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Lumbar Sonography

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LUMBAR SONOGRAPHY - A COMPARATIVE RADIOLOGICAL STUDY

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ABSTRACT: A method for depiction of the lumbar spinal canal by ultrasound has been reported previously. According to experiments carried out on bone specimens, bone was depicted. In this study, the experiments have been repeated on specimens consisting of bone, ligaments and dura. Images were obtained which show, when compared with findings made on direct observation, myelography or computed tomography, that the origin of the signals is the interface between the cerebrospinal fluid and the dura and fatty soft tissue in the dorsal and ventral parts of the lumbar spinal canal.

By measuring the attenuation of soft tissue and bone in specimens from the spine and the thoracic wall, it is also found that there is considerable attenuation of ultrasound through the bone. This means that there will be no depiction of soft tissues situated distally to the bone in relation to the ultrasound transducer when a conventional diagnostic scanner is used even when the bone in question is thin.

Ultrasound examination on patients with measurements of the width of the lumbar spinal canal was also compared with myelography and computed tomography. A low coefficient of correlation for measurements was found on comparison with myelography. This is explained by a wide distribution of measurement values at ultrasound examination and myelography. The coefficient of correlation is higher when comparing ultrasound examination with computed tomography with perpendicular reconstruction. When the depiction of the spinal canal by ultrasound and by computed tomography was compared it was found that there was no depiction of the spinal canal ventrally to the laminae. The part of the canal depicted corresponded to the interfaces between cerebrospinal fluid and adjoining soft tissues at the levels between the laminae.

The method error in different parts of the registration - measurement procedure of ultrasound examination of the spinal canal was studied on healthy volunteers. Registration is responsible for a method error which is small when compared with that of measurement where the standard deviation is approximately six times larger. By repeated measurements of the same registration the results will improve.A comparison of digital static B-scanning with analogue static B-scanning and dynamic B-scanning, respectively, was made in the same study. Analogue and digital static B-scanning have the same accuracy, a systematic overestimation results, however, at analogue scanning. When a dynamic B-scanner is used there is an increased variation of the measurements and also a systematic overestimation with considerable variation.

Key words: myelography, radiography, spinal canal, spine, ultrasonics, x-ray computed tomography.

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A comparative radiological study

by

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Göteborg 1983

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THE NARROW LUMBAR SPINAL CANAL

Although there are several reports in the early literature on single cases with symptoms from lumbar and sacral nerve roots in individuals with a narrow spinal canal, the first systematic report on the importance of the width of the lumbar spinal canal for the development of symptoms from lumbar and sacral nerve roots was made by Sarpyener (1945) in a study of children with congenital malformations. Schlesinger and Taveras (1953) called attention to the importance of the anatomical variation of the width of the spinal canal among other factors for the development of symptoms from cauda equina. The importance of a narrow spinal canal in individuals with normal skeleton development became more widely known through the study by Verbiest (1954). In a report on seven cases, a clinical condition was described including symptoms from lumbar and sacral nerve roots in connection with "standing, working, but not at rest". Myelography showed a block for the contrast-filling of the lumbar spinal canal and operation revealed a narrowing of the spinal canal in the corresponding area.

After this publication a large number of studies have been presented on the condition with symptoms from lumbar and sacral nerve roots and a narrow spinal canal. Extensive reviews have been made by Epstein et al. (1962), Schatzker and Pennal (1968), Jones and Thomson (1968), Pennal and Schatzker (1971), Nelson (1973), Kirkaldy et al. (1974), Verbiest (1975), Kirkaldy-Willis and McIvor (1976), Epstein et al. (1977), Hawkes and Roberts (1980), Wackenheim and Babin (1980), Yates (1981) and Critchley (1982).

The diagnosis of spinal stenosis is made largely on the basis of clinical findings. For confirmation of the diagnosis, however, most authors stress the need of an objective measurement method. One of Verbiest´s earlier studies (1955) described a method for peroperative measurement of the width of the lumbar spinal canal with a specially designed calliper (stenosimeter). Verbiest also presented the following measurement values: cases with an anterio-posterior mesurement of the lumbar spinal canal of 10 mm or less were described as "absolute stenosis"; cases with an anterio-posterior diameter between 10 and 12 mm were described as "relative stenosis". In his work, Verbiest also pointed out that it was only the anterio-posterior diameter of the spinal canal which could indicate the presence of a narrow spinal canal. This fact was later confirmed by Eisenstein (1977) in examinations on specimens.

The possibility of measuring the width of the lumbar spinal canal using a radiological method has been discussed by several authors. Jones and Thomson (1968) measured a relation (spinal ratio) between the area of the vertebral body and the spinal canal on X-ray films in frontal and lateral projections and thus they did not have to depend on the magnification of the films. Several authors have made measurements directly on to X-ray films (Hinck et al., 1965; Roberson et al. , 1973 and Roberts, 1978). The reliability of the anterio-posterior measure of the lumbar spinal canal obtained this way has been questioned, however, by Christenson (1977), Verbiest (1979) and Yates (1981).

Several authors have used myelography to measure the width of the lumbar spinal canal. The films have been evaluated in two different ways; by description or measurement.

1. Findings described as generalized or localized narrowing of spinal canal, blockage of the flow of the contrast agent, increased distance between the dorsal part of the vertebral body and the contrast-filled subarachnoidal space, swelling and, in certain cases, elongation of the nerve roots in the cauda equina have been found important by Jones and Thomson (1968), De Villiers (1976), McIvor and Kirkaldy-Willis (1976) and Morris (1976).

2.Measurement of the anterio-posterior measure on myelography films has been made by Epstein et al. (1962) and Paine and Haung (1972). Both authors estimated diameters below 15 mm as pathological. None of them, however, presented any correction for magnification on the films. Sortland et al. (1977) presented the same measure as the lowest normal value, 10 mm was presented as absolutely pathological. Sortland had also calculated the geometrical magnification of the films and presented the corresponding real measurements as 10.5 mm and 7 mm, respectively. The same values were used by Larsen and Smith (1980) in a retrospective study on patients examined by myelography and a clear correlation between a narrow spinal canal and symptoms of spinal stenosis was then found.

Another method for the study of narrowing of the spinal canal is venography, Bestawros et al. (1979) could show that extradural venous plexus dorsally in the spinal canal was compressed and shifted ventrally in cases of spinal stenosis.

Transverse axial tomography, a development of conventional X-ray technique, has been used by Gargano et al. (1974) for studies of spinal stenosis.Technical problems and particularly the introduction of computed tomography have led to the method being discarded.

The introduction of whole body computed tomography enabled several authors to examine patients with suspect spinal stenosis. Among several articles are those by Sheldon et al. (1977), Donovan-Post et al. (1978), Lee et al. (1978), Lancourt et al. (1979), Roub and Drayer (1979), Verbiest (1979), Postacchini et al. (1980), Ulrich et al. (1980) and Veiga-Pires et al. (1981). Lee et al. (1978) consider it important that with computed tomography it is possible to measure the width of the lumbar spinal canal as an area. Verbiest (1978) and Veiga-Pires et al. (1981), however, were of the opinion that the anterio-posterior measure was most important and that the area was less interesting. Several authors stressed the importance of being able to assess the shape of the lateral recesses i. e. to estimate the degree of "trefoilness" of the spinal canal. In a study on skeleton specimens, Eisensten (1980) points out, however, that a trefoil spinal canal is comparatively common in the lower part of the lumbar spine and warns against equating the finding of a trefoil vertebra with spinal stenosis.

ULTRASOUND EXAMINATION OF THE SPINAL CANAL

One of the difficulties which the concept of spinal stenosis creates for the orthopaedic surgeon is that there is no clear indication for the clinical dividing-line between patients with spinal stenosis and patients with other conditions of the spine. The possibility of measuring the width of the lumbar spinal canal should, therefore, exist for examination of a large number of patients. Such an ambition cannot be fulfilled as long as the method is invasive, like myelography or expensive and not always available like computed tomography. Consequently, attention has been directed to a common and completely non-invasive method such as diagnostic ultrasound.

The possibility of examining the spinal canal and possible disc herniations through the abdomen and the intervertebral spaces by ultrasound was described by Meire (1975). The method is hard to reproduce and often impossible to apply owing to gas in the bowels which obscures, or too large an attenuation caused by the abdominal wall and the abdominal organs, largely because of their fat content in a great many of patients. The introduction of ultrasound examination from the back by Porter et al. (1977, 1978a) presented openings for a more systematic examination of the lumbar spinal canal by ultrasound. Porter then continued his work within the area by discussing the anatomical basis for the images obtained, the accuracy of the measurements and the clinical importance of the measurements obtained.

The measurement method was described (Porter et al., 1978a). The patients were examined lying prone. The examination was made with an analogue static B-scanner in a longitudinal plane tilted 15° towards the sagittal plane of the patient. By moving the examination plane a little medially or laterally, a depiction of the lumbar spinal canal could be obtained in the shape of "echoes reflected from the laminae and from the posterior surfaces of the vertebral bodies". In the same work there was a short presentation of an examination of skeleton specimens, which confirmed this assumption as to the origin of the signals.

When the transducer was placed on the back so that echoes were obtained from the frontal and dorsal delineation of the spinal canal as described above, the corresponding A-mode could be studied and the distance between the echoes measured with the calliper device of the scanner. Porter et al. (1978a) also presented normal values for the width of the lumbar spinal canal after examining 150 healthy volunteers (100 males, 50 females). In another study, published at the same time, by Porter et al. (1978b) there was a description of the findings at ultrasound examination of the lumbar spinal canal in different groups of patients with symptoms from the back. The examination of 73 patients with "symptomatic disc lesion" showed that the majority of the patients had measurements which were below the tenth percentile of the material of healthy volunteers. Further studies (Porter et al., 1980a) with comparison of the photographic image of skeleton specimens and the result of ultrasound examination of the lumbar spinal canal in a large number of individuals served as a basis for a discussion on the possibilities of evaluating the lateral recess of the lumbar spinal canal in order to define the degree of trefoilness. On the basis of the presence of a marked lateral recess in skeleton specimens and the relation of this finding to the anterio-posterior and the oblique anterio-posterior measure of the spinal canal the authors decided that there may always be a narrow lateral recess in a "trefoil" spinal canal and this should be suspected when the ultrasound measure is below normal. Another study, published at the same time (Porter et al., 1980b) presented a substantial material of ultrasound examinations of patients with different types of symptoms from the back. Generally, it was found that the width of the lumbar spinal canal in individuals with differenttypes of symptoms from the lumbar back was below normal.

In his thesis, Porter (1980) gave his opinion as to the origin of the ultrasound image obtained as above. The basic idea was that the origin of the strong echoes at ultrasound examination was interfaces between areas with a large difference in acoustic impedance. If evaluated in this way, the largest difference is present between bone and soft tissues of different kinds. On the basis of this discussion, a hypothesis was presented describing the origin of the echoes obtained as the dorsal and ventral aspect of the lamina and the dorsal aspect of the vertebral body. The attenuation possible when the ultrasound passes through the lamina was hardly discussed but intimated to be insignificant, since part of the skeleton was described as "thin" and the concept "laminar window" was introduced.

Owing to the presentation of the work by Porter in a widely read medical journal, it attracted considerable attention. Stockdale and Finlay (1980), Veiga-Pires et al. (1981), Ottewell and Howells (1981), Nachemson and Asztély (1981) and Chatterton (1981) with comments by Porter (1981) discussed questions on reproducibility, methods and the origin of the signals. Finlay et al. (1981) presented an examination made of skeleton specimens which illustrated the difficulties of obtaining reproducible data. The reproducibility of the method was discussed in a study by Hibbert et al. (1981). Hibbert, who is a co-worker of Porter´s also discussed on reproducibility and the origin of the signals.The measurement, obtained at examination of the patients, showed a "mean repeatability" of less than half a millimeter and the importance of having a trained examiner was shown by comparing the results of one examiner before and after a period of training. During a discussion about the origin of the signals, Hibbert hesitated and concluded "it is difficult to say exactly what is being measured". Hibbert recapitulated her results in a thesis (1982). The comparatively good values concerning measurement accuracy presented by Porter et al. were questioned by Davies (1982). The question of the reproducibility of the method also was discussed by Legg (1982, in press) in a study where healthy volunteers had been examined. Data on variation within and between examinations were presented. Legg had been using the same equipment as Porter and his co-workers and found that there was considerable difficulty in discerning the echo which delineates the dorsal aspect of the lumbar spinal canal.

The results of ultrasound examination of the lumbar spinal canal, which have been presented above, can now be summarized. A method was developed for examining the lumbar spinal canal using a type of analogue static B-scanner which used the A-mode for distance measurements. The echoes obtained were considered to originate from the ventral and dorsal aspect of the osseous spinal canal. A large number of measurements from groups of healthy volunteers and from different patient groups were presented. The origin of the signals was discussed mainly on the basis of results of experiments made in vitro on skeleton specimens, but also on the basis of observations made on images obtained after examining in vivo.

CURRENT PROBLEMS AND AIMS OF THIS STUDY

The assumption about the origin of the signals described above was based entirely on a discussion about the difference in acoustic impedance between different media. The importance of the attenuation of ultrasound in different types of tissue was discussed no further. The reports on attenuation of ultrasound in different types of tissue varies considerably (Parry and Chivers, 1979). A substantial collection of data has been presented by Goss et al. (1978). The main part of the work performed has been made on tissues from laboratory animals. Some data from homo is available, however. The variation between different reports is considerable. For the frequencies 1.5 - 2.5 MHz there are data on attenuation in muscle between 0.55 dB/cm (Hüter, 1958) and 2.7 dB/cm (Nakaima et al., 1976) and for bone between 12 dB/cm (Güttner et al., 1952) and 113 dB/cm (Fry and Barger, 1978). The difference in attenuation of ultrasound between soft tissues and bone is thus considerable and probably of the size several tens of dB per cm. There is thus reasonable doubt that the depiction of the lumbar spinal canal obtained in studies published previously has its origin in structures situated behind the laminae. The interrupted depiction of the spinal canal is probably caused by echoes obtained from structures situated between the laminae. The area in front of the laminae, however, is completely obscured for the examiner. This assumption has been made by Reid (1978) in a presentation of a case where the cervical spinal canal was examined.

The examinations of specimens, which have been presented have all been made of bone specimens, thus it has not been possible to assess the depiction of soft tissues of the spine at ultrasound examination. An examination of spine specimens consisting not only of bone but also of dura and ligaments could thus reveal more about the origin of the signals at ultrasound examination of the spine.

The comparison with computed tomography can serve as a basis for evaluating the origin of the signals in vivo because a comparison between computed tomography and ultrasound examination can provide directly comparable images from the same examination plane.

Another way of testing Porter´s assumption as to the origin of the ultrasound image, is to find out whether the attenuation of the ultrasound in the laminae is low enough to make it possible to depict structures distal to the laminae as viewed from the transducer.

The method of examining patients, which has been presented by both Porter (1978a) and Legg (1982, in press) involves the use of an analogue static B-scanner with a special distance measurement device. The most usual type of equipment for ultrasound examination today is the digital static B-scanner. This equipment is widely used and easier to handle than an analogue scanner. It would, therefore, be of value to have an estimation of reproducibility of measurements of the width of the lumbar spinal canal as well as an estimation of differences compared with the use of other methods.

Another important evaluation would be a comparison of ultrasound examination of the spinal canal with myelography or computed tomography to find out whether ultrasound examination of the lumbar spinal canal can help decide the presence of spinal stenosis.

The purpose of this thesis, therefore, is to carry out the following:

a comparison of the result of ultrasound examination by ultrasound B-scanning of the spinal canal of specimens with the result of myelography (I) and computed tomography (IV), respectively,

the measurement of the attenuation of ultrasound in specimens consisting of bone and soft tissue compared with the macroscopic depiction of the corresponding tissue slice by computed tomography (III), a comparison in vivo of ultrasound B-scanning of the lumbar spinal canal with the result of myelography (II) and of computed tomography, including perpendicular reconstruction (IV), respectively,

repeated examination of a number of volunteers and the use of different types of equipment for estimation of reproducibility and measurement accuracy (V).

MATERIALS

SPECIMENS

All the specimens were obtained at routine autopsies. For the study of the comparison of ultrasound examination with myelography (I) and computed tomography (IV), respectively; four or five segments of the lumbar spine were dissected. All the muscles were removed, as were the contents of the spinal canal except for the dura. Thus a specimen was obtained consisting of vertebral body and arch, ligaments and spinal dura. The specimens were deep-frozen for further use. Before examination they were slowly thawed in refrigerator temperature. Ten specimens were used for the comparison of ultrasound with myelography (I). Four of the specimens were also used for the comparison of ultrasound scanning with computed tomography (IV).

For the attenuation study (III) two kinds of specimens were used: 1) two spine specimens consisting of vertebral arches, dorsal ligaments, erector spinae muscle and the dorsal half of the dura, but not the central part of the dura nor the vertebral bodies; 2) six specimens consisting of two or three ribs with the interjacent soft tissue from the lower part of the thorax.

PATIENTS AND VOLUNTEERS

The material for comparison of ultrasound scanning with myelography (II) comprised 59 patients, i. e. 33 males and 26 females with different symptoms from the spine which had motivated myelography with positive contrast.

The material for comparison of ultrasound scanning with computed tomography (IV) comprised 11 patients who were to have an extensive examination with computed tomography with multiple parallel slices.

For the method analysis study (V) 35 healthy volunteers were examined.

METHODS

SPECIMEN STUDIES

Myelography

For the specimen study comparing ultrasound examination and myelography (I), the spinal canal of the specimens was filled with a two-component silicon rubber (RSKO with hardener RSV, H. Röck Co., Kirchheim - Teck, FRG) which sets at room temperature after approximately 15 minutes. The silicon rubber had been mixed with barium sulphate and could thus be used as a positive contrast agent at X-ray examinations. X-ray films of the specimens in frontal and lateral projections were obtained. Because of the elastic properties of the rubber, the cast could be removed from the spinal canal without damaging the dura. Direct measurements of the cast could then be made because the silicon rubber regains its initial shape with less than 0.1 per cent deviation after deformation. The anterio-posterior measurement of the spinal canal was then obtained by measuring on the films. Correction for the geometrical enlargement was made. Before the cast was removed from the spinal canal, the level of each disc was marked by putting needles through the cast. The cast was then cut into slices 4 - 5 mm thick. Measurement of the largest anterio-posterior measure and the two measurements at a 15° angle to the sagittal plane from the middle of the ventral side of the spinal canal and dorsally, were then made on the cast with a micrometer with a relative accuracy of 0.1 mm.

Computed tomography

In the study making a comparison of B-scanning and computed tomography (IV), a whole-body scanner (Philips Tomoscan 300) was used. The specimens were examined with their length axis in the examination plane of the CT-scanner and with a 15° inclination of the gantry towards the sagittal plane of the specimens. Serial scans with a thickness of 3 mm with no distance between the slices were carried out. Scan parameters for high linear resolution and high contrast were used (118 kV, 600 exposures of 235 mAs together, high precision scan and reconstruction to a field of view of 160 mm). Measures on the image were taken by the calliper device of the CT-scanner.

For computed tomography of specimens in the attenuation study (III), the specimens were examined with a whole-body scanner (Philips Tomoscan 310). Examination was made in planes corresponding to those marked at the ultrasound examination. A slice thickness of 3 or 1.5 mm was used. Scan parameters for high linear resolution were used (120 kV, 1200 exposures of 360 mAs altogether, high precision scan and reconstruction to a field of view which varied between 80 and 160 mm for different specimens). Measures on the image were taken by the calliper device of the CT-scanner.

Ultrasound examination

A scanner consisting of a water tank and a mobile transducer-reflector-gantry was specially designed for the attenuation study (III). The specimens thus could be suspended in the tank and a longitudinal slice of the specimen could be examined by moving the gantry. In order to avoid varying attenuation caused by temperature variations (Bamber and Hill, 1979), the water temperature was regulated. Before scanning the specimens were stored in the water bath for a period lasting between 30 minutes (for thoracic wall specimens) and 60 minutes (for spine specimens) for equilibration of temperatures. The entire examination took between one and two hours, thus time-dependent variations of attenuation were not to be expected (Bamber et al., 1977). A modification of the measurement method according to Papadakis et al. (1973) and Chivers and Hill (1975) was used. By using specially designed electronics (Reier and Hansson, 1982), the degree of attenuation of ultrasound could be registered continously. An attenuation scan of a slice of the specimen could be obtained by recording both the signal amplitude and the position of the gantry on a X-Y-recorder. All the specimens were examined with a transducer with a frequency of 2 MHz. One of the spine specimens was also examined with transducers with the frequencies 1.6, 2.25 and 3.5 MHz.

For conventional B-scanning of the specimens in the studies for the comparison with myelography (I) and computed tomography (IV), respectively, digital static B-scanners were used: one with a transducer with the frequency of 2.25 MHz (I) (Searle Pho/Sonic-SM) and a second with transducers with the frequencies of 1.6, 2.25, 3.5, 5 and 7 MHz, respectively, (IV) (General Electric Datason). The specimens were then examined with repeated scans in a plane tilted 15^{o} to the sagittal plane, 10 to 20 mm from the mid-line in the dorsal aspect of the specimen. After making small changes of the examination plane, one was chosen which afforded a distinct depiction of the spinal canal and the largest measure between the anterio-posterior delineations of the spinal canal. Different parts of the image could be related to different parts of the specimen by marking the position of the transducer on the image in the scanner at the same time as its position in relation to the specimen was observed. The position of the discs was also indicated by putting needles into the specimens at disc level. The needles could then be observed on the image screen of the scanner. Measurements on the images were obtained with a relative accuracy of 1 mm with the built-in calliper device of the ultrasound scanner.

EXAMINATION OF PATIENTS AND HEALTHY VOLUNTEERS

Myelography

All patients were examined according to routine procedures with water soluble contrast. For comparison with ultrasound examination (II), films with horizontal rays and of the patient prone were obtained. For the best filling of the spinal canal with contrast, the patient had been rotated before the examination. The anterio-posterior measurement of the spinal canal at disc level and at a third of the segment height above it was measured directly onto the films. No correction for geometrical enlargement was made.

Computed tomography

For comparison between computed tomography and ultrasound scanning (IV) all the patients were examined with a whole-body scanner (Philips Tomoscan 310). The slice thickness was 3 mm with no distance between the slices. Scan parameters for high linear resolution and high contrast were used (120 kV, 1200 exposures of 480 mAs altogether, high precision, spatial resolution scan with reconstruction to a field of view which varied between 118 and 152 mm between patients). Between 12 and 30 slices (average 23) were registered at each examination. To match the slices obtained with the ultrasound examination a radiodense marker was placed on the skin. The patient was placed prone on the examination table with small pillows below one side of the pelvis and below the corresponding side of the thorax in order to obtain a rotation of the trunk of approximately 15° to the right or to the left. Reconstruction of images in vertical planes perpendicular towards the transverse plane of the patients could be obtained by processing the multiple transverse computed tomography slices which had been registered (Glenn et al., 1975). Images were thus obtained in a plane corresponding to that used for ultrasound scanning.

Ultrasound examination

A digital static B-scanner (Searle Pho Sonic-SM) with a transducer frequency of 2.25 MHz was used for ultrasound examination of patients and healthy volunteers (II, IV and V). The method for scanning previously presented by Porter was used. The grey scale was set for detection of weak echoes. The scanning plane was altered in order to obtain the largest anterio-posterior measurement.

For the ultrasound examination for comparison with computed tomography, the patient stayed on the examination table of the whole-body scanner without changing position. By carrying out the ultrasound examination with examination plane vertical, an image was obtained in the same plane as that which was obtained at the perpendicular reconstruction of the computed tomography images.

The images were photographed and recorded on magnetic discs (the ultrasound examinations of the first 20 patients in study II were only photographed). Distances on the images were measured with the callipers of the scanner and the results were displayed with a relative accuracy of 1 mm.

For method analysis (V), an anlogue static B-scanner (Nuclear Enterprises Diasonograph 4200) and a dynamic B-scanner with a linear multi-element transducer (Toshiba SAL-20) were also used. The examination with the analogue static B-scanner was performed according to the method presented by Porter et al. (1978a). Measurements were also made according to Porter with observation and measurement on the A-mode oscilloscope during the ultrasound examination. A similar technique was chosen for examination with the dynamic B-scanner. An examination plane inclined 15° towards the sagittal plane was chosen and, with slight adjustments of the position of the transducer, the image was chosen which gave the largest measurement of the spinal canal. The image, which also contained an electronically displayed length scale, was photographed. Measurements were obtained from the photograph using the length scale as a reference.

CALIBRATION

At myelography of specimens (I), the enlargement factor was calculated by measurement on the specimens themselves and on the X-ray equipment. For myelography of patients (II), the enlargement factor was calculated using radiodense rods placed on the skin on the mid-line of the patients and by calculating the enlargement on the X-ray films. The average enlargement for seven patients was 1.4 (SD=0.1).

For computed tomography (III, IV), all measurements were made utilizing the calliper device of the scanner. This is calibrated fortnightly according to a test program. A test object consisting of a lucite box fitted with nylon wires of a diameter of 0.3 mm placed parallel to each other at carefully measured distances, was designed for calibration of the calliper devices of the computed tomography scanner and one of the digital static ultrasound scanners (Searle Pho-Sonic-SM) and for direct comparison of the linearity of the depictions between the scanners. No difference was found between measurements made on the test object and on the image of it in the CT-scanner. The calliper function in all the ultrasound scanners was checked with the AIUM-test object. No discrepancy between the measurements obtained at scanning and those fixed upon for the test object could be found. The test objects when used for calibration of the ultrasound scanner were filled with 9 volume per cent ethanol in water at 20°C (speed of sound 1540 m/s).

The specially designed test object, mentioned above, was also used for comparison of the linearity between the CT-scanner and the ultrasound scanner for the study comparing ultrasound examination with computed tomography (IV). Both video systems were set to the best linearity with a video signal generator. The images were recorded and the linearity error was calculated both on the image from the signal generator and of the test object. The largest error in the depiction of the test object between the ultrasound scanner and the CT-scanner was found to be 4 per cent of the width of the image.

The linearity of the attenuation measuring system (III) was controlled with a lucite step wedge manufactured from a single piece of lucite.

STATISTICAL METHODS

Means, standard deviation, regression coefficient and correlation coefficient were calculated using the standard methods. Split-unit analysis of variance (Armitage, 1971) was carried out for the method analysis study (V).

RESULTS

COMPARISON ULTRASOUND - MYELOGRAPHY, SPECIMENS (I)

A depiction of the spinal canal, in the shape of two parallel echoes interrupted by entirely echo-free areas behind an arch-shaped strong echo, was obtained at ultrasound examination of all the specimens. When the position of the transducer during the examination was observed, the depiction of the spinal canal could be related to the space between the laminae, which was found to correspond to the level of the disc and the area slightly above it. If the dura was removed, the depiction of the spinal canal was less distinct. By measuring the distance between the ventral and dorsal delineation of the spinal canal on the ultrasound images and by measuring on the cast of the spinal subarachnoid space and on the X-ray film, at the same level, i. e. the disc level, any possible correspondence could be studied. 36 segments were examined in this way. The best correspondence between these data was obtained between the anterio-posterior measurements of the cast and the corresponding measurements from the X-ray films of the specimens filled with the contrast-mixed silicon rubber. The average error was less than 1 per cent. Comparison between ultrasound measurements and measurements from the cast showed an average deviation of between 3 and 6 per cent. There was less deviation when measurements from the casts at the same angle as from the ultrasound examinations were compared than when the straight anterio-posterior measurements were used for comparison. The best correspondence between ultrasound measurements and measurements from the cast was obtained when multiple parallel measurements at an angle of 15^{o} to the sagittal plane were obtained and the mean measurement was compared to the ultrasound measurement.

ULTRASOUND - MYELOGRAPHY (II)

Ultrasound measurements were compared with the anterio-posterior measurements from the corresponding level on myelography. Two myelography measurements were registered, one from disc level and one from a level a third of a segment height above the disc. Two sets of 170 pairs of numbers were thus obtained. The two sets were plotted in scatter diagrams, the line of regression and the correlation coefficient was calculated. In both cases, the regression coefficient significantly deviates from null; the correlation coefficient in both cases was comparatively low: 0.33 at disc level, 0.27 at the higher level.

THE ATTENUATION STUDY (III)

Six thoracic wall specimens and two spine specimens were examined. The dimensions of the ribs and the laminae were measured by computed tomography and the attenuation curve and the computed tomography image were compared. In those cases where bone completely obscured the passage of sound from the transducer to the reflector, no reflected signal could be detected. When the sound entirely or partly passed soft tissue, some attenuation occurred, which was considerably larger for spine specimens (7.0 dB) than for thoracic wall specimens (1.4 dB). Detailed study of ribs and laminae on the computed tomography images, respectively, revealed that both ribs and laminae have the same thickness, i. e., 5 mm close to the upper edge, but that while the laminae consist to a greater extent of compact bone, the ribs largely consist of cancellous bone.

The space between the ribs is considerably larger than between the laminae (13.7 mm and 5.5 mm, respectively). Any possible passage of ultrasound through bone was studied with a semi-qualitative method. No passage through the laminae could be detected whatsoever. Ultrasound passage was found, however, through a 5 mm thick rib with an attenuation of approximately 40 dB.

Any gas bubbles in the specimens could be detected by computed tomography. In one case, a gas bubble was found, which caused an artefact of the attenuation scan owing to total reflection.

ULTRASOUND - COMPUTED TOMOGRAPHY, SPECIMENS AND PATIENTS (IV)

By using the outlines of the examined specimens, a linear correspondence was found between the depiction by ultrasound scanner and computed tomography. By superimposing the computed tomography image onto the ultrasound image in the same scale, it was found that the linear depiction of the spinal canal on the ultrasound image corresponded to the part of the lumbar spinal canal situated between the laminae on the computed tomography image. There was no depiction of structures ventral to the laminae. Transducers with different frequencies were used. When transducers with higher frequencies were used in soft tissues, the attenuation of the ultrasound was higher. The linear depiction of the spinal canal also became slightly shorter when scanning was performed at a higher frequency.

ULTRASOUND - COMPUTED TOMOGRAPHY, PATIENTS (IV)

Images from ultrasound examination and computed tomography in the same scale were matched using the depiction of the marker used at both examinations. A satisfactory correspondence was thus obtained between the depictions in nine cases. In two cases, the correspondence was unsatisfactory especially in the longitudinal direction of the patient. In some parts of the images obtained of the nine cases mentioned above, there was a large attenuation of the ultrasound with impaired depiction of one or more segments. This corresponded to areas where surgery had been performed. In two cases, there had been laminectomy. The corresponding area was well defined on the computed tomography images. On the ultrasound images, the depiction of the spinal canal corresponded to the entire area between two segments. In the remaining cases the observation was made that the linear depiction of the spinal canal was slightly longer than could be expected from the computed tomography images and that the direction of this line did not entirely correspond to the direction of the spinal canal.

Comparison of ultrasound examination and computed tomography could be carried out in 16 segments altogether. Measurements were registered according to criteria presented by Porter et al. (1978a) for the ultrasound examination and as the distance between the dorsal part of the vertebral body and the soft tissues ventral to the extradural fat in the spinal canal for the computed tomography images (Haugthon et al., 1980; Haughton and Williams, 1981). The correlation coefficient for the measurement values was 0.82.

The dimension of the laminae was measured on images of specimens and of patients. When both specimens and patients were examined it was found that the laminae consisted almost entirely of compact bone and that the thickness of the laminae at the upper edge was several millimeters.

METHOD ANALYSIS (V)

In the first series comprising 25 volunteers where 1000 observations were made using digital static B-scanning, the average ultrasound measure of the lumbar spinal canal was 14.9 mm (standard deviation 2.0 mm). The standard deviation was 1.6 mm for the random error introduced during measurement and 0.2 mm for the random error introduced during registration. There was a significant difference ($P < 0.001$) with a mean of 0.6 ± 0.1 mm ($\pm$ SEM) between the results of measurements obtained by different examiners from the same registration.

In the second series comprising 10 volunteers, 1600 observations were made using digital static B-scanning. The mean of the ultrasound measures as above was 14.9 mm (standard deviation 1.9 mm). The standard deviation for the random error introduced during both measurement and registration was the same size as in the first material, i. e. 1.6 mm and 0.2 mm, respectively. There was a significant difference ($P < 0.001$) in the result of measurement obtained by different examiners from the same registration. There was also a significant difference ($P < 0.05$) in the results of measurement obtained by the same examiner on the same subject at different registrations.

In the third series comprising 10 volunteers where 120 observations were made, dynamic and static B-scanning were compared. The standard deviation for the random error introduced during both measurement and registration was 1.3 mm and 1.0 mm, respectively. A significant difference ($P < 0.01$) was found, the result of measurements obtained by dynamic B-scanning om average 2.8 $\pm$0.4 mm ($\pm$ SEM) larger than those obtained by static B-scanning. When the material was divided into two series according to examination method, the standard deviation was found to be larger for values obtained by dynamic scanning than for those obtained by static scanning (2.1 mm and 1.5 mm, respectively). The difference was significant ($P < 0.05$).

In the fourth series comprising 10 volunteers, 200 observations were made. In this examination, analogue and digital static B-scanning were compared. There was a significant difference ($P < 0.001$) between the methods, with the results obtained by analogue scanning on average 1.0 $\pm$0.2 mm ($\pm$ SEM) larger than those obtained by digital scanning. The standard deviation for the random error introduced during both registration and measurement was 0,5 mm and 1.2 mm, respectively. When studying the material divided according to examination method, the standard deviation was found to be the same for measurements obtained with either method.

GENERAL DISCUSSION

The morphological basis for the depiction of the spinal canal obtained at ultrasound examination has been discussed previously. In their early studies, Porter et al. (1977, 1978a) stated that the structures depicted corresponded to the osseous delineation of the spinal canal, which means the dorsal aspect of the vertebral body and the ventral aspect of the upper part of the laminae. Reid (1978), on the other hand, presumed that the origin of the depiction of the spinal canal was interfaces between different kinds of soft tissue and the liquid in the spinal canal. General knowledge of the basis for the depiction obtained during ultrasound examinations support the latter presumption.

EXAMINATIONS ON SPECIMENS

Depictions of the lumbar spinal canal obtained during the ultrasound examination on specimens (I) correspond to those obtained during examination of patients. By observing the position of the transducer in relation to the specimen, it was noticed that, when there were signals identified as originating from the ventral and dorsal delineation of the spinal canal, the transducer was placed above the space between the laminae. Knowledge of the structure of these tissues would indicate that this observation is correct. The ventral wall of the spinal canal consists of dura and the loose fatty tissue of the venous plexus between the dura and the vertebral body. The dorsal delineation is of the same kind, which means dura and fatty soft tissue and a venous plexus inside the ligamentum flavum reaching between and in front of the laminae. By removing the dura from the specimens, it was found that a depiction of the spinal canal could still be obtained, although less distinct than before. This means that signals from the dura contribute to the ultrasound depiction of the spinal canal. The level of the depiction in relation to the different structures of the spine could be settled by direct observation of the position of the transducer during the examination and by observation of the needles in the lumen of the spinal canal on the ultrasound images. It was found that the part of the spinal canal depicted during ultrasound examination thus corresponds to that area which is situated at the level of the discs and the adjoining vertebral bodies. The fact that the disc is, to some extent, a part of the ventral delineation of the spinal canal on the ultrasound image could be shown by removing a disc. As a result, the depiction of the ventral aspect of the spinal canal at that level was less distinct because of impairment of the echo level from this area. The result of studies of specimens, as described above, gave a good idea of which structures are giving the echoes forming a depiction of the spinal canal. The discussion which has been continued during the work on these problems has also led to a modification of the original statement by Porter et al. (1977, 1978a) concerning the origin of the signal. This modification (Porter, 1982) is that the echoes, which are registered, originate from the interface between bone and dura at the "cranial lip" of the laminae and from the interface between soft tissues and bone at the upper part of the vertebral body.

In order to reject or confirm the presumption as to the origin of the signals, which has been made on the basis of the specimen experiments mentioned above, the study (III) on bone-soft tissue specimens has been carried out to study whether or not diagnostic ultrasound can pass through thin bone and still produce strong enough echoes to provide a depiction of the structures behind the bone. In these experiments, which have been carried out on specimens from the spine and the thoracic wall, it could be shown that the attenuation of ultrasound, when passing the laminae or the ribs, is of such an extent that the dynamic range of commercially available ultrasound scanners is inadequate for depiction (Kremkau, 1980). Thus useful signals cannot be obtained from structures situated distal to bone even if the bone is thin.

Another way of finding out which structures are depicted is to compare the depiction obtained at ultrasound scanning with depictions obtained by another method in the same plane. A suitable method would be computed tomography. Specimens have been examined with computed tomography in the same plane as for ultrasound scanning (IV). The images obtained have been reproduced photographically to the same scale and then compared so that the main outlines of the computed tomography image could be superimposed on the ultrasound image. The images were matched, vertically and horisontally, using the depiction of the structures which were clearly visible on both as a reference. On the basis of the image thus obtained, it could be deduced that it is the part of the spinal canal between the laminae which is depicted by ultrasound examination of the spinal canal.

The third means of direct comparison between ultrasound examination and another method is to make direct measurements on the specimens. In the present study (I), this has been done on casts of the spinal canal made of a plastic material. Measurements on the casts showed that the measurements obtained during ultrasound examination corresponded to those obtained from the "myelography cast" of the dural sac.

IN VIVO EXAMINATIONS

The findings resulting from the comparison of ultrasound images and computed tomography images of the specimens raised the question as to the feasibility of a similar examination in vivo. The same methods cannot be used because computed tomography examination was made with the length axis of the specimens transversly in the gantry of the computed tomography scanner. The introduction of a system for perpendicular reconstruction of longitudinal slices based on the transverse computed tomography slices (Glenn et al., 1975) enabled such an examination to be made in vivo. 11 patients were examined both by computed tomography and ultrasound examination. Longitudinal slices in the same plane as for ultrasound examination were made using perpendicular reconstruction. The images were compared and they were matched using the depiction of the marker seen on both computed tomography and ultrasound examination images. The computed tomography examination was complicated because of the length of time needed (30 - 45 min), which is why some movement artefacts had to be allowed for. Comparison of the images was made in the same way as for the specimen images and in 9 cases out of 11 there was a satisfactory correspondence between computed tomography and ultrasound image. In 2 cases there was unsatisfactory correspondence in the longitudinal direction of the patient, probably due to involuntary movements by the patient. Measurements of the width of the spinal canal on the ultrasound image and the computed tomography image were made at 16 levels. The correlation coefficient was 0.82. A higher correlation coefficient was not to be expected since there is a method error inherent in distance measurements by ultrasound examination (V) and by computed tomography (Koehler et al., 1979, Baxter and Sorensen, 1981). In some cases a satisfactory depiction was not obtained in segments where surgery had been performed. This was probably due to an increased attenuation and scattering in scar tissue (Sarti and Sample, 1980). The elongated depiction of the spinal canal, in some cases with a deviating course, is probably due to the fact that the structures examined lay at a considerable distance from the focus of the transducer (Jaffe and Taylor, 1979; Hefner et al., 1980).

The above observations made would, therefore, indicate that the lumbar spinal canal can be examined by ultrasound. It is also made clear that the origin of the signals is the interface between the contents of the spinal canal (cerebrospinal fluid) and the surrounding soft tissue (dura, epidural fat). Measurements of the width of the spinal canal at the levels between the laminae are also possible.

An important clinical application of the measurement of the lumbar spinal canal is in the diagnosis of spinal stenosis. The method normally used for this is myelography with positive contrast, so a comparison has been made between the results of ultrasound examination and those of myelography (II). The study comprised a mixed material of patients who were examined by myelography. The distribution in the relation between measures obtained at myelography and at ultrasound examination was striking and on this basis, the ultrasound measurement which should ensure the presence of a narrow spinal canal when measuring at myelography is rather large. On the basis of the present study, a measurement of 14 mm or more obtained by ultrasound of the lumbar spinal canal is needed to exclude a measure at myelography of 8 mm or less.

A considerable variation is described in the study mentioned above. Problems concerning variation and questions about reproducibility of ultrasound examination of the spinal canal have been discussed by several authors (Porter, 1980; Hibbert, 1982; Legg, 1982; Davies, 1982). On the basis of these discussions two questions remain to be answered:

Can other measurement methods than that presented by Porter be used? In our study, a digital static B-scanner was used instead of the analogue static B-scanner used by Porter. It would also be interesting to know whether a dynamic B-scanner, which is easier to handle, can be used.

Irrespective of method, it would also be important to know what the measurement accuracy is and which factors in the measuring process influence the accuracy.

Such a comparison has been carried out (V). When a digital static B-scanner was compared with an analogue static B-scanner, it was found that there was a systematic overestimation of the width of the spinal canal when an analogue B-scanner was used, probably because the measurement method used requires the transducer to be set precisely in a small angle towards the perpendicular cross-section of the spinal canal. The measurement accuracy of both methods is the same, however, and an important observation is that the random error at registration is small (standard deviation 0.2 mm - 0.3 mm). The random error at measurement, however, is larger (standard deviation 1.6 mm). The total error of the measurement can be diminished by using a procedure where the measurements are made independently of registration and by repeating the measurements. This has been intimated in a study by Ottewell and Howell (1981), who state that improved measurement results could be obtained after repeated measurements and averaging. When the digital static B-scanner and the dynamic B-scanner were compared, a systematic error with a considerable variation was found when the dynamic B-scanner was used. The measurement accuracy was also poorer. This is probably due to the fact that a satisfactory depiction of the dorsal delineation of the spinal canal cannot be obtained with a dynamic B-scanner with a linear multi-element transducer. The geometry of the transducer causes the dorsal aspect of the spinal canal to be obscured, more or less entirely, by the lower part of the lamina of the segment above.

SUMMARY

A method for depiction of the lumbar spinal canal by ultrasound was reported by Porter et al. (1977, 1978a). The method is reproducible and a depiction of the spinal canal in the shape of two parallel lines interupted by areas in "echo shadow" is obtained. The origin of the signals obtained has been discussed. According to Porter et al. (1978a) bone is depicted. Their experiments, however, were carried out on clean bone specimens. If the experiments are repeated on specimens consisting of bone, ligaments and dura, images are obtained which show, when compared with findings made on direct observation, myelography or computed tomography of the specimens, that the origin of the signals is the interface between the cerebrospinal fluid and the dura and adjacent fatty soft tissue in the dorsal and ventral parts of the lumbar spinal canal.

On studying the attenuation of soft tissue and bone in both spine specimens and specimens from the thoracic wall, it was also found that there is considerable attenuation of ultrasound by the ribs and that there is no measurable passage of ultrasound through the laminae. This means that there will be no depiction of soft tissues situated distally to the bone in relation to the ultrasound transducer when a conventional diagnostic scanner is used even when the bone in question is thin.

Ultrasound examination of the lumbar spinal canal has also been compared with other established methods for the study of the spinal canal such as myelography and computed tomography. On comparison with myelography, a comparatively low coefficient of correlation for measurements was found. This could be explained by a wide distribution of the measurements at ultrasound examination and myelography. The distribution was less when comparing measurements at ultrasound examination with computed tomography with perpendicular reconstruction. When the depiction of the spinal canal by ultrasound and by computed tomography was compared it was found that there was no depiction of the spinal canal ventrally to the laminae. The part of the canal depicted corresponded to the interfaces between cerebrospinal fluid and adjoining soft tissues at the levels between the laminae.

The method error in different parts of the registration - measurement procedure of ultrasound examination of the spinal canal was studied using analysis of variance. It was thus found that the registration procedure was responsible for a method error which was small, compared with the measurement procedure where the standard deviation of the method error is approximately 6 times larger. Considerably better accuracy could be gained, therefore, by repeated measurements of the same registration.

A comparison of digital static B-scanning with analogue static B-scanning and dynamic B-scanning, respectively, was made. Analogue and digital static B-scanning are equally accurate. A systematic overestimation results, however, at analogue scanning. When a dynamic B-scanner is used, there is also a systematic overestimation with considerable variation and the variation of the measurements also increases.

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