SPINE Volume 24, Number 8, pp 755–762

New *In Vivo* Measurements of Pressures in the Intervertebral Disc in Daily Life

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Study Design. We conducted intradiscal pressure measurements with one volunteer performing various activities normally found in daily life, sports, and spinal therapy.

Objectives. The goal of this study was to measure intradiscal pressure to complement earlier data from Nachemson with dynamic and long-term measurements over a broad range of activities.

Summary of Background Data. Loading of the spine still is not well understood. The most important *in vivo* data are from pioneering intradiscal pressure measurements recorded by Nachemson during the 1960s. Since that time, there have been few data to corroborate or dispute those findings.

Methods. Under sterile surgical conditions, a pressure transducer with a diameter of 1.5 mm was implanted in the nucleus pulposus of a nondegenerated L4–L5 disc of a male volunteer 45-years-old and weighing 70 kg. Pressure was recorded with a telemetry system during a period of approximately 24 hours for various lying positions; sitting positions in a chair, in an armchair, and on a pezziball (ergonomic sitting ball); during sneezing, laughing, walking, jogging, stair climbing, load lifting; during hydration over 7 hours of sleeping, and others.

Results. The following values and more were measured: lying prone, 0.1 MPa; lying laterally, 0.12 MPa; relaxed standing, 0.5 MPa; standing flexed forward, 1.1 MPa; sitting unsupported, 0.46 MPa; sitting with maximum flexion, 0.83 MPa; nonchalant sitting, 0.3 MPa; and lifting a 20-kg weight with round flexed back, 2.3 MPa; with flexed knees, 1.7 MPa; and close to the body, 1.1 MPa. During the night, pressure increased from 0.1 to 0.24 MPa.

Conclusions. Good correlation was found with Nachemson's data during many exercises, with the exception of the comparison of standing and sitting or of the various lying positions. Notwithstanding the limitations related to the single-subject design of this study, these differences may be explained by the different transducers used. It can be cautiously concluded that the intradiscal pressure during sitting may in fact be less than that in erect standing, that muscle activity increases pressure, that constantly changing position is important to promote flow of fluid (nutrition) to the disc, and that many of the physiotherapy methods studied are valid, but a number of them should be re-evaluated. [Key words: biomechanics, exercises, intervertebral disc, intradiscal pressure, low back pain, spinal loading, spine] **Spine 1999;24:755–762**

Reporting of back pain has increased dramatically in the past years,[22,23] and back pain is now the most frequent reason for absence from work. The consequences are serious for the patient and for the cost of health care. The reason most often cited in workers' compensation claims is overload of the spine. Unfortunately, loading of the spine still is not well understood. Direct measurements of spinal loading through *in vivo* studies are normally avoided because of concerns about the effect of introducing a transducer into the disc. Indirect methods or mathematical approaches are unvalidated. Thus, those conducting spinal research are left to rely on the data from Nachemson's studies in the 1960s and 1970s for the best estimations of the mechanical response of the spine to various activities. These data are the basis for physiotherapy, rehabilitation programs, and workplace recommendations.

From Nachemson's studies it was assumed, for example, that sitting increases the pressure in the nucleus pulposus approximately 40% when compared with standing.[16,17,21] Throughout the years, this finding has been applied broadly, especially by orthopedic surgeons. Patients with a herniated disc or recent disc surgery, for example, commonly are advised to stand rather than sit during recovery.

In recent years, however, the results of some indirect analyses of spinal loading have disputed this important finding from Nachemson. One study involved precise measurement of body stature, which indicates loss or gain of disc height and thus allows the qualitative assessment of changes in spinal loading.[5] With this method, it was concluded that in sitting posture, spinal loading is lower than in standing. Similar results were found with another indirect method using an instrumented internal spinal fixator for stabilization.[24] These indirect indications that the intradiscal pressure in various postures may differ characteristically from that classically thought to exist prompt consideration of a renewed investigation with direct measurements.

The goal of this study was to measure intradiscal pressure with a more advanced transducer than that used by Nachemson and to complement those earlier data with dynamic and long-term measurements over a broad range of activities. Intradiscal pressure measurements were obtained with one volunteer performing various activities normally found in daily life, sports, and spinal therapy.

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Supported by Kieser Training AG, Zurich, Switzerland.
Acknowledgment date: April 18, 1998.
First revision date: July 13, 1998.
Acceptance date: September 14, 1998.
Device status category: 1.

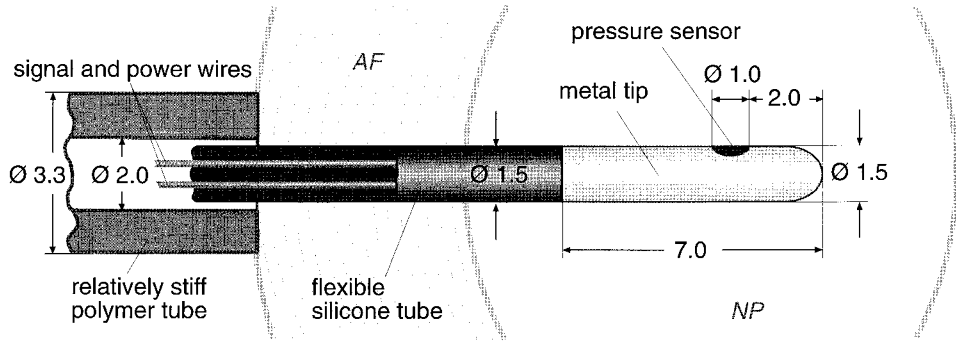


Figure 1. Schematic diagram of the total implantation system (all dimensions in millimeters). To prevent shifting of the transducer caused by the pressure in the nucleus acting at its tip, the transducer was guided through a relatively stiff polymer tube with an inner diameter of 2.0 mm and an outer diameter of 3.3 mm, which was then secured to the belt. Thus, the total implantation system was divided between a stiffer section beginning at the skin surface and extending to the disc, a pliant section within the anulus fibrosus, and finally, a metal tip within the nucleus.

Methods

Because of the risk involved in this investigation, just two subjects (both volunteer male orthopedists) were enlisted for the operation, which was approved in this single instance by the state ethics review board (Landesärztekammer Baden–Württemberg, Germany). The measurements in the first subject (MC) had to be terminated directly after the implantation of the transducer because of technical problems with slippage of a relatively unsupported transducer cable. The second and actual subject (PN), implanted with a modified cable, was 45 years old, weighed 70 kg, stood 1.68 m, was in good physical condition, and had no history of back pain.

Because intradiscal pressure can only be reliably measured in a nondegenerated disc, magnetic resonance imaging (MRI) was used to evaluate the viability of the lumbar discs of the subject. Based on these findings the L4–L5 disc, which showed no signs of degeneration or dehydration, was used. The cross-sectional area was 1800 mm^2.

A flexible-pressure transducer with a constant diameter of 1.5 mm was used (Figure 1). A piezoresistant pressure sensor with a measuring range up to 3.5 MPa (35 bars) was integrated in a 7-mm-long metal tip (5 French; Mammendorfer Institut für Physik und Medizin GmbH, Hattenhofen, Germany). This tip was fixed to a flexible silicone tube, which carried the power and signal wires to a telemetry unit (Biotel 33, Glonner, Martinsried, Germany) mounted to a special belt worn by the subject to maintain the position of the transducer (Figure 2). The signal was amplified (DMCplus; HBM Hottinger Baldwin Messtechnik, Darmstadt, Germany) then collected at 200 Hz on a laptop computer (Macintosh, Powerbook 5300cs; software package beam-1D, ver. 3.3; AMS Gesellschaft für angewandte Mess-und Systemtechnik mbH, Flöha, Germany). The transducer was calibrated in an air chamber to 0.8 MPa to verify partially the manufacturer's calibration to 3.5 MPa.

After the volunteer was premedicated with antibiotics for 1 day, the transducer was implanted from a dorsolateral transforaminal approach into the center of the intervertebral disc under local anesthesia using a trocar in a manner similar to that used in performing percutaneous nucleotomy (Figure 3). To prevent shifting of the transducer caused by the pressure in the nucleus acting at its tip, the transducer was guided through a relatively stiff polymer tube with an inner diameter of 2.0 mm and an outer diameter of 3.3 mm (Reichert Chemie GmbH & Co., Heidelberg, Germany; Figure 1), which was then secured to the belt (Figure 3).

Measurements were first made of the intradiscal pressure with the subject in various lying positions; then during sneezing and laughing; then for a series of activities, including various sitting positions in a chair, in an armchair, and on a pezziball (ergonomic sitting ball); while standing, walking, jogging, stair climbing, load lifting (Figure 4); and finally, during sleeping to monitor the biomechanical effect of hydration during 7 hours. For this overnight measurement the sampling rate was reduced to 1 Hz.

The total test period was approximately 24 hours. During this time, the position of the transducer in the disc was periodically verified by radiograph (Figure 2) and by monitoring the pressure in prone and standing positions. The reproducibility of these pressure measurements obviated the need for further verifying radiographs after the third verification obtained 4 hours into testing. Most activity measurements reported were obtained during a 6-hour period in the afternoon. On the morning of the second day, sometime after the pressure was verified, the reproducibility of the signal was unexpectedly lost, thus ending the study, but not before all activities in the protocol and physiologic events were measured at least once. Examination of the radiographs showed that the transducer had slipped out of the disc, probably as a result of the subject's getting into the car to transfer to another test site.

The subject had slight back pain in the next few days caused

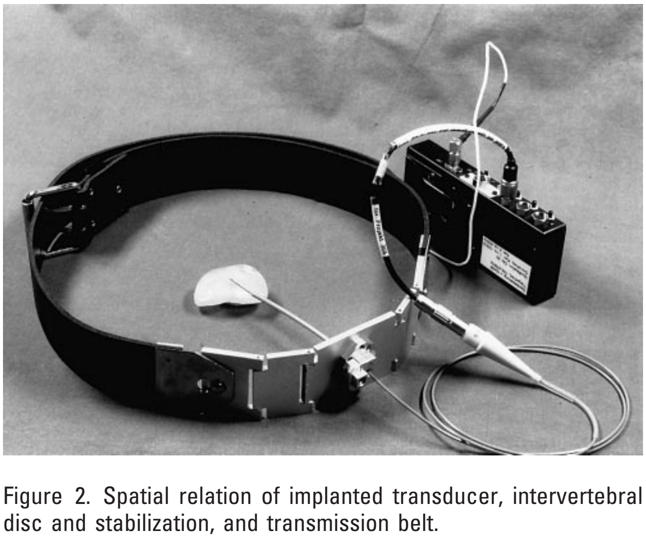


Figure 2. Spatial relation of implanted transducer, intervertebral disc and stabilization, and transmission belt.

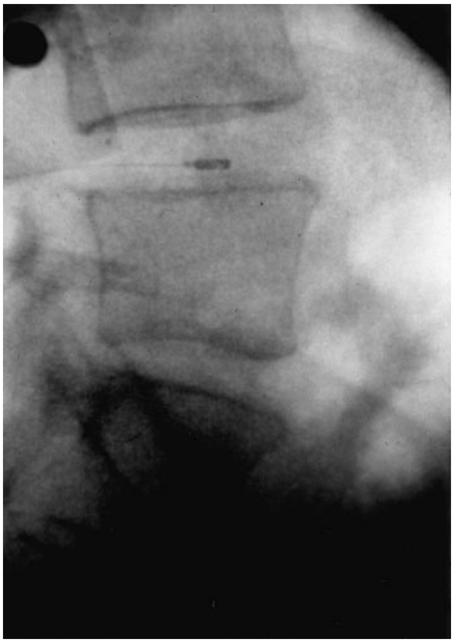


Figure 3. Radiograph with implanted pressure transducer approximately in the center of the L4–L5 nucleus pulposus.

by muscle spasms that resolved with training of the back muscles. Two years after the experiment, the subject reported no further episodes of back pain, and an MRI investigation did not show any change of the treated disc in comparison with the status before the experiment.

Results

All positions and activities were achieved or performed actively by the volunteer without assistance. Position-related measurements were recorded usually after two pretrials; activities required some training.

Table 1. Intradiscal Pressure Values for Different Positions and Exercises

Position	Pressure (MPa)
Lying supine	0.10
Lying on the side	0.12
Lying prone	0.11
Lying prone, extended back, supporting on elbows	0.25
Laughing heartily, lying laterally	0.15
Sneezing, lying laterally	0.38
Peaks by turning around	0.70–0.80
Relaxed standing	0.50
Standing, performing vasalva maneuver	0.92
Standing, bent forward	1.10
Sitting relaxed, without backrest	0.46
Sitting actively straightening the back	0.55
Sitting with maximum flexion	0.83
Sitting bent forward with tight supporting the elbows	0.43
Sitting slouched into the chair	0.27
Standing up from a chair	1.10
Walking barefoot	0.53–0.65
Walking with tennis shoes	0.53–0.65
Jogging with hard street shoes	0.35–0.95
Jogging with tennis shoes	0.35–0.85
Climbing stairs, one stair at a time	0.50–0.70
Climbing stairs, two stairs at a time	0.30–1.20
Walking down stairs, one stair at a time	0.38–0.60
Walking down stairs, two stairs at a time	0.30–0.90
Lifting 20 kg, bent over with round back	2.30
Lifting 20 kg as taught in back school	1.70
Holding 20 kg close to the body	1.10
Holding 20 kg, 60 cm away from the chest	1.80
Pressure increase during night (over a period of 7 hr)	0.10–0.24

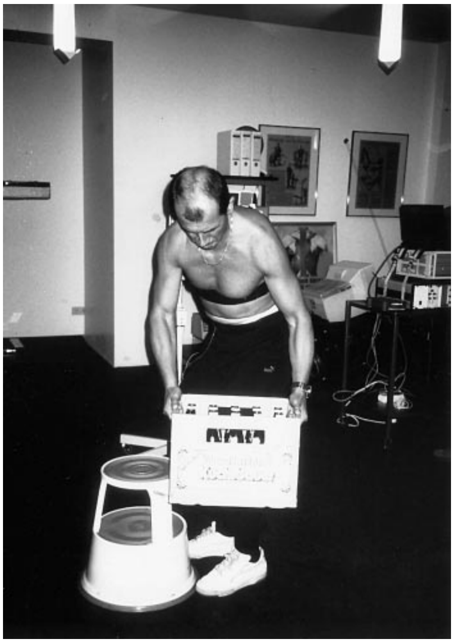


Figure 4. Lifting was performed in various positions of posture and weight proximity.

The first data were recorded while the subject was still on the operating table. Lying supine with legs relaxed and slightly flexed produced a pressure of 0.08 MPa (0.1 MPa equals approximately 1 bar), which then increased to 0.11 MPa when straightening out the legs, possibly because of an increase of muscle forces involving also the lumbar spine (Table 1). With flexed knees and either elevated or nonelevated feet, as is often prescribed for the healing back pain patient, the pressure returned to 0.08 MPa. Turning from a relaxed supine position to the side increased the pressure from 0.10 to 0.12 MPa. Further turning to the prone position decreased the pressure slightly to 0.11 MPa. However, supporting upper body weight with the elbows, as when reading prone and thus extending the spine, doubled the pressure to approximately 0.25 MPa. Monitoring the pressure as the subject turned around in bed produced dynamic peak values of 0.70 to 0.80 MPa. Sneezing while lying laterally increased the pressure to 0.38 MPa (Figure 5A), whereas laughing heartily increased it only to 0.15 MPa (Figure 5B).

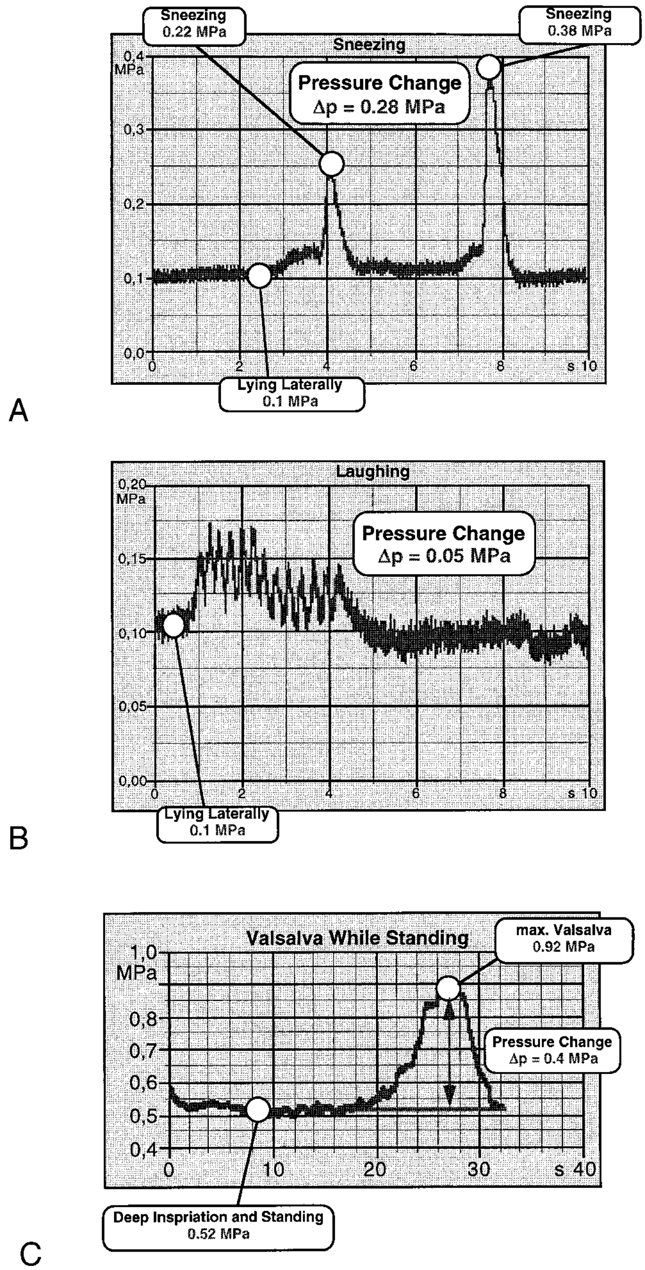


Figure 5. Intradiscal pressure during (**A**) sneezing, (**B**) laughing, and (**C**) performing the Valsalva maneuver.

In relaxed standing, intradiscal pressure was reproducibly 0.48 to 0.50 MPa. Performing the Valsalva maneuver increased the pressure to as much as 0.92 MPa (Figure 5C).

In sitting, fluctuations in pressure occurred with changes in posture and support. Relaxed sitting on a stool with a normally straight back produced a pressure peak of 0.45 to 0.50 MPa, similar to pressure in standing (Figure 6A). Actively straightening and extending the back, as taught in some back schools, increased the pressure to 0.55 MPa. Bending forward without arm support while seated increased the pressure to 0.83 MPa in maximum flexion, (simulating, for instance, the position of tying shoes). The maximum pressure reached by bending forward was 0.90 MPa. Bending forward with the thighs supporting the elbows, as in relaxed sitting, reduced the pressure to 0.43 MPa.

The pressure in sitting decreased when leaning backward in an armchair (Figure 6B). The lower the subject slouched in the chair, the more the pressure decreased (to a minimum of 0.27 MPa), despite his further increasing the flexion in his back. Standing up from the chair led to a pressure peak of 1.1 MPa.

For the following activity, ranges represent means within the regions surrounding maximums and minimums. During walking, intradiscal pressure ranged from 0.53 to 0.65 MPa, showing a double-peak curve of the ground-reaction force similar to that reported for the hip[9] (Figure 7). No differences were found between walking slowly and quickly or between walking barefoot and with tennis shoes (Figure 7, A and B). The range of pressures during jogging in hard street shoes was much higher at approximately 0.60 MPa (range, 0.35–0.95 MPa) than that during walking. Jogging with tennis shoes decreased the mean peak pressure to approximately 0.85 MPa, whereas the minimum pressure stayed the same. When climbing stairs one stair at a time, the pressure ranged from 0.5 to 0.7 MPa, but climbing two stairs at a time increased the range from 0.3 to 1.2 MPa

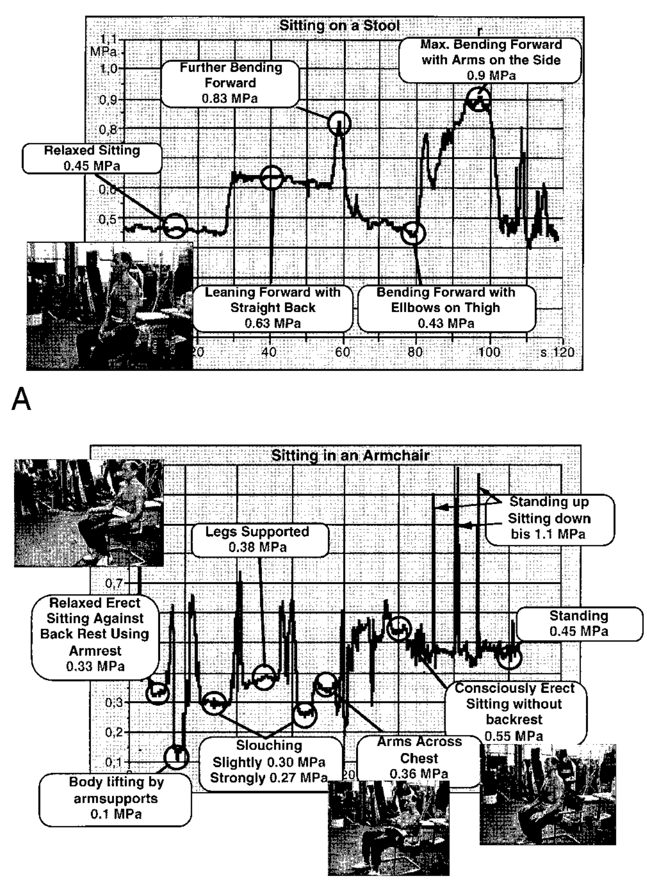
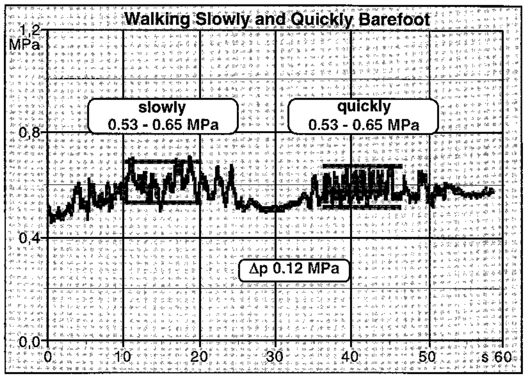


Figure 6. Intradiscal pressure during sitting in variously supported positions (**A**) on a stool and (**B**) in an armchair.



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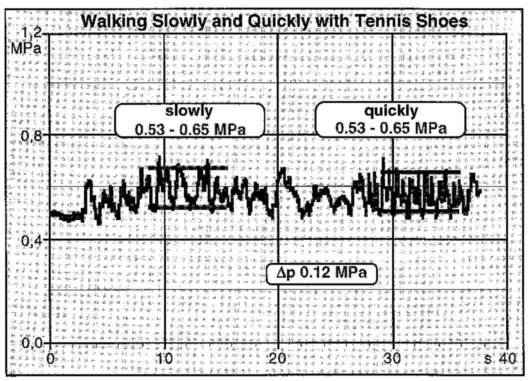
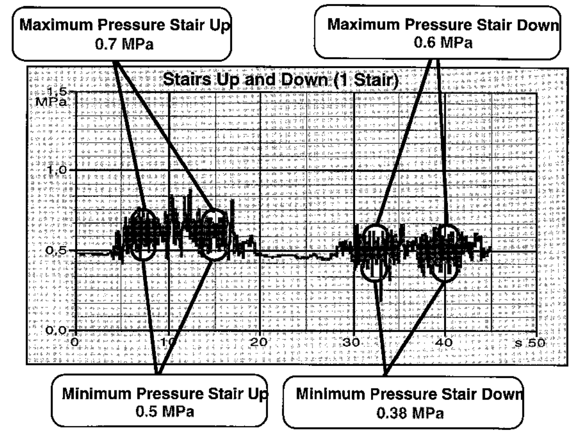


B

Figure 7. Intradiscal pressure in normal gait (**A**) without shoes and (**B**) with shoes.



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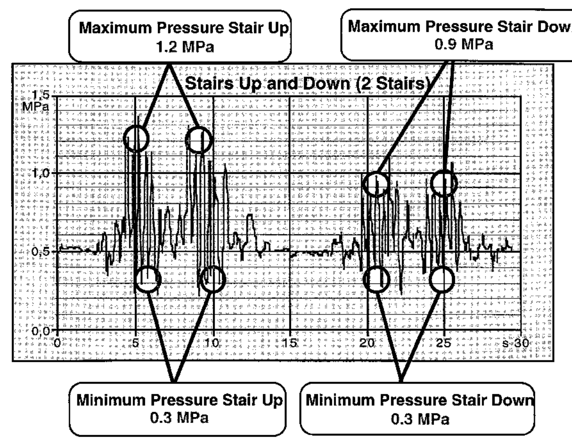

B

Figure 8. Intradiscal pressure during stair climbing (**A**) one stair at a time and (**B**) two stairs at a time.

(Figure 8, A and B). With the subject walking down stairs one stair at a time, the pressure ranged from 0.38 and 0.6 MPa and for two steps at a time, 0.3 to 0.9 MPa (Figure 8, A and B).

The highest pressure range was found during lifting and carrying a case of bottled beverage with a weight of 19.8 kg (Figure 9). Lifting and lowering the case with knees bent and in an upright posture, with actively extended back as taught in some back schools, increased the pressure from 0.5 MPa with quiescent standing to 1.72 MPa during lifting and 1.68 MPa during lowering. Lifting the case by bending over with the legs almost straight increased the pressure to as much as to 2.3 MPa. Holding the case close to the body at chest level produced a pressure of approximately 1.1 MPa, whereas holding it 60 cm away from the chest increased the pressure to 1.8 MPa.

When the subject went to sleep, the nominal pressure was 0.1 MPa, similar to that measured earlier in the day just after surgery. During the last half hour after 7 hours of sleep it steadily averaged 0.24 MPa (Figure 10). Pressure peaks probably resulted from movement of the volunteer (Figure 10, A and C) and apparent noise, not from the transducer but from the breathing of the subject (Figure 10, A and B).

■ Discussion

This study appears to be the first to build substantially on the seminal *in vivo* intradiscal pressure measurements begun in the 1960s by Nachemson and later continued by Schultz et al and Andersson et al.[8,14–16,18–21,25] Although some of the absolute values were readjusted in 1981, the relation between the pressures obtained in var-

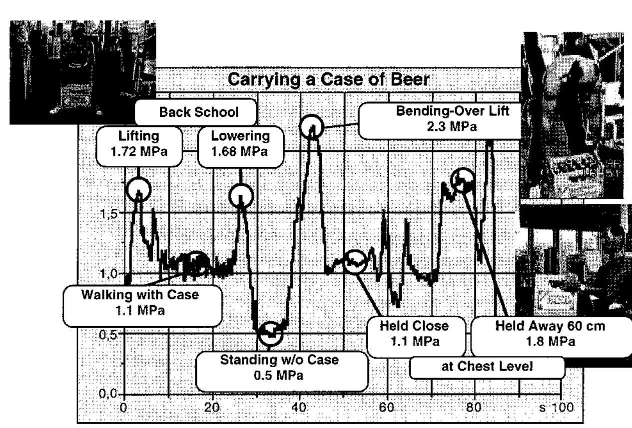

Figure 9. Intradiscal pressure during lifting in various positions of posture and weight proximity.

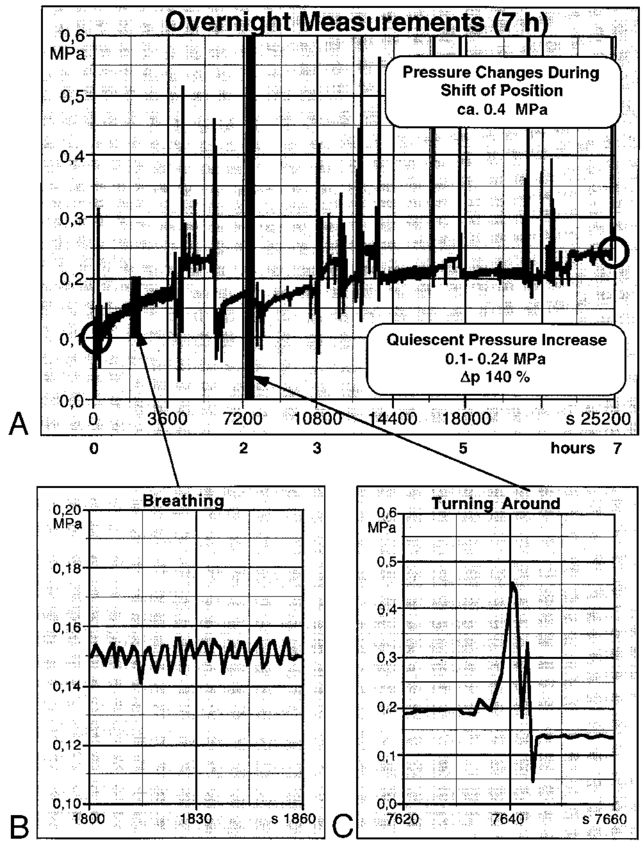

Figure 10. Intradiscal pressure variations during sleep (**A**) for 7 hours, detail of several breathing cycles (**B**), and detail of a movement event (**C**), showing characteristics of pressure peaks seen in (**A**).

ious bodily positions, movements, and exercises always remained the same.[21] Because transducer technology has improved since that time, and because a widening need has emerged to understand the role daily activities play in burdening the back, the time was appropriate to renew such an investigation. In many cases, the data of this study corroborate those of Nachemson, but in some notable cases they differ.

Good agreement was found, for instance, in intradiscal pressure in the supine position compared with that in standing—approximately 20% in this study and 24% in Nachemson's (Figure 11). Another point of agreement is that leaning forward, both in sitting and standing, substantially increased the intradiscal pressure. For lifting a load of 20 kg with bent posture and straight legs, Nachemson found approximately a 4-fold increase in pressure, compared with the current 4.5-fold increase. Lifting with knees bent and upright trunk reduced the pressure approximately 25% from that of bent-posture loading. Reduction in the associated compressive stress in the disc may be less, because the reduction in the intradiscal pressure may be accompanied by an increase in compressive stress in the posterior anulus.[4] Holding the load close to the body reduced the pressure almost twofold. As expected, this validates the lifting technique commonly taught in back school programs.[18]

The absolute pressures measured in many cases were similar as well to those reported earlier. Nachemson reported pressures between 0.56 and 0.97 MPa in relaxed standing.[18] A related study by a group of colleagues, however, reported a value of 0.27 MPa for relaxed standing.[25] The pressure found in the current study was 0.5 MPa for the 45-year-old subject weighing 70 kg.

In contrast to these general similarities, distinct differences were found in pressures in the different lying positions. Whereas Nachemson found a threefold pressure increase from lying supine to lying on the side, the intradiscal pressure measured in the current study was essentially the same between these positions. This raises the question of whether assuming a side-lying position really should be advised against, as many orthopedists believe it should in cases of low back pain.

In agreement with Nachemson's findings, intradiscal pressure was found to be higher in leaning forward in sitting positions than in relaxed sitting; however, in contrast, that intradiscal pressure was lower in relaxed sitting than in relaxed standing. These new data contradict the general perception of orthopedists and physiotherapists, whose knowledge is largely based on the earlier findings of Nachemson. The data of this study, in contrast, confirm those from other investigators who found with various indirect methods that spinal loading is similar between sitting and standing.[5,24]

It was found in this study that only sitting with the back consciously straightened, as taught in some back schools, increased intradiscal pressure approximately 10% compared with pressure in relaxed standing, probably because of increased muscle activities.[11,12] The same relative change in pressure was found when the subject straightened his back while standing. It was also interesting that intradiscal pressure decreased with slouching in a chair. Apparently, more load is transferred

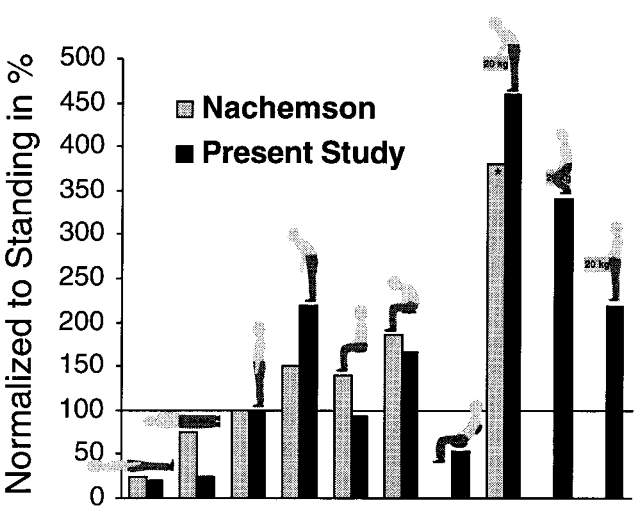

Figure 11. A comparison between data of Nachemson[17,19] and those of the current study (both for 70-kg individuals) regarding intradiscal pressure in common postures and activities, normalized to standing. Lifting weight = 20 kg in the current study; *lifting weight = 10 kg in Nachemson study.

through the back rest with increased slouching, as suggested also by earlier results.[6,17] This finding may have implications for the rehabilitation of back pain patients.

People generally prefer to sit in a nonchalant position[26] that is said to be unhealthy for the spine. This axiom was not supported by the results of this study, which show that, at least in the context of intradiscal pressure, sitting upright created higher demands on the spine. The relaxed position with reduced muscle activity, as a rule, was found in this study to reduce intradiscal pressure, which may help explain why people assume such a position as regular course.[12] This preference for sitting relaxed rather than upright may be different for people with back pain problems, depending on the symptoms.[28] In this instance, it is important to mention that when comparing different sitting and standing postures, two separate influences on disc pressure should be distinguished: muscle activity, and lumbar curvature. Lumbar curvature affects disc pressure by changing the distribution of load between nucleus and anulus, and between disc and apophysial joints, and by changing tension in the intervertebral ligaments.[4] These effects must be superimposed on the effects of changing muscle activity.

The important physiologic finding in the current study was that, during sleeping, intradiscal pressure increased substantially, presumably because of rehydration of the disc. Pressure increased after 7 hours in the lying position to 240% of its pressure at the time of going to bed. This is perhaps not surprising, given that results of *in vitro* studies indicate that fairly moderate loading over a few hours can reduce intradiscal pressure.[1,3,7] This may be because of the diurnal variation in fluid flux that *in vivo* findings indicate to be approximately 20%,[10] which may explain findings from *in vitro* studies showing that discs prolapse more easily after a good night's rest.[2]

Some limitations in the study design should be noted. The most critical point is that this study was performed with only one subject, thereby limiting the significance of the data to the individual trends observed. The study was limited to only two subjects by the regulations of the ethics committee, which required that only someone from the research group could undergo surgery. It should be further noted that because the subject was in good health, the findings cannot be extended to those with back problems. It has been demonstrated, for instance, that some patients with severe low back pain show irregular intersegmental motion patterns[27] and pressure distribution,[13] thereby leaving open the question of comparability of intradiscal pressure between healthy and diseased spines.

The implantation of the transducer, furthermore, caused some discomfort for the subject that increased through the day but did not change with the level of activity. Because this did not substantially alter his movements or coordination, it is proposed that the effect of this discomfort on the results was minimal. As a further indication of the effect of the discomfort, a reference measurement in standing was taken before each activity, and the value remained nearly constant throughout the day.

Data from the pressure transducer, as from any measuring device, are only as reliable in respect to the degree to which the transducer is suitable for the intended environment. It was assumed in this case that the nucleus behaves hydrostatically, that its contact to the face of the pressure transducer was constant, and that no artifact occurred that was caused by bending of the sensitive components. Differences with Nachemson's findings, in fact, may be explained by the pressure transducer used in the earlier studies being mounted into a needle that could rather easily be bent in positions other than upright standing, either in musculis spinae contraction and shifting of joint movement itself. The transducer in this study was mounted in a metal tip just 7 mm long and was verified by radiograph to maintain its position within the nucleus throughout the experiment.

This study, using the latest transducer technology, provided an exceptional chance to repeat critically the measurements of Nachemson from the 1960s and expand the breadth of activities over which intradiscal pressure has been studied. It was found that the intradiscal pressure during relaxed sitting may in fact be less than that in relaxed standing. This and the other findings detailed herein may be important information for directing the clinical treatment of disc diseases and the development of back school programs.

Acknowledgments

The authors thank Ulrike Rhode for the MRI, Bernd Sigl and Peter Felleiter for technical support, Reinholde Langer and Ulrike Zürn the physiotherapists, Dipl.-Ing., Jürgen Marx and Toni Negele for the measuring technique, Karl Maute for video assistance, and Karl Wenger for consultation on the manuscript.

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