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INTRACRANIAL PRESSURE MONITORING

A continuously recording device that measures fluid pressure inside the skull and its value in the management of a variety of diseases are discussed.

INTRODUCTION

The ability to measure the pressure of fluid inside the skull (intracranially) on a continuing basis is an important aid in diagnosing and managing a number of neurological diseases. If undetected, excessive cerebrospinal fluid pressure presents a great risk, particularly in unconscious patients who may exhibit no immediate or obvious symptoms until irreversible damage to the central nervous system has occurred. The ability to monitor intracranial pressure is particularly important in post-operative and post-traumatic neurosurgical patients.

The conventional methods of determining the pressure of the cerebral spinal fluid are by tapping the lumbar sac of the spinal column in the lower back or by introducing a catheter into one of the fluid-filled ventricular spaces in the brain; however, neither technique is suitable for prolonged recording of the fluid pressure. In addition to the danger of infection and patient discomfort, leakage and blockage of the hydraulic system and patient movement induce inaccuracies in the measurement.

Because of the many requirements in neurosurgical practice to measure intracranial pressure on a continuous basis, a new instrument was devised for this purpose at the Applied Physics Laboratory.

PRESSURE MONITOR DESIGN

APL became actively involved in the design of an intracranial pressure sensor after receiving a National Institutes of Health grant in May 1974. The grant called for the device to be designed and laboratory tested at APL and animal tested at the Department of Neurological Surgery at Johns Hopkins Hospital. Requirements were for a sensor to be implanted outside of the brain; i.e., a capsule would be placed outside of the dura mater (a tough membrane enclosing the brain) in a burr hole made in the skull, a location that avoids brain disturbance and minimizes the likelihood of infection. No wire or tubing connections through the skin were permitted. The device was required to have a pressure range of -200 to $+1500$ mmH_2O with an accuracy of ± 50 mmH_2O.

The most promising way to monitor intracranial pressure is by using a passive sensor that consists only of an electrical inductance and capacitance circuit. Such a sensor does not require batteries or transistors, has an indefinite life, and requires no wire connections. The basic concept has been known for over 20 years.[1]

The practical design[2] for such a sensor is shown in Fig. 1. The interior of a plastic case is filled with medical-grade silicone oil and is sealed. Pressure external to the sensor causes a plastic diaphragm to deflect, raising the pressure in the silicone oil which, in turn, compresses the nitrogen-filled bellows. As a result, the closed end of the bellows is pushed farther away from a brass plate, decreasing the electrical capacitance between the bellows and the plate. The ends of the inductance coil are connected to the bellows and brass plate, forming

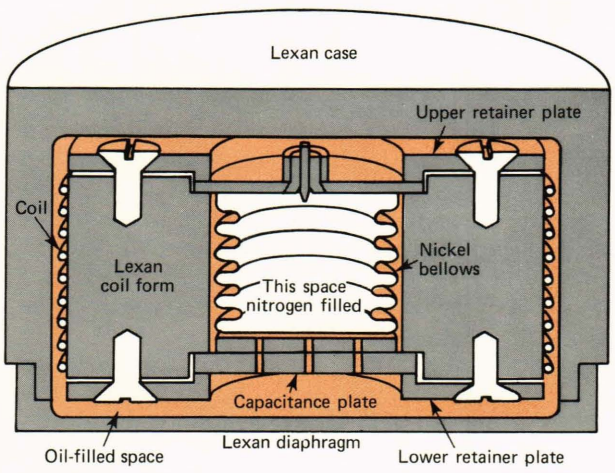

Fig. 1—A cross section of the implantable intracranial pressure (ICP) sensor. The sensor is a short cylinder 16 mm in diameter and 7 mm in height. For ICP measurement monitoring, the sensor is implanted in a burr hole made in the skull. The thin diaphragm rests on the dura mater, which envelops the brain. By replacing the removed disc of skull bone by the sensor, there is minimal cosmetic change and interference with brain function.

Fig. 2—The ICP sensor is shown in the middle of the photograph. The external pickup coil shown to the left of the sensor radiates a frequency modulated VHF radio signal. When the pickup coil is placed near the ICP sensor, RF energy is absorbed by the sensor at the resonant frequency of the tuned circuit inside the sensor.

Fig. 3—Measurement of the ICP sensor in a patient with hydrocephalus. The pickup coil is held over the site of the implanted sensor. The display on the oscilloscope shows a pulse (one division to the right of the display's center) that indicates the RF absorption frequency of the sensor. The movement of this pulse is caused by ICP variations resulting from the heartbeat. The pulse at the 5th division is a 50 MHz calibration marker. The absorption frequency versus pressure of the sensor is known from previous calibration.

an electrical resonant circuit consisting of an inductance and a capacitance. The smaller capacitance from increased pressure results in a higher resonant frequency of this tuned resonant circuit.

A sensing coil (Fig. 2) located outside the body, about 3 to 4 cm from the sensor, radiates a swept-frequency RF signal that varies between 40 and 70 MHz. Energy absorbed by the implanted sensor at its resonant frequency is detected by the coil. External equipment measures the frequency at which this absorption takes place. Calibration establishes the relationship between the resonant frequency and the pressure imposed on the sensor.

For implantation of the sensor, a burr hole is made in the upper right area of the skull under sterile conditions; the sensor is placed in the hole with its sensing diaphragm in contact with the dura mater. Galea tissue under the scalp is sewn over the sensor to fix it in place, and the wound in the scalp overlaying the sensor is closed. (The procedure is usually performed under local anesthesia.) The external pickup is taped on the patient's head over the site of the sensor so that pressure can be recorded continuously.

Figure 3 shows the pickup coil positioned to sense the frequency of an implanted sensor. The monitor displays the absorption pulse (vertical) versus frequency (horizontal). The relationship between RF frequency (MHz) and pressure (mmH_2O) is established prior to implantation, and a calibration chart is provided for each sensor. Figure 4 shows a patient on whom overnight recordings are being made for diagnostic purposes.

CLINICAL USES

For the past five years, the intracranial pressure monitoring system has been clinically evaluated[3] at the Johns Hopkins Hospital and the Baltimore City Hospital. Analyses of the results during that time have led to improvements in the instrumentation. Sensors were implanted in 56 patients, of whom 28 had hydrocephalus (an abnormal accumulation of body fluids inside the skull), 14 had pseudotumor, and 14 had brain tumors, head trauma, aneurysms (abnormal blood vessel dilation), cerebral anoxia, and cerebral blood clots.

The intracranial pressure was normal in most cases of adult hydrocephalus that we studied.[4] However, X-ray studies showed that the patients had enlarged ventricles. Patients complained of some loss of coordination, urinary incontinence, and memory loss; in extreme cases the patients showed signs of dementia. These patients are diagnosed as having "normal pressure hydrocephalus." Our findings in such cases are that the ultimate damage to the brain from excessive pressure occurs during rapid eye movement (REM) sleep. During REM sleep, it is normal[5] for the cerebral blood vessels to dilate. This admits more blood to the brain and causes the intracranial pressure to rise about 50%. However, in patients with normal pressure hydrocephalus, the compliance (i.e., compressibility) of the brain is much less. This causes intracranial pressure rises to levels 3 to 10 times above normal, rises that are accompanied by large pulsations resulting from the arterial pressure changes from the heartbeat (Fig. 5). These large pressure changes cause severe stretching of the lateral ventricles, which leads to neural tissue damage in the surrounding (periven-

tricular) spaces. To lower the pressure changes, a ventriculo-atrial shunt is implanted with a valve that opens if the pressure exceeds a given value, draining the excess cerebral spinal fluid from the ventricles, and emptying it into a vein in the patient's neck. If the damage has not progressed too far, the results of a shunt implant are dramatic. Patients who were bedridden have been able to return to their former jobs or professions.

To determine if a shunt operation would be of value, the positive end expiratory pressure (PEEP) test, which measures brain compliance is conducted. This test requires the patient to breathe into a standard anesthesia mask in which the pressure is systematically raised. This procedure causes the PEEP to rise. As it does, the intracranial pressure, as measured by the intracranial pressure sensor, is recorded. In these tests, the PEEP is first raised to 50 mmH_2O and held at that level for three to four respiratory cycles. The test is repeated at 50 mmH_2O increments with several minutes of rest between tests until 200 mmH_2O is reached. The slope of the curve of intracranial pressure versus PEEP (Fig. 5) is taken as a measure of brain compliance.

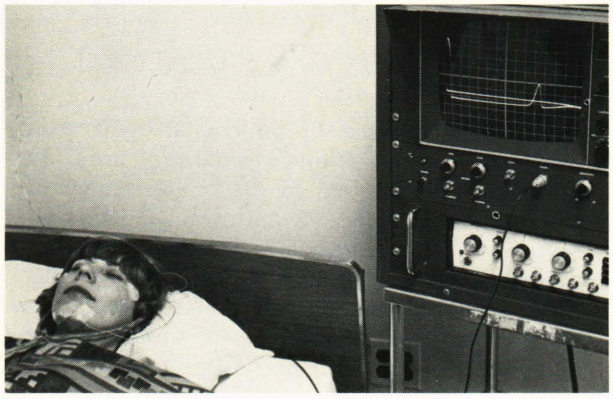

Fig. 4—A patient with an ICP sensor in an overnight study of the dynamic behavior of the ICP during the various stages of sleep. External electrodes on the head are for electroencephalography, near the eyes for electrooculography, and under the chin for electromyography. To avoid disturbing the patient, the pen recorders for the four functions are in another room. A continuous record of the ICP is made, and the recordings of the latter three functions identify the stage of sleep.

After the shunting operation, the monitor permits a person to be checked periodically on an outpatient basis in order to verify that the shunt is functioning satisfactorily. If the enlarged ventricles are caused by brain atrophy, the intracranial pressure recordings will show only a normal rise during REM sleep and the PEEP test will show normal brain compliance. These results indicate that a shunt operation would be of no value to the patient.

Other patients for whom intracranial monitoring is valuable are those having pseudotumor,[6] a disease that is caused by an abnormal swelling of the brain. This swelling, in turn, causes a swelling of the optic discs that may lead to blindness if not controlled. Pressure recordings are useful for evaluating the efficacy of the medication. Abnormally high intracranial pressure is also found in these patients during REM sleep. Failure of medication to control the pressure instability usually necessitates implanting a thecoperitoneal shunt to tap the spinal dura mater sac in the lumbar spinal cord region and emptying the excess cerebral spinal fluid into the peritoneal space whenever the intracranial pressure exceeds a given value. Frequent pressure measurements and ophthalmological examinations are necessary to ensure that the medication or the shunting remains effective. In two cases, pressure monitoring indicated a return to uncontrolled pressure levels that were traced to a blocked shunt.

The instrumentation was used in seven cases to provide early warning of rising intracranial pressure in brain tumors and of acute cases of intracranial hypertension caused by cranial trauma, hemorrhages below the arachnoid brain membrane, and aneurysms. Surgical intervention was needed in two of these cases. In two other cases, where brain

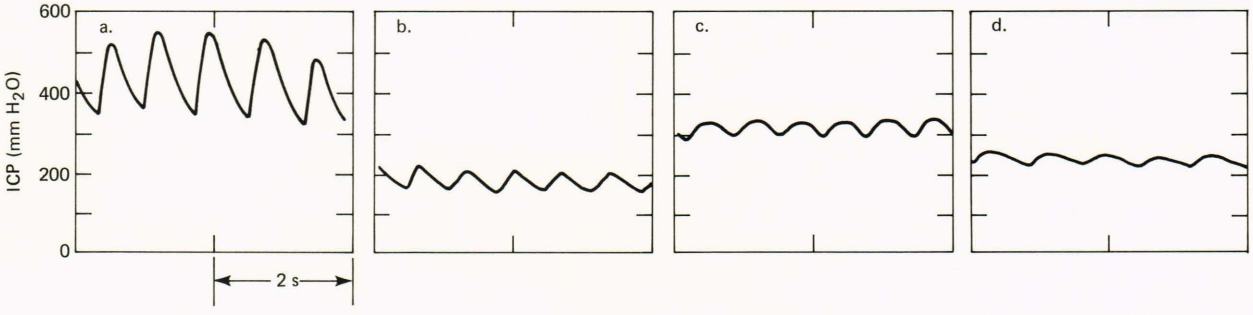

Fig. 5—Pen recordings in a patient in two overnight diagnostic studies. Recordings a and b were made prior to treatment, while **c** and **d** were made after the patient received a shunt. In **a**, the recording was made during REM sleep. Note the high average intracranial pressure and pressure pulsations of over 500 mmH_2O from cardiac pulsations of the cerebral vascular system. In **b**, the pressure recorded during deep sleep was normal. After a shunt was implanted, the pressure in **c** during REM sleep rose to only 300 mmH_2O, and in **d** returned to about 200 mmH_2O during deep sleep. The pressures in **c** and **d** are within normal limits, verifying the effectiveness of the shunt.

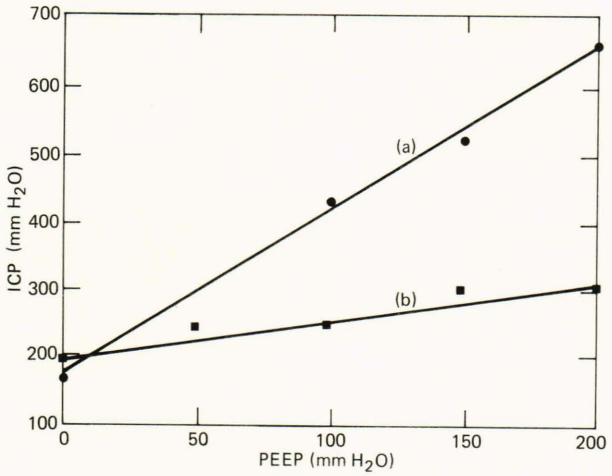

Fig. 6—PEEP test on the same patient discussed in Fig. 5. This test is designed to measure the patient's brain compliance. An oxygen mask is placed over the face to raise post-expiratory pressure. Before the shunt was installed, curve **a** was obtained. The steep slope of this curve shows compromised brain compliance. After the shunt was installed, curve **b** was obtained. The slope of this curve indicates a normal degree of compliance.

tumors were excised, recordings of intracranial pressure are being made since the operations to inform the physician if tumors recur; two of the other patients have since died.

DISCUSSION

The implantable sensors have had an excellent record of reliability and survivability,[7] having operated satisfactorily for three years in four patients and for two years in ten others. A design limitation of the present sensors is a baseline drift of between 1 and 2 mmH_2O per day, always in the direction of higher pressure, that requires an additional correction in the computation of the intracranial pressure. The baseline drift rate is greater than we would like; it is attributed to diffusion of water and gases through the plastic parts of the sensor, and perhaps also to the porosity of the metal bellows, which contains nitrogen gas. It is expected that these problems will be solved by a different choice of materials.

As presently designed, the bedside monitor displays the value of the radio frequency at which the sensor is resonant. The frequency value is converted to pressure by means of calibration charts. Further corrections are required to account for changes in barometric pressure and in the patient's temperature, if it deviates from normal. It is expected that in a commercial bedside monitor all the computations will be performed automatically, giving a continuous display and recording of intracranial pressure.

None of the 56 patients who received implants of the pressure monitor showed any untoward effects from the implants. There were no infections, nor was there tissue irritation even when a sensor ruptured in a patient who received a head injury. No neurological effects were noted as a result of the presence of the implant. Most patients had only a barely visible and palpable depression at the site of the implantation. No pain or discomfort was reported after the incision had healed.

This method of monitoring intracranial pressure has proved to be useful in the diagnosis, treatment, and continuous observation of patients with chronic disturbances in the regulation of intracranial pressure. In diagnosis, measurements were valuable in identifying whether the cause of enlarged ventricles was a periodic increase in intraventricular pressure or cerebral atrophy. They were also valuable in assessing the effects of medication and shunts on the variations in intracranial pressure. Another benefit is the ease of patient follow-up; in a number of cases, medication failed to control intracranial pressure or obstructions to shunts were discovered. The greatest advantage to the patients is that they do not have to submit to frequent and inconvenient lumbar punctures to measure their intracranial pressures.

THE INTRACRANIAL PRESSURE MONITORING CENTER

The large number of patients with diseases for which surveillance of intracranial pressure is an important factor has led to the establishment of the Intracranial Pressure Monitoring Center at the Baltimore City Hospital in September 1979. The Center allows outpatients who come for a checkup to be accommodated rapidly. This service is possible because of the availability of unique equipment and specialized personnel. Hospital rooms are set aside so that patients' pressure can be measured during sleep.

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