percent gradient). *B*: Running on a treadmill (ten kilometers per hour, 0 percent gradient). These findings demonstrate that the monitoring system has a high degree of responsiveness and that strong movements of the limbs produced no electronic artifacts; thus, valid recording of data is possible during strong muscular activity. (Probe 1 was in the distal position; probe 2, in the middle position; and probe 3, in the proximal position.)

Clinical Studies of Pressure in the Tibialis Anterior Muscle

Healthy Volunteers

Normal pressure at rest: The resting pressure in the relaxed tibialis anterior muscle of the twenty volunteers in the supine position was a mean (and standard deviation) of 13.1 ± 8.3 millimeters of mercury (1.75 ± 1.11 kilopascals) (range, 5.4 to 22.6 millimeters of mercury [0.72 to 3.01 kilopascals]). The system was very sensitive and immediately registered changes in intramuscular pressure during several maneuvers such as wiggling the toes or moving the foot.

Externally applied pressure and injection of fluid into the muscle: The tests on the four volunteers demonstrated a relationship between the pressures applied with the antishock trousers (zero, ten, twenty, forty, sixty, eighty, and 100 millimeters of mercury [zero, 1.33, 2.67,

5.33, 8.00, 10.66, and 13.33 kilopascals], x axis) and the measured pressures (y axis), even when high pressures were applied (correlation coefficients, 0.997 to 0.999) (Fig. 3). The tip of the electronic transducer also showed a high degree of responsiveness to the injection of sterile saline solution into the tibialis anterior muscle (Fig. 4). Immediately after the first, second, and third injections of ten milliliters of saline solution, probe 1 (P1), which was 2.5 centimeters from the injection site, registered increases of pressure (compared with a baseline pressure of fifteen millimeters of mercury [2.00 kilopascals]) to twenty-eight, forty-eight, and seventy-nine millimeters of mercury (3.73, 6.40, and 10.53 kilopascals), respectively. Probe 2 (P2), which was 7.5 centimeters from the injection point, showed only a slight reaction. After the two additional injections of saline solution, at the midpoint between P1 and P2, the con-

TABLE III
DATA ON THE TWENTY-FIVE PATIENTS IN WHOM INTRAMUSCULAR PRESSURE WAS MEASURED

No. of Patients	Setting for Measurement	Intramuscular Pressure*	Treatment Based on Measurement
16	Tibial fracture	Median, 45 (6); range, 32 to 88 (4.27 to 11.73)	Fasciotomy (n = 9)
		Median, 17 (2.27); range, 9 to 33 (1.20 to 4.40)	No fasciotomy (n = 7)
2	Soft-tissue injury, intramedullary nailing	Maximum values in 8 or 12-hr. period postop.: 19 (2.53) and 23 (3.07)	No fasciotomy
6	Corrective osteotomy	Maximum values in 17 to 21-hr. period postop.: median, 18 (2.40); range, 15 to 26 (2.00 to 3.47)	No fasciotomy
1	Exertional compartment syndrome	140 (18.66) at 18 hrs. after exercise	Fasciotomy

*The values are given in millimeters of mercury, with kilopascals in parentheses.

tinuously recorded pressure with P1 showed an increase to seventy-two and 119 millimeters of mercury (9.60 and 15.86 kilopascals) and that with P2 showed an increase to fifty-five and 138 millimeters of mercury (7.33 and 18.40 kilopascals), followed by a decrease to approximately thirty-five to fifty millimeters of mercury (4.67 to 6.67 kilopascals), which indicated a rapid fluid convection down a pressure gradient within the muscle.

High-frequency recording during exercise: Intramuscular pressure during exercise was recorded, at a frequency of ten hertz, simultaneously at three sites in the tibialis anterior muscle (Fig. 5, A and B). When the catheter was raised or lowered from the reference point during exercise, there were no hydrostatic pressure artifacts. As the subject walked on the treadmill at six kilometers per hour on a 0 percent gradient, the pressures ranged from seven to ninety-nine millimeters of mercury (0.93 to 13.20 kilopascals) (Fig. 5, A) and increased to a peak pressure of 175 millimeters of mercury (23.33 kilopascals) at eight kilometers per hour on a 10 percent gradient. When the volunteer ran at a rate of ten kilometers per hour on a 10 percent gradient, the pressure increased to 180 millimeters of mercury (24.00 kilopascals) (Fig. 5, B). The movement of the limbs produced no displacement or breakage of the inserted electronic transducer-tipped catheter probes and no electronic artifacts. The subject had no discomfort during or after the forty minutes of muscular exercise.

Patients with Suspected Compartment Syndrome

Since 1994, tissue pressures in patients with a suspected compartment syndrome have been measured by residents and consultants in the Department of Surgery at our institution with use of the electronic handheld device (Table III). The measurements of tissue pressure proved to be helpful, reliable, and reproducible in our experience with twenty-five patients. When the catheter was raised or lowered from the point of insertion, the hydrostatic pressure artifact was zero throughout all changes in level. No deficit developed in

any patient after the physician elected not to perform a fasciotomy on the basis of the tissue pressures. Conversely, when the decision to perform a fasciotomy was based on the measurement of tissue pressure and the clinical findings, intraoperative evidence of a compartment syndrome — that is, tightly stretched crural fascia, poorly perfused (grayish-white or livid-colored) muscle, and muscle-bulging immediately after decompression — was seen in all of the patients. After tibial fracture, intramedullary nailing, or elective corrective osteotomy of the proximal part of the tibia, fifteen patients had normal values for intracompartmental pressure. Measurement of the tissue pressure led to the diagnosis of an acute compartment syndrome in nine patients who had a tibial fracture, although only three of them had clinical findings that supported the diagnosis. In these nine patients, who had a fasciotomy, the absolute pressures ranged from thirty-two to eighty-eight millimeters of mercury (4.27 to 11.73 kilopascals) (median, forty-five millimeters of mercury [6.00 kilopascals]). In one additional patient, in whom an acute exertional compartment syndrome had developed eighteen hours after exercise, the intramuscular pressure was 140 millimeters of mercury (18.66 kilopascals) and a fasciotomy was performed³⁰.

Discussion

Our findings show that the electronic transducer-tipped catheter system accurately measures intramuscular pressure. The new catheter is small, with a diameter of 0.99 or 1.32 millimeters (French size 3 or 4); is minimally traumatic; and is easy to use. The responsiveness of the pressure-measuring system is extremely high, and no equilibration time is necessary to provide accurate results. Because of the ease of use and the uncomplicated technique for insertion, the method is highly suitable for clinical monitoring of tissue pressure in injured extremities.

Our laboratory studies demonstrated that the general range of accuracy with this method, in the tested range of pressures between zero and 160 millimeters of

mercury (zero and 21.33 kilopascals), is approximately one millimeter of mercury (0.13 kilopascal). The internal software of this handheld device allows an automatic compensation of the measured values between 20 and 40 degrees Celsius, resulting in good thermal stability and a clinically unimportant drift of 1.25 millimeters of mercury (0.17 kilopascal) at most. Furthermore, the drift from 20 to 40 degrees Celsius was less marked if calibration was performed in warm water (20 degrees Celsius) rather than at dry room temperature. At the temperature of the resting muscle (33 degrees Celsius), the measurement was shown to be highly stable, with no relevant drift during long-term measurements. Generally, the extremely small drift that was observed corresponded to the physical characteristics of the semiconductor piezoelectric crystal.

In the tibialis anterior muscle of twenty normal limbs, the resting pressure was a mean (and standard deviation) of 13.1 ± 8.3 millimeters of mercury (1.75 ± 1.11 kilopascals). This finding is consistent with those of Matsen et al.¹¹ (mean, 11.5 ± 0.5 millimeters of mercury [1.53 ± 0.07 kilopascals]), Reneman¹⁸ (range, 7.0 to 16.0 millimeters of mercury [0.93 to 2.13 kilopascals]), Logan et al.⁹ (mean, 13.2 ± 6.7 millimeters of mercury [1.76 ± 0.89 kilopascals]), Rorabeck et al.²⁰ (mean, 10.9 ± 1.1 millimeters of mercury [1.45 ± 0.15 kilopascals]), and Nkele et al.¹⁷ (range, -2 to 17.5 millimeters of mercury [-0.27 to 2.33 kilopascals]), all of whom used infusion techniques that recorded the total tissue pressure. Other investigators have reported lower pressures with use of the wick method, which measures only the fluid pressure in the tissue.^{1,6,12,14,22} In contrast with these studies, in which values between zero and 10.0 millimeters of mercury (zero and 1.33 kilopascals) were observed, the findings in our study showed a tendency toward a higher resting pressure in the tibialis anterior muscle. Although the recorded pressures depend on the method that is used, one possible explanation for this observed tendency is that the new catheter measures the total tissue pressure as the sum of the fluid and solid components. According to Guyton et al.⁵, the diagnosis of acute compartment syndrome in an injured extremity must be based on the total tissue pressure because both the solid and the fluid components act on the local vasculature. A potential source of error associated with use of the new electronic system is placement of the needle into the intramuscular tendon, which gives a falsely high reading^{16,22,26}. A falsely high reading theoretically can also be obtained if crosswise-tensed muscle fibers press on the sensing area of the probe^{22,26}. Therefore, the probe should be inserted parallel to the muscle fibers^{22,26}.

The responsiveness of the electronic transducer-tipped catheter was observed during the injection of saline solution and during the application of an external pressure. The high sensitivity of the measurement technique allowed an immediate reaction to artificial elevations of intramuscular pressure and demonstration of

the subsequently slow decrease of intramuscular pressure that was due to fluid convection down a pressure gradient within the muscle. Several investigators have shown that tissue pressure is linearly dependent on the resting or internal pressure of the tissue and the superimposed, or external, pressure^{11,12}. An excellent correlation was observed between the pressures applied externally by the antishock trousers and the measured intramuscular pressures ($r = 0.997$ to 0.999), indicating the validity of the measurement of pressure in human muscle with use of the electronic transducer-tipped catheter. The total pressure was almost exactly the sum of the externally applied pressure and the baseline resting pressure (Fig. 3).

The catheter did not lose its accuracy as long as twenty-one hours after corrective osteotomy or intramedullary nailing of tibial fractures. In our experience, no clotting was observed when the probes were placed directly into a hematoma or into tissues with large collections of blood. Unlike the currently used fluid-filled systems, such as the wick, slit, and solid-state transducer intracompartmental catheter^{3,6,7,10,19,20}, the new catheter could measure the pressure course continuously over the long term without any additional manipulation. The major problem with fluid-filled catheters is that they can become blocked by a blood clot during long-term monitoring^{7,13}. Although the fibers at the orifice of the wick catheter prevent occlusion caused by impingement of the surrounding soft tissue and thus maintain channels for interstitial fluid, coagulation around the tip is possible. Therefore, the wick catheter can record pressure for only as long as eight hours⁷. Compared with the wick catheter, the slit catheter, described in 1981 by Rorabeck et al.¹⁹, allows a more sensitive response to changes in fluid pressure in tissue and is usable for a longer time because of the more open design of the tip of the probe. Nevertheless, the slit catheter requires as many as three, four, or five flushes with saline solution to maintain patency throughout several hours of recording⁸. In contrast to other catheter systems, our new probe can provide accurate recording for as long as twenty-four hours. In our clinical experience (not reported in this study), accurate recording was observed for as long as several days.

The piezoresistive technique allows measurement without additional handling or additional disposable items. It is not necessary to inject saline solution, which creates an artificially high pressure around the orifice at the tip^{14,15}. Compared with the needle technique of Whitesides et al.²⁷, described in 1975, the new technique avoids bubbles of air in the catheter. Although the needle technique is uncomplicated, it is considered the least accurate of those available because it produces falsely high values when low pressures are measured and falsely low values when high pressures are measured^{3,11,13,20,25}.

The absence of hydrostatic artifacts caused by movement of the tip of the catheter or of the limb is an

additional characteristic of the electronic transducer-tipped catheter system that makes it preferable for long-term measurement of intramuscular pressure in a patient at rest. As described in 1990 by Crenshaw et al.⁴, a change in the position of the transducer or the limb can induce measurement artifacts of as much as forty millimeters of mercury (5.33 kilopascals). Therefore, in contrast to the needle technique of Whitesides et al.²⁷ and to the wick and slit-catheter techniques, it is not necessary to calibrate hydrostatic fluid pressure continuously or to hold the fluid's meniscus stationary in a capillary tube by adjusting its hydrostatic height above the catheter when the patient is moved^{6,14,21,29}. Our study demonstrated that even when the catheter was raised or lowered from the reference point during extreme muscular activity there were no hydrostatic pressure artifacts. Similar to our new catheter, the transducer-tipped fiber-optic catheter described by Crenshaw et al.⁴ was not affected by changes in the position of the patient because of the independence of the system from hydrostatic pressure. However, although it measures intramuscular pressure without fluid artifacts, the fiber-optic transducer is relatively large and must be attached to an intracath sheath (outer diameter, 2.1 millimeters) filled with saline solution. This large sheath causes trauma to the tissue and is uncomfortable for the patient, especially during studies of muscular activity. In addition, a ten-minute equilibration period after insertion should be allowed before a reading of the tissue pressure is obtained. Another problem is the possible breakage of the optical fibers caused by strenuous exercise. Therefore, this procedure is not commonly used in clinical applications.

In our experience, movement of the limbs produced no dislocation or breakage of the inserted electronic transducer-tipped catheter probes and no electronic artifacts. The catheter could record data during strong muscular activity with a high temporal resolution of one to 200 hertz and with a very dynamic response to exercise; thus, computer-assisted instantaneous recording of the pressure course during the gait cycle is possible. In our study, the intramuscular pressure during muscular activity increased to as much as 180 millimeters of mercury (24.00 kilopascals) in a healthy volunteer. This finding is consistent with the range of recorded pres-

ures of 100 to 250 millimeters of mercury (13.33 to 33.33 kilopascals) that has been observed by other authors^{2,22,23}. Although the Myopress catheter technique, which was described by Styf and Körner²² in 1986, is simple and responsive, there are problems with regard to hydrostatic artifacts caused by the saline-solution-filled catheter line that connects a subject to the pressure transducer during exercise⁷. The other currently used catheters, such as the wick and slit catheters, are not suitable for high-fidelity dynamic studies of subjects during exercise and gait analyses because of low-frequency response, hydrostatic pressure artifacts, and occlusion of the catheter tip^{7,25,26}. For this reason, slit catheters must be flushed repeatedly²⁶. Another electronic transducer-tipped catheter, the small Millar catheter, also provides good dynamic response to changes in intramuscular pressure^{7,26}. Both the Millar catheter and the catheter described in the present study incorporate the current technology for measurement and provide artifact-free, excellent dynamic response to changes in intramuscular pressure.

In summary, acute compartment syndrome must be diagnosed early in order to prevent severe neuromuscular deficits. To meet this objective, the results of the clinical examination must be evaluated in relation to measurements of compartment pressure. The electronic instrument described in the present report is suitable for accurate and valid measurements, as it prevents hydrostatic pressure artifacts and obviates the need for infusion of fluids. The system also provides long-term monitoring without the need for additional manipulation either intraoperatively or during nonoperative management of patients in the hospital. The connection of the probe with the monitoring system automatically initiates the software-controlled self-calibration procedure, which allows immediate use. The electronic transducer-tipped catheter can be resterilized and reused. The catheter, which causes little trauma, offers dynamic responses and provides high-frequency recordings of intramuscular pressure during exercise. It can be recommended for routine use in the diagnosis of acute and exertional compartment syndromes.

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References

1. Allen, M. J.; Stirling, A. J.; Crawshaw, C. V.; and Barnes, M. R.: Intracompartmental pressure monitoring of leg injuries. An aid to management. *J. Bone and Joint Surg.*, 67-B(1): 53-57, 1985.
2. Aratow, M.; Ballard, R. E.; Crenshaw, A. G.; Styf, J.; Watenpaugh, D. E.; Kahan, N. J.; and Hargens, A. R.: Intramuscular pressure and electromyography as indexes of force during isokinetic exercise. *J. Appl. Physiol.*, 74: 2634-2640, 1993.
3. Barnes, M. R.; Gibson, M. J.; Scott, J.; Bentley, S.; and Allen, M. J.: A technique for the long term measurement of intra-compartmental pressure in the lower leg. *J. Biomed. Eng.*, 7: 35-39, 1985.
4. Crenshaw, A. G.; Styf, J. R.; Mubarak, S. J.; and Hargens, A. R.: A new "transducer-tipped" fiber optic catheter for measuring intramuscular pressures. *J. Orthop. Res.*, 8: 464-468, 1990.
5. Guyton, A. C.; Granger, H. J.; and Taylor, A. E.: Interstitial fluid pressure. *Physiol. Rev.*, 51: 527-563, 1971.
6. Hargens, A. R.; Mubarak, S. J.; Owen, C. A.; Garetto, L. P.; and Akeson, W. H.: Interstitial fluid pressure in muscle and compartment syndromes in man. *Microvasc. Res.*, 14: 1-10, 1977.
7. Hargens, A. R., and Ballard, R. E.: Basic principles for measurement of intramuscular pressure. *Op. Tech. Sports Med.*, 3: 237-242, 1995.
8. Heppenstall, R. B.; Sapega, A. A.; Scott, R.; Shenton, D.; Park, Y. S.; Maris, J.; and Chance, B.: The compartment syndrome. An

- experimental and clinical study of muscular energy metabolism using phosphorus nuclear magnetic resonance spectroscopy. *Clin. Orthop.*, 226: 138-155, 1988.
9. **Logan, J. G.; Rorabeck, C. H.; and Castle, G. S.:** The measurement of dynamic compartment pressure during exercise. *Am. J. Sports Med.*, 11: 220-223, 1983.
 10. **McDermott, A. G. P.; Marble, A. E.; and Yabsley, R. H.:** Monitoring acute compartment pressures with the S.T.I.C. catheter. *Clin. Orthop.*, 190: 192-198, 1984.
 11. **Matsen, F. A., III; Mayo, K. A.; Sheridan, G. W.; and Krugmire, R. B., Jr.:** Monitoring of intramuscular pressure. *Surgery*, 79: 702-709, 1976.
 12. **Matsen, F. A., III; Winkquist, R. A.; and Krugmire, R. B.:** Diagnosis and management of compartmental syndromes. *J. Bone and Joint Surg.*, 62-A: 286-291, March 1980.
 13. **Moed, B. R., and Thorderson, P. K.:** Measurement of intracompartmental pressure: a comparison of the slit catheter, side-ported needle, and simple needle. *J. Bone and Joint Surg.*, 75-A: 231-235, Feb. 1993.
 14. **Mubarak, S. J.; Hargens, A. R.; Owen, C. A.; Garetto, L. P.; and Akeson, W. H.:** The wick catheter technique for measurement of intramuscular pressure. A new research and clinical tool. *J. Bone and Joint Surg.*, 58-A: 1016-1020, Oct. 1976.
 15. **Mubarak, S. J.; Owen, C. A.; Hargens, A. R.; Garetto, L. P.; and Akeson, W. H.:** Acute compartment syndromes: diagnosis and treatment with the aid of the wick catheter. *J. Bone and Joint Surg.*, 60-A: 1091-1095, Dec. 1978.
 16. **Nakhostine, M.; Styf, J. R.; van Leuven, S.; Hargens, A. R.; and Gershum, D. H.:** Intramuscular pressure varies with depth. The tibialis anterior muscle studied in 12 volunteers. *Acta Orthop. Scandinavica*, 64: 377-381, 1993.
 17. **Nkele, C.; Aindow, J.; and Grant, L.:** Study of pressure of the normal anterior tibial compartment in different age groups using the slit-catheter method. *J. Bone and Joint Surg.*, 70-A: 98-101, Jan. 1988.
 18. **Reneman, R. S.:** The anterior and the lateral compartmental syndrome of the leg due to intensive use of muscles. *Clin. Orthop.*, 113: 69-80, 1975.
 19. **Rorabeck, C. H.; Castle, G. S.; Hardie, R.; and Logan, J.:** Compartmental pressure measurements: an experimental investigation using the slit catheter. *J. Trauma*, 21: 446-449, 1981.
 20. **Rorabeck, C. H.; Bourne, R. B.; Fowler, P. J.; Finlay, J. B.; and Nott, L.:** The role of tissue pressure measurement in diagnosing chronic anterior compartment syndrome. *Am. J. Sports Med.*, 16: 143-146, 1988.
 21. **Scholander, P. F.; Hargens, A. R.; and Miller, S. L.:** Negative pressure in the interstitial fluid of animals. Fluid tensions are spectacular in plants; in animals they are elusively small, but just as vital. *Science*, 161: 321-328, 1968.
 22. **Styf, J. R., and Körner, L. M.:** Microcapillary infusion technique for measurement of intramuscular pressure during exercise. *Clin. Orthop.*, 207: 253-261, 1986.
 23. **Styf, J. R., and Körner, L. M.:** Diagnosis of chronic anterior compartment syndrome in the lower leg. *Acta Orthop. Scandinavica*, 58: 139-144, 1987.
 24. **Styf, J. R.:** Evaluation of injection techniques for recording of intramuscular pressure. *J. Orthop. Res.*, 7: 812-816, 1989.
 25. **Styf, J. R.; Crenshaw, A.; and Hargens, A. R.:** Intramuscular pressures during exercise. Comparisons of measurements with and without infusion. *Acta Orthop. Scandinavica*, 60: 593-596, 1989.
 26. **Styf, J. R.:** Intramuscular pressure measurements during exercise. *Op. Tech. Sports Med.*, 3: 243-249, 1995.
 27. **Whitesides, T. E., Jr.; Haney, T. C.; Harada, H.; Holmes, H. E.; and Morimoto, K.:** A simple method for tissue pressure determination. *Arch. Surg.*, 110: 1311-1313, 1975.
 28. **Whitesides, T. E., Jr.; Haney, T. C.; Morimoto, K.; and Harada, H.:** Tissue pressure measurements as a determinant for the need of fasciotomy. *Clin. Orthop.*, 113: 43-51, 1975.
 29. **Wiig, H.:** Evaluation of methodologies for measurement of interstitial fluid pressure (P_i): physiological implications of recent P_i data. *Crit. Rev. Biomed. Eng.*, 18: 27-54, 1990.
 30. **Willy, C.; Becker, H. P.; Evers, B.; and Gerngross, H.:** Unusual development of acute exertional compartment syndrome due to delayed diagnosis. A case report. *Internat. J. Sports Med.*, 17: 458-461, 1996.