THE DETECTION OF SPONDYLOLYSIS
USING LUMBAR SONOGRAPHY.

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Doctor of Philosophy at the
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by

Brian R. Hammond. D.C.

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SUMMARY

Diagnostic ultrasound has mainly been utilised in the field of back pain for the detection of lumbar canal stenosis and the identification of visceral pathologies, with associated referred lumbar pain.

Following the published accuracy of lumbar canal measurement using a compound scanner, it was postulated that the instability of the neural arch, in patients with spondylolysis, could be objectively demonstrated. A technique was designed for the detection of this instability using a compound ultrasound scanner. A pilot study indicated that the method was able to distinguish between affected and unaffected patients.

The procedure was, however, time consuming, the equipment expensive and being non-portable made preventative screening in school children impractical.

The suitability of different scanners for lumbar canal measurement was thus assessed.

A method for measuring the lumbar canal, using a portable realtime scanner was developed. Subsequent investigations to detect spondylolysis, however, gave errors greater than the variations expected in an affected subject.

A number of in vitro experiments were therefore designed to determine the geometrical parameters, sources of error and origins of echoes during lumbar sonography.

Echoes were found to come from both the bony and soft tissue elements of the spine. Pulsations were visualised from the soft tissues within the spinal canal though these were dependent on scanning plane.

The precision of the ultrasound system was investigated and considered not to be a limiting factor in the success of this technique providing suitable equipment was used. The major sources of error were considered to be biological or due to operator error.

The literature relative to spondylolysis and lumbar sonography was reviewed.

The physical principles of pulse-echo ultrasound were discussed especially in relation to lumbar sonography.

Other possible uses of diagnostic ultrasound in the field of back pain were briefly investigated.

DEDICATION

This work is dedicated to my wife Elizabeth and my children Nicole, Samantha and Daniel for their patience and tolerance over the last six years.

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INTRODUCTION

Every year in Great Britain a proportion approaching 1% of the population experience a spell of certified sickness incapacity because of back pain. This leads to the loss of more than 11.5 million days from work. Not only are most married women, the self employed and the elderly not represented in this data but many more people are able to continue at work or do not claim sickness benefit when they are suffering from back pain (Cochrane 1979).

There are few common radiological signs associated with a significant increase in symptoms of low back pain above that expected in the general population.

Spondylolysis (fig 1) is a condition which almost exclusively affects the lower lumbar spine and can be defined as a discontinuity of the interarticular portion of the neural arch. It is now generally considered to be a stress fracture of the pars interarticularis (Cyron et al 1976, Murray and Colwill 1968, Wiltse 1969, Newman 1963).

Spondylolisthesis of the lumbar spine is a condition where there is forward slipping of a vertebra on the segment below. There are many causes

but the condition is most often associated with spondylolysis (Newman 1963).

In 1954 Hult carried out a field investigation on a non-selected material of 1200 workers in different occupations with special reference to disc degeneration and low back pain. He found that 84% of a population with spondylolisthesis complained of low back pain compared to an incidence of 59.9% in his entire material ($0.01 < P < 0.02$) and concluded that in cases with spondylolisthesis there was a clear increased incidence of both back pain and disc degeneration.

FIG 1 Spondylolysis and Spondylolisthesis.

Spondylolisthesis is the commonest cause of low back pain and sciatica in children and adolescents (Laurent and Osterman 1969), and a major cause of spinal surgery under the age of 20 years (Blackburne and Velikas 1977).

The incidence of spondylolysis and spondylolisthesis varies considerably with race, sex, athletic activities and also the technique used to identify the defect. Roche and Rowe (1952) in a skeletal study found an incidence of 1.95% in American negroes, and an incidence of 6.4% in white American males. Stewart (1953) again in a skeletal survey, found an incidence as high as 53% in some Eskimo communities north of the Yukon River.

In a mass radiological survey of 400, 6-year-old children Baker and McHollick (1956) found an incidence of pars defects in 4.5%, yet defects in children under the age of 5 are considered rare (Wiltse et al 1975). The incidence of spondylolysis is considered to be approximately 6% (Wiltse et al 1975) and spondylolisthesis approximately 3% (Allen & Lindem 1950).

Pre-employment radiography of the lumbar spine is now being required with greater frequency by many industrial organisations. Most employers consider

spondylolysis a disqualifying defect, presumably on the basis of potential ease of injury or the subsequent development of spondylolisthesis (Colbert 1968). It is also unfortunate that the identification of spondylolysis and spondylolisthesis, using standard radiographic procedures, utilises the largest doses of ionizing radiation used in bone radiography (Meschan 1959).

If pre-employment lumbar sonography could be used to identify conditions which predispose to back pain, this may reduce the need for radiography of the lumbar spine and hence decrease the incidence of diseases associated with the use of ionizing radiation (International Commission on Radiological Protection 1951).

Following the published accuracy of lumbar canal measurement using a compound ultrasound scanner (Porter et al 1978a) and the reported instability of the posterior arch in patients with spondylolysis (Sandoz 1971, Lowe et al 1971, Wiltse 1969, Bailey 1947), it was postulated that the instability could be detected by measuring the canal diameter in unstressed and stressed positions and that this would produce an objective method of detecting spondylolysis (fig 2).

FIG 2. The dimension of the canal (a) increases in the stressed position (b).

The object of this work was to determine if diagnostic ultrasound could be used for the early detection of this condition in asymptomatic children and adolescents. If successful, this could possibly be useful in decreasing the incidence of pain in patients affected with this condition, either by permitting preventative counselling or via direct treatment of the condition before the onset of symptoms. It has been shown that immobilisation of the spine in selected cases of spondylolysis can result in reunion of the bony segments (Wiltse et al 1975). Also its early detection may shed further light on the aetiology of the condition or its causative agents.

The literature relative to spondylolysis (chapter 1) and lumbar sonography (chapter 3) was reviewed. Prior to selecting apparatus it was necessary to assure its suitability for lumbar canal measurement. A critical review of different scanners was therefore undertaken (chapter 2.2). The physical principles of pulse-echo ultrasound were reviewed with particular reference to signal processing, range resolution and the precision of measurement (chapter 2.1). Two approaches were investigated simultaneously:- in vitro experiments to determine the origins of echoes, sources of error and parameters for scanning (chapter 4) and in vivo examinations of patients (chapter 5).

1.1 HISTORY

1.1.1 THE PRE-RADIOGRAPHIC ERA (1741-1895).

For over one and a half centuries there were a number of clinical and pathological observations of spondylolysis and spondylolisthesis. By the end of the 19th century the cause of the vertebral slipping was still a controversial subject. Unfortunately at that time it was not generally realised that there was more than one clinical condition with the same physical sign of anterolisthesis.

One of the earliest references to spondylolisthesis possibly dates back to 1741 when Andry described a "hollow back" as a warping of the spine inwards.

A more definite description of the condition was made in 1782 by Herbiniaux, a Belgian obstetrician, who described a number of cases in which the foetal head was prevented from passing into the pelvic canal. He said, " this narrowing (of the pelvic canal) is caused by the travel of the last lumbar vertebra inside the pelvic inlet, and by a kind of very sharp exostosis which is formed at its articulation with the sacrum." He was almost

certainly describing spondylolisthesis as the cause of the obstruction.

Nearly seventy years passed until Kilian (1854) introduced the term spondylolisthesis (spondy = vertebra, listhesis = slip). He considered the condition was due to a slow slipping of the last lumbar vertebra due to the superimposed body weight.

A year later Robert (1855), who was more concerned with the method of slipping, demonstrated that in a normal lumbar spine anterior slipping was impossible with intact facets and neural arch. "If one removes the posterior arch of an L5 vertebra and cuts the L5-S1 disc, whereby the rest of the spine remains intact, then a little vertical pressure would cause such sliding. If however the posterior arch remains intact, and the anterior ligamentous support is removed, no sliding will occur when pressure is applied."

The fact that such a lesion existed naturally was demonstrated by Lambl (1858) who showed specimens of spondylolisthesis with a discontinuity in the neural arch. He suggested that the lesion was secondary to a disease of the spinal cord and in some cases due to a supernumerary vertebral anlage. He

maintained that these were the main causes of spondylolisthesis but also considered luxation of the lumbosacral facets and fractures of the arch as possible causes.

In 1864 Rambaud and Renault published their treatise on the origin and development of bones. They stated that each half of the neural arch ossified from two centres, one for the pedicle and superior articular process, the other for the inferior articular process, lamina and spinous. Their paper, together with that of Schwegel (1859) formed the basis of the congenital theory of spondylolysis (§ 1.4.1) which, though later disproved, dominated medical opinion for almost three quarters of a century.

Konigstein (1871) suggested that spondylolisthesis was caused by an abnormal "tensibility" in the interarticular portion and pointed out that the posterior intervertebral joints were intact. This had previously been noted clinically by Hartmann (1865) who observed that whilst the body of the vertebra slipped forward the spinous appeared to stay in its normal position, indicating that there was a division or elongation of the neural arch.

Neugebauer (1881, 1882a & 1882b) made extensive pathological and clinical investigations into spondylolisthesis. In 1881 he considered the deformity consisted of an elongation and angulation of the saggital axis of the vertebra, mainly in the interarticular portion. He made no mention however of the discontinuity of bone previously described by Lambl (1858). It seems at this time he may have been describing either the degenerative or dysplastic varieties of spondylolisthesis (§1.2). By 1889 he had observed many anatomical specimens. He described the spectrum of spondylolysis and spondylolisthesis having found some specimens with a pars defect and no listhesis, some with pars defects and a listhesis and some with a listhesis and no pars defect. In 1882 he described the first case of spondylolisthesis in the male, previously thought a condition exclusive to females.

In 1885 Lane suggested that spondylolisthesis was due to an erosion of the interarticular portion of the 5th lumbar vertebra by the sharp edges of the inferior articular process of L4 and of the superior sacral processes. He considered the condition was associated with and more frequent in heavy manual workers.

1.1.2 POST RADIOGRAPHIC ERA. 1896-1938

With the discovery of X-Rays by Roentgen in 1895 the diagnosis of spondylolisthesis slowly became a radiological rather than an anatomical problem. Early radiographs of the lumbar spine however, were not clear enough to show vertebral position let alone a neural arch defect. Putti (1910) doubted it would ever be possible to demonstrate spondylolisthesis radiologically, though only three years later Wiemers (1913) succeeded in demonstrating a picture of the lumbar spine. It was not until 1927, however, that Jaroschy showed acceptable pictures of the lumbosacral area.

Improvement of radiographic quality yielded a considerable increase in the number of published cases and for many the identification of a neural arch defect became a prerequisite for the diagnosis of "true" spondylolisthesis. Junghanns (1930) thus described a slipping of the 4th lumbar vertebra on the 5th with an intact neural arch as "pseudo-spondylolisthesis".

In 1931 Meyer-Burgdorff suggested the use of oblique projections to show small defects in the pars and noted that these could not be seen on the lateral projection.

In 1939 Friberg extensively reviewed the subjects of spondylolysis and spondylolisthesis, describing an increased familial occurrence and a series of patients treated with surgical fusion.

Since 1940 a mass of literature has been published notably by Wiltse (1957a, 1957b, 1962, 1964, 1969, 1975 and 1976), Newman (1955, 1963), Stewart (1953, 1956) and Roche and Rowe (1952, 1953).

These papers amongst others are reviewed in the following sections.

1.2 CLASSIFICATION

In 1976 Wiltse, Newman & Macnab, three authorities on the subject of spondylolisthesis, proposed a new classification derived from those previously published (table 1 & fig 3):

1. Dysplastic.
2. Isthmic.
 - a. Lytic fatigue fracture of the pars.
 - b. Elongated but intact pars.
 - c. The acute fracture.
3. Degenerative.
4. Traumatic.
5. Pathological.

CLASSIFICATION OF SPONDYLOLISTHESIS

Table 1

1. DYSPLASTIC.

There is a deficient development of the inferior facets of L5 and/or superior sacral facets (fig 3b). This is frequently associated with spina bifida.

FIG 3. Classification of Spondylolisthesis.
 (a) normal. (b) dysplastic. (c) isthmic.
 (d) traumatic. (e) degenerative. (f) pathological.

2. ISTHMIC.

a. Lytic. There is a discontinuity of bone at the pars interarticularis, with or without slipping of the vertebral body (fig 3c).

b. Elongation of the pars without separation. This is considered to be a variation on the lytic variety with listhesis, where the stress fracture has healed in an elongated position.

c. Acute pars fractures, secondary to severe trauma.

3. DEGENERATIVE.

Due to longstanding segmental instability there is remodelling of the articular processes at the level of involvement (fig 3e).

4. TRAUMATIC.

There is a fracture through the neural arch in a position other than through the pars (fig 3d).

5. PATHOLOGICAL.

Because of local or generalised bone disease the posterior element of the motor unit fails to hold against the shearing stress, e.g. Paget's disease and syphilitic disease (fig 3f).

1.3 INCIDENCE.

The reported incidence of spondylolysis and spondylolisthesis varies considerably with race, sex, athletic activities and also the technique used to identify the defect.

The two main techniques used are skeletal studies and radiological surveys. With skeletal studies there is probably little room for observer error. In radiological surveys however the variations in radiographic quality will introduce error. Even with high quality exposures many of the smaller defects are not visible (Roberts 1947). Also the interpretation of the radiographs may be subject to observer bias. It is interesting to note that in the many surveys there are no reports of interobserver error, though Wiltse (1962) refers to the lack of detection of these conditions "despite good quality radiographs interpreted by competent radiologists".

1.3.1. RADIOLOGICAL SURVEYS.

A summary of radiological surveys is found in tables 2a and 2b.

Author	Year	Material	Number affected	% affected
Bohart	1929	TH 931 Railway employees	3	0.32
Hodges & Peck	1937	TH 447 Pts with LBP & sciatica 538 controls	36 ?	8.1 ?
George	1939	TH 3301 Patients with LY back pain	108 7	3.3 0.21
Friberg	1939	TH/LY 1834 Selected cases	102	5.6
Gallucio	1944	TH/LY 142 routine spine examinations	15	10.6
Friedman et al	1946	TH/LY 100 Soldiers controls	6	6.0

TABLE 2a. RADIOLOGICAL SURVEYS
FOR SPONDYLOLYSIS (LY) & SPONDYLOLISTHESIS (TH)

Author	Year	Material	Number affected	% affected
Lerner and Gazin	1946	TH/LY Airforce employees 511 with back pain	52	10.1
Bailey	1947	TH/LY 2080 Male candidates for the armed forces	92	4.4
Allen and Lindem	1950	TH 3000 Male applicants Pre-employment exam	89	2.96
Rowe and Roche	1953	LY 40 children 3-6 yrs 100 white males 3-16	0 3	0 3
Baker and McHollick	1956	TH/LY 400 school children 5-7 yrs	18	4.5
Kettelkamp and Wright	1971	LY 153 Eskimos non/orthopaedic	43	28.1
Haukipuro et al	1978	TH/LY 105 members of a Finnish Kindred	30	29

TABLE 2b. RADIOLOGICAL SURVEYS
FOR SPONDYLOLYSIS (LY) & SPONDYLOLISTHESIS (TH)

One of the first mass radiological investigations was made by Bohart (1929). He examined 931 employees of a railway company but found only 3 (0.32%) had spondylolisthesis. This low figure was probably a reflection of the poor radiographic quality which existed at this time.

A higher incidence was found by Hodges and Peck (1937), who made a clinical and radiological study of 447 patients with low back pain and sciatica and compared the radiological findings with a control group of 538 patients (though 353 of these did complain of low back pain). Routine views taken included antero-posterior and lateral lumbar with occasional spot and stereoscopic views. Of the 447 patients 36 (8.1%) were reported as having spondylolisthesis. Unfortunately no figures were given for the incidence of spondylolysis or spondylolisthesis in the control group as these conditions were grouped under the general heading "miscellaneous".

An example of an increase in incidence because of greater interest in the condition was demonstrated by George (1939). He reviewed the records of 210,000 patients examined in an orthopaedic department between 1911 and 1938 and found 313 (0.15%) who presented with evidence of a diagnosis of

spondylolysis or spondylolisthesis.

During the 4 year period 1934-1937 (supposedly a time of increased awareness and interest in these conditions) examination of a group of 3,301 patients revealed 108 (3.3%) with spondylolisthesis, yet surprisingly only 7 (0.2%) had the more prevalent spondylolysis. These results, once again, were probably a reflection of poor radiographic quality.

In 1939 Friberg found an incidence of 5.6% for spondylolysis in 1,834 cases but added that this figure was of limited value because of selection.

Galluccio (1944) reported on 142 routine examinations of the lumbar spine which disclosed 15 cases (10.6%) of spondylolysis or spondylolisthesis.

Bailey (1947) reported an incidence of 4.4% for spondylolysis in 2080 unselected young men who were candidates for the armed forces, however, only one lateral radiograph was taken. It was interesting to note that only 1 in 10 of those affected complained of any previous or present low back pain though the possibility of this precluding their employment may have biased these figures.

Allen & Lindem (1950) in a pre-employment

radiological examination of 3000 male subjects found 89 (2.96%) had spondylolisthesis.

A report on two series of children was made by Rowe and Roche (1953). The first included 40 children between 3 and 6 years of various ethnic groups in whom no defects were found. The second series of 100 white males aged 3 to 16 years showed 3 children with arch defects.

Baker and McHollick (1956) in another radiological survey of children aged 5 to 7 years, found 6 out of 175 females and 12 out of 225 males had spondylolysis or spondylolisthesis (4.5%).

Kettelkamp and Wright (1971) examined 153 Eskimos who attended hospital for non orthopaedic problems and found 43 (28.1%) had pars defects. This high incidence in the Eskimo community is believed to be due to a high familial incidence and inbreeding (Stewart 1953).

Haukipuro (1978) in a radiographic study of 105 of 170 members of a Finnish kindred found 22 (21%) had spondylolysis and 8 (8%) had spondylolisthesis demonstrating an increased familial incidence.

The incidence of spondylolysis and spondylolisthesis found in these radiological surveys varies considerably. This probably relates to varying radiographic quality, the interest and views of the author as well as the population sample. A more reliable indication of incidence is almost certainly indicated by skeletal studies.

1.3.2. SKELETAL SURVEYS.

A summary of skeletal surveys is found in table 3.

With such a direct method of observing defects, there is probably little room for error, and thus the individual surveys are not discussed at length.

Some factors however, relating to age, sex, race and segmental incidence have been noted.

Stewart (1953) reported on the age incidence of neural arch defects in Alaskan natives. He found a progressive increase in the incidence with age which suggested the defect was acquired and not congenital. There was also a spreading segmental involvement with age, i.e., as the age groups progressed more segments could be affected in the same individual. Defects at more than one level did not seem to occur before the

Author	Year	Material	Total number	% affected
Neugebauer	1889	European	90	5
Shore	1930	Bantu South African	81	6
Willis	1931	American	1520	5.2
Stewart	1931	Eskimo north of Yucon Eskimo south of Yucon	187 225	39 14.7
Congdon	1931	American Aboriginies	200	5
Mitchell	1933	European	?	3
Roche & Rowe	1952	American white and negro mixed sexes	4200	4.2
Stewart	1953	Eskimo	786	26.3
Nathan	1959	American white and negro mixed sexes	450	4.2
Lester and Shapiro	1968	Eskimo Tigara Eskimo Ipiutak	248 47	45 21
Eisenstein	1978	South African Blacks South African Whites	372 113	3.0 4.8

Table 3
SKELETAL SURVEYS FOR SPONDYLOLYSIS

age of 19 but multisegmental involvement was found in 9% of adults.

1.3.3. INCIDENCE OF SEGMENTS AFFECTED.

Whilst there has been much debate concerning the aetiology, incidence and symptomatology of spondylolisthesis, there is general agreement on the segmental incidence in the lumbar spine (table 4).

Author	Material	L5	L4	L3	L2	L1
Stewart (1953)	Skeletal 786	75	21	2	1	1
Roche and Rowe (1952)	Skeletal 4,200	156	17	5	3	0
Haukipuro (1978) et al	radiological 105	18	4	0	0	0

SEGMENTAL INCIDENCE OF SPONDYLOLYSIS
TABLE 4

1.3.4. MALE TO FEMALE RATIO

Spondylolysis and spondylolisthesis were initially considered exclusive to the female sex until 1882 when Neugebauer described the first case in the male. It was slowly realised that the

condition was more prevalent in the male. Roche and Rowe (1952) found an incidence of 2.3% for females and 6.4% for males.

1.3.5. RACIAL AND REGIONAL DIFFERENCES

There are obvious racial and regional differences in the incidence of spondylolysis and spondylolisthesis. The condition seemingly most prevalent in the Eskimo communities up to 53% (Stewart 1953), and least prevalent in Negroes. Roche and Rowe (1952) found 1.1% of negro females and 2.8% of negro males had pars defects.

Even in the same races regional differences in the incidence of spondylolysis have been reported. When Stewart (1953) analysed cases over 30 years of age, he found there were considerable regional differences:- north of Yukon (52.6%), south of Yukon (18.6%), Alutians and Kodiak Islands (31.6%).

1.4 AETIOLOGY

In view of the different varieties of spondylolysis and spondylolisthesis (§ 1.2.), the confusion which has previously existed concerning the aetiology may well have been justified.

The aetiology of spondylolysis remained fairly controversial until the early fifties when most authorities concluded that a weak neural arch is inherited and subsequent multiple microtrauma leads to a pars defect. Many theories were proposed regarding the aetiology, each often dominating medical opinion of that era. These theories include:

1. THE CONGENITAL THEORY. Schwegel (1859). The lesion was due to two separate ossification centres in the neural arch which fail to unite.
2. THE BIRTH FRACTURE THEORY. Hitchcock (1940). The lesion was considered to be a fracture during the birth process.
3. THE ACUTE FRACTURE THEORY. Roche (1948), Sullivan & Bickell (1960). Some pars defects are ordinary fractures which fail to unite.

4. PATHOLOGY AT THE PARS. Nathan (1959). Aseptic necrosis, osteochondritis, and bone cyst formation were considered as possible causes.

5. THE STRESS FRACTURE. Roberts (1947). A stress fracture due to multiple microtrauma of the pars leads to spondylolysis.

6. THE SPONDYLOLYTIC GENE. Wiltse (1957a), Amuso & Mankin (1967), Haukipuro et al (1978). A weakness of the neural arch is inherited.

1.4.1 CONGENITAL THEORY

The theory that spondylolysis was caused by a failure of ossification of the neural arch was first proposed by Schwegel in 1859. He stated that he had found neural arches in several foetus with two ossification centres, and that spondylolysis was due to a failure of ossification of these two centres. This view was supported for many years by a number of authors (Rambaud and Renault 1864, Neugebauer 1884, Farabeuf 1885, Bardeen 1905, Dieulafe and Dieulafe 1930, and with reservations by Poirier and Charpy

1911, and LeDouble 1912), even though many authors (Mall 1905, Bailey and Miller 1916, Prentiss and Arey 1917, Keith 1921, Hayek 1928, Willis 1931 and LeDouble 1912) had found no more than one primary ossification centre in each side of the neural arch.

A reason for the differing opinions was suggested by Willis (1931), who showed that the ossification centre in the arch was dumbbell shaped. In those sections which did not cut through the ossification centre about its mid point it appears as if there were two centres of ossification. The neck connecting the two halves of the dumbbell was in fact so small that it appeared in only one-sixth of his serial sections. In none of the arches he examined was this connecting neck absent. Paradoxically however Willis concludes "It (spondylolysis) is the ultimate result of imperfect ossification, whether this be caused by failure of the ossific process itself or by a defect of the pre-existing cartilage".

Batts (1939), attacked the still then generally accepted view that spondylolisthesis was due to a congenital defect. He postulated that if spondylolysis occurs in 5% of fully developed skeletons it would be present in at least 5% of foetal or new born skeletons. He found that in a

series of 200 foetal spines examined, neither the fourth nor the fifth lumbar vertebra showed a single instance of a double ossification centre. He concluded "Whatever may be the aetiology of spondylolisthesis, it is probably not on the basis of a congenital defect".

Rowe and Roche (1953), carried out a further examination of 20 cleared and stained human foetus and 53 stillborn infants and failed to reveal a case with two ossification centres in the neural arch. They reviewed all the investigations on foetal and neonatal cadaver and concluded that of the 509 foetal specimens and cadavers of new born infants not one case of double centres of ossification in the neural arch was found. They concluded that at the 2% level, if a lesion is congenital and therefore as frequent in the foetus as in adults, there is less than one chance in 30,000 that 509 negative observations could occur.

1.4.2 THE BIRTH FRACTURE THEORY.

Hitchcock (1940) reported that he had produced traumatic pars defects in stillborn children, and proposed that trauma during delivery or shortly afterwards may be the cause of spondylolysis. He

found that hyperflexion of the spine, often of a very moderate degree and with little force, readily fractured the neural arch in the lower lumbar region. The fractures were usually bilateral, but unilateral fractures could be produced by combining flexion with lateral bending and some torsion. Any attempts to produce a fracture using hyperextension completely failed.

Rowe and Roche (1953) carried out flexion, extension and lateral bending on several dissected specimens. In addition, the experiments were repeated on three unembalmed specimens. Flexion was carried out until the pubis touched the abdomen. In one specimen hyperextension to the extent of producing contact between the sacrum and the upper lumbar vertebra was carried out. In no instance was a pars fracture produced. They noted however, that the conditions relating to the cadaver are quite different from those in the living infant.

1.4.3. THE POST-NATAL FRACTURE THEORY.

It has been suggested (Roche 1948 and Sullivan & Bickell 1960) that some pars defects are "ordinary" fractures which fail to unite. This theory is supported by the observation that the incidence of

spondylolysis increases from zero at birth to a maximum in adulthood (Stewart 1953). However when other parts of the neural arch are fractured there is usually evidence of attempted bony repair but this is not found in pars defects (Stewart 1953). Two cases have been reported by Roche (1948) and Wiltse (1957a), where severe spinal trauma produced a pars fracture both of which repaired. Acute fracture is considered to account for a small percentage of spondylolytic vertebrae (§1.2).

1.4.4. PATHOLOGY AT THE PARS

Aseptic necrosis, osteochondritis and bone cyst formation have all been considered as possible causes of spondylolysis. Interference with the blood supply of the pars by the inferior articular process above and the superior articular surface below was considered the most likely cause by Nathan (1959). She reported depressions in the pars which she considered are in all likelihood the result of traumatic mechanical erosion between the two impinging articular processes. A zone of osteoporosis and osteolysis probably develops, possibly as a result of local circulatory deficiency, and ultimately the bone is replaced by fibrous tissue

of that particular type found in spondylolytic clefts.

Taillard (1957) suggested spondylolysis may be due to osteochondritis of the isthmus developing under the mechanical influence of the erect posture.

1.4.5. THE STRESS FRACTURE THEORY

This is the present generally accepted aetiology for the majority of spondylolytic defects. Roberts (1947) originally suggested that a stress fracture developed because of multiple microtrauma of the pars, and that this leads to spondylolysis. This view has been supported by several authors (Newman 1955, 1963, Murray and Colwill 1968, Cyron et al 1976). Newman (1955) considered a patient may be predisposed to a spondylolytic defect because of secondary instability due to absent supporting structures, e.g. spina bifida. Pfiel (1971) subjected specimens of childrens' lumbar spine to cyclic loading and reported typical spondylolytic defects. Cyron (1977) subjected the neural arches of 21 adult vertebrae to a slow displacement rate of 0.05cm per second, and 23 to a faster rate of 5cm per second (considered to be a more realistic in vivo fracture rate). Of the 44 vertebrae tested, 32 fractured across the pars and 10 across the pedicle.

Nearly all authors agree that movement and mechanical stress are essential to produce a defect. There has been some debate as to which movements produce most stress on the pars.

Harris and Wiley (1963), suggested that flexion combined with rotation produced most stress on the pars, whereas Troup (1977) considered extension to be a significant factor. This was supported by Shah et al (1978) who measured the distribution of surface strain in the cadaveric lumbar spine using metal foil strain gauges. They found that movement simulating extension produced increased strain at the pars interarticularis, and that flexion decreased this strain.

1.4.6. THE SPONDYLOLYTIC GENE. INHERITED WEAKNESS OF THE NEURAL ARCH

There is now little doubt that spondylolysis shows a demonstrable increase in familial incidence (Friberg 1939, Stewart 1953, Wiltse 1957a & Wiltse 1962). Initially it was considered that the inheritance was consistent with transmission as a single recessive gene with incomplete penetrance though Wiltse stated that from his studies it cannot be said definitely whether the trait is dominant or

recessive (Wiltse 1957a).

Later however it has been considered to be consistent with autosomal dominant inheritance with incomplete penetrance (about 75%) for spondylolysis (Haukipuro et al 1978). This was deduced by a radiographic study of 105 of 170 members of a Finnish kindred. Of the persons examined 22 (21%) had spondylolysis. Of these 22, 8 had spondylolisthesis.

Amuso and Mankin (1967) reported a family of seven of which 5 members of three consecutive generations had spondylolisthesis. They concluded that the mode of transmission was as an autosomal dominant.

Friberg (1939) found 15 persons with a pars defect in a family of 61. Toland (1955) reported the lesion in identical twins and Stewart (1953) found an incidence of 53% in an inbred group of Eskimo skeletons. Wiltse (1969) reporting his own studies and reviewing the world literature concluded that a defect of the pars is seen 5 times more frequently in near relatives of patients with spondylolysis, than in the general population. He said that incomplete penetrance is understandable if the upright posture and other environmental stresses are essential for the final breakage of the congenitally weak point in the pars interarticularis of the spinal arch.

1.5 SYMPTOMATOLOGY.

There is still much controversy concerning the symptomatology of spondylolysis and spondylolisthesis. Haukipuro et al (1978), on the subject of symptomatology state "Since only a minority of those affected ever have clinical symptoms and very few people are severely disabled, this disorder hardly raises problems in family planning. Physicians should exercise caution so as not to cause iatrogenic disease in individuals with such a common and in most cases symptomless abnormality as spondylolysis." They unfortunately gave no figures for the number of their subjects that had symptoms or their ages and thus this appears to be a personal opinion.

Hult (1954) however, in a field investigation of 1,200 workers, found that 84% of a population with spondylolisthesis complained of low back pain, compared to an incidence of 59.9% in his entire material. He stated that "in spondylolisthesis there was a clearly increased incidence of both back pain and disc degeneration" ($0.01 < P < 0.02$).

The high cost of low back pain to industry and unfavourable decisions in American Workmans compensation courts has increased the incidence of

pre-employment radiography. Most employers consider spondylolysis a disqualifying defect because of the ease of injury and the possibility of the worker developing spondylolisthesis (Colbert 1968).

It seems from the many references that the symptomatology and incidence of spondylolysis varies with the activities, race and age of the subjects. Ferguson (1974), on examining 12 college footballers with low back pain, found 2 with spondylolisthesis and 4 with unilateral spondylolysis. In this select population there was an incidence of pars defects of 50%, 10 times greater than in the general population. In the entire group of 25 football linesmen the incidence of spondylolisthesis was 8% and spondylolysis 24%.

Semon and Spengler (1981) reviewed 506 consecutive college football players in whom they found an incidence of low back pain of 27%. Of these, 58 had radiographs with the subsequent identification of spondylolysis in 12 (21%). Two groups the first with spondylolysis (N=8), the second a randomly selected control group (N=12) without spondylolysis, were compared with respect to time lost from games. There was no significant difference in time lost between the two groups (4.8% verses 4.0%). They then

continue to state that "the long term implications of lumbar spondylolysis are clearly important but are not addressed in this study."

Jackson and Wiltse (1974), stated that the incidence of fatigue fracture of the pars interarticularis is high among young athletes with lumbar pain and muscle spasm though no figures are given because of the method of sampling.

Jackson et al (1976), documented a four times higher incidence of pars defects in female gymnasts, than the 2.3% reported in the general female Caucasian population. Eleven out of 100 subjects had bilateral pars defects. Six of these 11 had spondylolisthesis. Of the 89 without pars defects 19 (23%) had suffered an episode of low back pain which interfered with training. In the group with spondylolysis or spondylolisthesis 6 of the 11 (54.5%) had similar attacks of low back pain.

Laurent and Osterman (1969) found that spondylolisthesis was the commonest cause of low back pain and sciatica in children and adolescents.

Kettelkamp and Wright (1971), took lumbar radiographs of 153 Northern Eskimos who were admitted

to hospital for non-orthopaedic problems. They found an incidence of spondylolysis of 28.1% (43/153). They obtained a history relating to back complaints and examined the lumbar spine of 101 of the 153 patients. In this group 31 had pars defects of whom 50% complained of chronic back pain. This compared with 27% without pars defects who complained of chronic back pain. The difference was significant at the 5% level that back pain was more frequent in those patients with spondylolysis.

Wiltse and Hutchinson (1964) estimated that the presence of a pars defect doubles the chance of significant back pain during the patients life.

One of the problems with spondylolysis is that the defect itself probably gives rise to few symptoms if any. At the ages of 5 to 7, the most common age of onset, few patients are aware the lesion is developing (Wiltse et al 1975). It is the resulting instability and the soft tissue damage which gives rise to symptoms (Roberts 1947, Sullivan & Bickell 1960). Unfortunately, because soft tissue injuries to the lumbar spine are so prevalent in the general population, the contribution that spondylolysis makes towards the suffering of low back pain is probably underestimated.

1.6 RADIOLOGY

It was over 30 years, following the discovery of X-rays by Roentgen in 1895 until Jaroschy (1927) was able to show acceptable pictures of the lumbo-sacral area. With the slow improvement of radiographic quality, there was a considerable increase in the number of published cases of spondylolisthesis. Radiographic quality was even more essential for demonstration of the more prevalent spondylolysis, and probably accounts for early reports which found spondylolisthesis 15 times more prevalent than spondylolysis (George 1939).

The use of oblique projections to show small defects in the pars was suggested by Meyer-Burgdorff (1931). He noted that these lesions could not be seen on the lateral projection and slowly it was realised pars defects were more common than a listhesis.

There have been many reports of the instability of the posterior arch and a tendency to further listhesis in patients with spondylolysis (Sandoz 1971, Lowe et al 1971, Wiltse 1969, Bailey 1947 & Meschan 1945).

Lowe et al (1971) reported an increase in the listhesis when comparing standing and recumbent

lateral radiographs of the lumbosacral spine. They showed radiographs of 4 patients with spondylolysis only, on recumbent radiographs, which progressed to definite listhesis when radiographed in the standing position.

Wiltse (1969) observed that about 50% of his cases with a pars defect did not show appreciable slipping. However, he found especially in younger patients that this could be converted to a spondylolisthesis by taking radiographs of the patient standing with an additional 30lbs of weight on the shoulders. He noted that the younger the patient, the more pronounced the instability would be.

Sandoz (1971) showed the instability of the arch by taking radiographs of the lumbar spine in torsion. He noted that the spinous of the affected vertebra remained aligned with the segment below and that a step occurred in the normal spiral pattern of the spinouses above the affected level (fig 4). Sandoz named this torsional instability "the lateral stair-step sign", and also described a method for palpating for this sign (fig 5).

Wedging of the vertebral body has been reported by Lerner and Gazin (1946), Stewart (1956), and Wiltse (1962).

Wiltse concluded that although the normal 5th lumbar body shows posterior wedging, this is more marked when there is a defect in the neural arch and there is a direct relationship between the amount of wedging and the degree of listhesis. He considered

FIG 4. The lateral stairstep sign.
(a) normal spinous configuration.
(b) with spondylolysis a step is present.

this wedging was an effect and not a cause of the listhesis as this trapezoid shape is not present in children at the age when the defect most frequently appears.

Sim (1973), statistically compared the degree of posterior wedging in cases of spondylolisthesis of L5 with the degree of slip. He found that the average

a

b

Fig. 5. The lateral stair-step sign (Sandoz 1971).
 (a) Palpation in torsion of a case of spondylolysis at L5 showing a step in the spiral pattern of the spinous
 (b) Radiographs taken in torsion demonstrating the step.

(Courtesy of Dr. R. Sandoz. Neuchatel, Switzerland).

wedging in spondylolisthesis is significantly greater than in patients without this condition.

It is unfortunate that the identification of spondylolysis, using standard radiographic procedures, utilises the largest doses of ionizing radiation used in bone radiography (Meschan 1959).

1.7 FAMILY STUDIES.

An increased familial occurrence of spondylolysis was first suggested by Bakke (1937), who reported two cases of spondylolisthesis in a family of four. Friberg (1939), Wiltse (1957a), Yano et al (1967) and Haukipuro et al (1978) have since carried out relatively large family studies.

Wiltse (1957a) radiographed siblings, direct descendants or direct forbearers of 24 patients with spondylolisthesis. Of the 67 relations radiographed (33 male & 34 female), 21 (31%) had arch defects. Of the 21 with defects, 13 (39%) were male and 8 (24%) were female. Eight out of the 13 male and six out of the 8 females had a listhesis. When separated into age groups, of those under 20, 13 out of 42 were found to have a defect, compared to 8 out of 25 who were over 20. From the study of these 24 families he could not conclude whether the trait was dominant or recessive. He considered it was probably recessive, with a varying expressivity. He did conclude however, that it was not sex linked.

Haukipuro et al (1978) looked at 105 of 170 living members of a Finnish kindred, consisting of 192 descendants from 2 marriages of 1 male.

Spondylolysis was found in 22 (21%), 8 of whom also had spondylolisthesis. They considered the pedigree was consistent with an autosomal dominant inheritance, with incomplete (75%) penetrance for spondylolysis.

Amuso & Mankin (1967) also considered the lesion was transmitted as an autosomal dominant, and reported on a family in which spondylolisthesis and spina bifida of the 5th lumbar and sacrum was found in 5 out of 6 surviving members from 3 generations.

Yano et al (1967) made a radiological study of 243 near relatives of 100 patients with spondylolysis. Spondylolysis was found in 29%. In order to determine the incidence of spondylolysis in Japanese, 218 necropsies were performed, in which 16 cases (7.4%) of spondylolysis were found. They concluded that the familial incidence of spondylolysis was high.

Friberg (1939) found 15 cases of pars defects in a family of 61. Toland (1955) reported the presence of spondylolysis in identical twins.

From the previous studies it seems there is approximately a one in four chance, that near relatives of patients with spondylolysis have a similar defect. This could provide a selective group for preventative screening.

1.8 SPONDYLOLYSIS AND SPONDYLOLISTHESIS IN CHILDREN AND ADOLESCENTS.

Most reports on the incidence and symptomatology of these conditions in children are based on populations complaining of low back pain. This is probably due to a reluctance to take radiographs of asymptomatic children because of the possible damage caused by the use of ionizing radiation.

Only one radiographic survey has been carried out on a section of normal population (Baker and McHollick 1956).

Laurent & Osterman (1969) published a study of 173 cases of spondylolisthesis in children and adolescents under the age of 20. Of these 173 patients, 119 had conservative treatment, whilst 54 had operative treatment. They considered that spondylolisthesis is the commonest cause of low back pain and sciatica in children and adolescents, and that while some people with spondylolisthesis never have medical symptoms, the symptoms are often severe enough to indicate operative treatment.

Baker & McHollick (1956) made a radiographic survey of 400 children between 5 and 7 years of age and found 18 (4.5%) with a pars defect or spondylolisthesis. The incidence of symptoms at this

age however, is considered low (Blackburne & Velikas 1977).

Blackburne & Velikas (1977) reported on a study of spondylolysis and spondylolisthesis in 142 children. In 16 patients (11%) there was spondylolysis only, the remaining 126 patients (89%) had spondylolisthesis. Sixty-nine (49%) underwent surgical fusion.

Turner and Bianco (1971) examined records of 173 patients with spondylolysis or spondylolisthesis who were under 19 years of age. Of these, 59 had spondylolysis only (50 boys and 9 girls), and 114 had spondylolisthesis.

Of the 59 patients with spondylolysis, 55 were seen with back pain, 4 had no pain. Twenty-four had minimal symptoms and subsequent follow up of 18 of these from 1-9 years later, showed that 7 had no complaints and 11 had only minimal discomfort. In addition 20 patients had conservative treatment because of the duration and severity of their pain. Follow up 1-9 years later on 13 patients showed that 5 had no complaints and 7 had minimal discomfort. Only 1 patient had become worse and had a spinal fusion. The remaining 15 patients had complaints severe enough at their initial examination to warrant spinal fusion.

Of their 114 patients with spondylolisthesis conservative therapy was recommended for 51. Follow up of 36 of the 51 patients, 1-9 years later showed 11 patients were free of symptoms, while 25 continued to have low back pain. Of the patients recommended to have a fusion, 10 patients chose not to have surgery, and 53 patients thus underwent spinal fusion.

Spondylolysis and spondylolisthesis in children was reviewed by McKee et al (1971). Based on 63 of their own cases and other reported series, they concluded that:

(1) Spondylolysis and spondylolisthesis occurred with equal frequency in males and females.

(2) Less than half the cases of spondylolysis and spondylolisthesis in children are symptomatic.

(3) Only one quarter of the symptomatic cases are associated with recent trauma.

(4) Only 12% of symptomatic cases were under 10 years of age, and in this group the symptoms are almost always lumbar pain. In the older group about one third of the cases also have a sciatic component.

Macnab (1970) considered if severe or recurrent symptoms developed before the age of 21 years, it was unlikely the patient would recover without surgery.

Roberts (1947) in a retrospective study of 29 cases of spondylolysis or spondylolisthesis found that about one third had symptoms of low back pain during school days.

Ultrasound is sound with frequencies beyond the range of human hearing ie. from 20 kHz to 10^{13} Hz and is a simple mechanical energy which travels in waves through a medium. Only a small range of these frequencies, 1 MHz to 20 MHz, is of general medical interest.

2.1.1 WAVE MOTION.

Four types of waves exist in solid materials:

- (a) longitudinal
- (b) transverse
- (c) Rayleigh
- (d) Lamb

With longitudinal waves, the vibration is parallel to the direction of propagation. For transverse waves the vibration is perpendicular to the direction of propagation.

In diagnostic ultrasound most waves are longitudinal in nature. There is no evidence for transverse waves except in bone. The wavelength (λ) is the distance in the medium between consecutive particles where the displacement amplitudes are identical (fig 6).

FIG 6. Particle oscillation during wave motion.
 (a) *Particle spacing.*
 (b) *related to distance.*
 (c) *related to time.*

The wave period, or cycle (T), is the time taken for the wave to move one wavelength. The frequency (f) is the number of cycles which pass a given point in one second. The frequency and wave period are related by the equation

$$f = \frac{1}{T}$$

The wavelength and the frequency are related to the propagation velocity (c) by the equation

$$c = f\lambda$$

Examining this relationship it can be seen that the higher the frequency the smaller the wavelength.

2.1.2 VELOCITY.

The velocity (c) with which sound travels through a medium is determined by the delay in passing the energy from one particle to its neighbour. This depends on the elasticity (K) and density (ρ) of the medium, and is related by the equation

$$c = \sqrt{K/\rho}$$

The average velocity in soft tissues is 1540m per second. Table 5 gives an indication of the varying velocities in different media (Wells 1977).

Medium	Velocity (metres/sec)
Air (STP)	330
Water	1480
Fat	1470
Liver	1550
Muscle	1585
Bone	3400

TABLE 5

The transmission of ultrasound is dependent on the product of the velocity (c) and the density (ρ). This product (Z) is given the term CHARACTERISTIC ACOUSTIC IMPEDANCE, and is related by the equation

$$Z = \rho c$$

The acoustic impedance of some biological tissues is shown in Table 6 (Wells 1977, *Goss & O'Brien 1979).

Tissue	Characteristic impedance $10^6 \text{ kg m}^{-2} \text{ s}^{-1}$
Blood	1.62
Bone	3.75-7.38
Brain	1.55-1.66
Fat	1.35
Kidney	1.62
Liver	1.64-1.68
Lung	0.26
Muscle	1.65-1.74
Spleen	1.65-1.67
Water	1.52
Collagen*	2.15

TABLE 6
ACOUSTIC IMPEDANCE OF SOME BIOLOGICAL TISSUES

2.1.3 REFLECTION OF A WAVE.

At a boundary between two media with different characteristic acoustic impedances, Z_1 and Z_2 , a partial reflection of a plane ultrasonic wave occurs (fig 7). The reflection coefficient (R) can be calculated as:

$$R = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2} \right)^2$$

FIG 7. At the interface of medium 1 and medium 2 a proportion of the wave is reflected. The remainder passes into medium 2.

This implies that the amount of reflection is dependent on the impedance mismatch at the boundary of the two media. The remaining sound energy will continue into the second medium.

As ultrasound used in scanning is directional, it behaves very much like light and obeys the same geometrical laws of reflection and refraction (fig 8).

2.1.4 ATTENUATION.

The intensity of sound progressively decreases as it propagates through a medium. This attenuation is caused by three basic mechanisms:

1. Divergence of the beam.
2. Scattering of the beam.
3. Absorption of the energy.

The absorption is proportional to the frequency.

There is thus greater tissue penetration using lower frequencies and less penetration using higher frequencies.

FIG 8. The angle of incidence ϕ_2 equals the angle of reflection ϕ_1 . The angle of refraction ϕ_3 is dependent on the velocity of sound in the two media.

2.1.5 BEAMWIDTH.

The shape of the ultrasound beam from a transducer of finite area can be computed using Huygens' principle. The resulting wave front at any point is the envelope of the sum of all the spherical waves that are radiated by each of the

infinite number of points at the surface of the radiating area. The addition of the ultrasonic fields gives a narrow beam of practically plane waves close to the transducer, (the near field), gradually changing into a spherical wave in the far field where the small radiating area appears as a point source. If the radiating area is not plane (i.e. when acoustic lenses are applied) the resulting pattern is altered. With a concave radiating plane the beam is focused at a distance determined by the construction of the transducer surface. This gives a narrower beam in the near field but after the focusing point the beam diverges more rapidly. The variations in beamwidth of different transducers affects their lateral resolution characteristics (§2.1.8).

2.1.6 TRANSDUCERS AND THE PIEZOELECTRIC EFFECT.

Ultrasound is both generated and detected by a piezoelectric effect. Piezoelectric material in the ultrasonic transducer is excited by the application of an electrical current. This causes a regular change in the thickness of the crystal which vibrates, sending out energy in the form of a sound wave.

When a reflection of the sound wave hits the piezoelectric disc this is converted into an electrical impulse which can be recorded on an

oscilloscope. The piezoelectric disc with its exciting electrodes and an absorbing backing material make up an ultrasonic transducer. The absorbing backing material enables the transducer to produce a short pulse. This damping however, affects the frequency and causes the nominal frequency to differ from the actual frequency.

2.1.7 THE PULSE-ECHO CONCEPT

This technique uses pulses of sound rather than a continuous wave. By allowing a suitable time lapse between pulses, a single transducer can be used as a transmitter and a receiver. The pulse is created by applying a short electrical potential across the piezoelectric crystal. This generates a pulse of sound which is usually between two and five wavelengths long.

The pulse travels into the body via a coupling gel continuing through the tissue until there is a change in tissue impedance (fig 9). At the interface of two different media a reflection of the pulse occurs. The strength of this reflection is dependent on the change in acoustic impedance between the two tissues (§ 2.1.3).

FIG. 9 THE PULSE-ECHO CONCEPT.

(a) The pulse of sound is generated by electrically stimulating the transducer. This stimulation is recorded on the oscilloscope.

(b) The pulse travels through medium 1. The oscilloscope trace remains silent.

(c) The pulse meets the interface between medium 1 and medium 2.

(d) The pulse divides into a reflected and propagated wave.

(e) The reflected wave travels back to the transducer through medium 1.

The propagated wave continues through medium 2.

(f) The reflected wave excites the transducer and via the piezoelectric effect produces an electrical current, which is recorded on the oscilloscope trace.

After the pulse has been generated, the transducer switches to a receiving mode so that it can collect the returning echoes and convert them into small electrical impulses. After electronic processing the reflections can be viewed on an oscilloscope. It is now possible to calculate the distance of the tissue interface from the transducer.

As the sound wave travels through a number of tissues with different acoustic impedances a number of different reflections are produced which can be displayed on the oscilloscope. This display is called an A-scan (fig 10).

FIG 10. Example of an A-scan through two interfaces x and y.

2.1.8 THE B-SCAN

The information may alternatively be displayed on a brightness modulated time base. If the transducer is connected to a mechanical gantry so that the position of the transducer is known, a two dimensional compound B-scan can be formed (fig 11). This is possible by simultaneously memorising the A-scan and the position of the probe. As an alternative, a number of small transducers can be mounted side by side in a linear array and switched electronically (fig 12). Each transducer or group of transducers produces a line of the image.

FIG 11. (a) The A-scan.
(b) The B-scan (A-scan viewed from above).
(c) The B-scan is orientated according to the information from the mechanical gantry.
(d) With movement of the probe a compound B-scan can be produced.

FIG 12. (a) A linear array transducer.
 (b) Test object.
 (c) The B-scan obtained.

The transducers are excited in sequence so that reflections are less distorted by scatter from neighbouring transducers. If the whole array of transducers is fired more than 20 times per second a flicker free picture is obtained. As movement of the tissues can be seen, this type of display is said to be in "real time".

2.1.9 DIGITIZATION AND GREY SCALE

The two dimensional B-scan was originally

displayed in a bistable mode. This meant that the display could only show echoes over a selected threshold. The introduction of a grey scale to the B-scan provides more information about the section and can be recorded and displayed using an analogue or a digital scan converter. With digital machines the A-scan is chopped into levels. When an echo falls between two levels it is designated a grey level between black and white. Most modern equipment now relies on digitizing the image for display and memory purposes. Many of these machines are unfortunately not suitable for spinal canal measurement as the digitization process introduces an unacceptable loss of precision.

2.1.10 RESOLUTION.

Resolution is defined as the ability to separate two closely spaced interfaces (Bartram & Crow 1977). It is generally discussed under two headings, range (or axial) resolution, which refers to resolution along the path of the sound beam, and lateral resolution, which describes the resolution along the beam diameter normal to the axis.

RANGE RESOLUTION.

Range resolution defines the ability of a system to separate targets spaced close together in range. The resolution is equal to the reciprocal of the effective duration of the ultrasonic pulse (Wells 1977).

Resolution can be no better than half the pulse length (fig 13). For a typical grey scale scanner each pulse lasts about 1 micro second. With an average velocity of 1540m per second the pulse length would be 1.54mm. The actual resolution of the system therefore is limited to 0.77mm.

When considering the relationship between wavelength and resolution, the actual resolution cannot be less than one wavelength (Bartram & Crow 1977).

FIG 13. Diagram to represent the effect of pulse length on axial resolution.

(A) The two interfaces X and Y are separated by a pulse length L . The transducer sees two separate echoes.

(B) The interfaces are separated by half a pulse length. The echoes do not overlap.

(C) Two interfaces separated by less than half a pulse length. The echoes overlap.

LATERAL RESOLUTION.

Lateral resolution is defined as the ability of a system to separate targets spaced close together along the beam diameter normal to the axis. This depends on many factors including transducer design, beamwidth, wavelength and pulse length as well as the distance of the targets from the transducer.

2.1.11 RANGE MEASUREMENT

Range measurement is assessed in terms of the precision of a system in measuring the position of a reflecting surface. The position of the leading edge of a pulse is quite well defined when the dynamic range is large because the pulse amplitude rapidly rises above the threshold (Wells 1977). A small error is introduced if the position of the interface is considered to correspond exactly to the beginning of the display registration (fig 14). This error is dependent on dynamic range and if half-wave demodulation is used there may be an additional error of half a wavelength.

When measuring between two reflecting surfaces however, this systematic error is introduced at each leading edge and may thus be eliminated.

The measurement shown on a caliper readout between two interfaces is in reality not a measure of distance but a measure of time. The average velocity with which the sound travels through the tissues is set for each scanner by the manufacturer or the operator. The readout on the calipers is then calculated by multiplying the average velocity by the time interval between the caliper pips. The precision of this conversion to measurement is

FIG 14. Diagram to show the effect of pulse length and wavelength on range measurement between two interfaces X and Y.
 (a) Short wavelength. Delay in registering position of interfaces = a .
 (b) Medium wavelength. Delay in registering position of interfaces = b .
 (c) Long wavelength. Delay in registering position of interfaces = c .
 Note the distance d is the same in each case and is independent of pulse length or wavelength.

therefore dependent on the accuracy of the clock and the accuracy of the estimated velocity of sound in the tissues under investigation. It is not dependent on the wavelength or pulse length (fig 14) providing the interfaces are separated by a relatively large time interval (eg. twice the pulse length) and the pulse shapes are identical.

This precision should not be confused with range or lateral resolution both of which are dependent on pulse length and wavelength.

2.2 ULTRASONIC APPARATUS

Prior to selecting a suitable real-time machine for lumbar canal measurement a critical review of the different scanners available was undertaken. A brief technical description of these scanners, and also those used by other authors working in this field is found in Tables 7 and 8.

2.2.1 CRITERIA FOR SUITABLE MACHINES

The criteria for machines suitable for spinal canal measurement were as follows:

1. A good quality B-scan with easy visualisation of bony landmarks. It was difficult to define B-scan quality. There appears to be no objective method of assessment and others have expressed difficulty in qualitative analysis of B-scan images (Chivers 1983).
2. A non-digitized, mildly smoothed, A-scan or a digitized A-scan with sample spacing less than 0.05mm. This was required because measurements of the canal were to be made to the nearest 0.1mm.
3. The probe.
 - a. The physical size of the probe was of some importance as the application to the patient had to

Make of Machine	Realtime (R) Compound (C)	A/B-scan	Probe frequencies (MHz)	Type of display
Sonicaid 5202	R	A/B	3.5, 5.0	Oscilloscope
Roche Axiscan	R	B	2.0 3.5	Magnetic deflection Oscilloscope
Roche Abdoscan 5	R	A/B	2.8 5.0	T.V.
Diagnostic Sonar System 85	R	A/B	3.0	Oscilloscope
Sonofluroscope 1	R	B	1.6 2.25 3.5 5.0	T.V.
Searle Pho/Sonic FM.	C	A/B	1.6 to 10.0	T.V.
Nuclear Enterprises Diasonograph	C	A/B	1.6 to 10.0	T.V. Oscilloscope for A-scan

TABLE 7.

Make of Machine	Caliper accuracy mm	Penetration in oil	Comments on Suitability (NS) not suitable
Sonicaid 5202	0.1	8cm. @ 3.5MHz	Poor image quality Lack of penetration Poor reflections from body. (NS)
Roche Axiscan	1	13cm. @ 2MHz	Good image quality Good penetration and A-scan available from T.M. socket (Suitable)
Roche Abdoscan 5	1		Excellent image quality no Analogue A-scan (NS)
Diagnostic Sonar System 85	0.5	9.5cm @ 3MHz	Fair image quality but poor penetration (NS)
Sonofluroscope	1		Poor image quality no analogue A-scan (NS)
Searle Pho/Sonic FM	1		Digital computer based no analogue A-scan Good image quality (NS)
Nuclear Enterprises Diasonograph	0.1		Good image quality Analogue A-scan (Suitable)

TABLE 8

be considered. There was some difficulty applying very large probes to the low back because of the lumbar lordosis.

b. The frequency of the probe. Low frequency probes provided much greater penetration than high frequency probes (§2.1.4), though this tended to vary between different manufacturers due to probe construction and variations in the nominal and operating frequencies (§2.1.6).

2.2.2 SCANNERS CONSIDERED SUITABLE.

Of the machines tested two were considered suitable for canal measurement. The Nuclear Enterprises Diasonograph and the realtime Roche Axiscan A. The A-scan from the Axiscan was obtained from the time/motion socket at the rear of the machine.

2.2.3 FREEZING OF THE A-SCAN

In order to facilitate measurement, by permitting freezing of the A-scan, an analogue to digital converter was constructed. The incoming video signal from either the Axiscan or the Diasonograph, was fed by a preamplifier to a fast A - D converter clocked

at 16 MHz, 4 bits resolution. The data was stored in a static random access memory in sequential addresses. The organisation of this memory was a 4K by 4 bit store.

On a trigger provided by operation of a foot switch, digitization occurred. When all the locations in the static ram were filled the digitization cycle was stopped. On release of the foot switch the system returned to read only from the memory. The sequential addresses in this memory were read at the same rate as they were digitized, fed to a 4 bit D - A converter and displayed on an oscilloscope.

To make measurements from this stored data, proximal and distal caliper pips could be moved left or right on command. The resolution of this counter system is defined by the 16 MHz sample rate of the A - D converter, which converts to 0.01mm resolution. The distance between the caliper pips is displayed on a 3 digit LED display.

Unfortunately the differing opinions on the use of ultrasound to measure the spinal canal has led to two schools of thought; those who consider the technique relatively accurate and valuable (Porter et al 1977, 1978a, 1978b, 1980, Porter 1980, 1981, 1982, Hibbert et al 1981, Ottewell & Howells 1981, Legg 1982, Legg & Gibbs 1984, Hibbert 1982, Macdonald et al 1984, Forsberg & Walloe 1982 and Drinkall et al 1984) and those who consider the technique relatively inaccurate and of limited value (Finlay et al 1981, Kadziolka et al 1981, Asztely et al 1983, Veiga-Pires et al 1981, Asztely 1983, Stockdale & Finlay 1980, Nachemson & Asztely 1981, Davies 1982, Howie et al 1983 and Chatterton 1981).

These varying opinions have possibly occurred because many authors have reported and discussed one or two aspects of the technique, at the expense of considering the subject in its entirety. This problem was noted by Nachemson and Asztely (1981) who considered the "debate had lost its structure" because of the many facets of the procedure which were under discussion.

The technique is thus discussed under four headings, though it should be noted that these

subjects are all inter-related and a knowledge of them all is essential when considering each part.

1. Repeatability. This includes intra and interobserver repeatability.
2. Precision of the ultrasound system.
3. Operator error. Selection of scanning plane, selection of echoes on the A and B-scans.
4. The origin of echoes.

INTRODUCTION

Ultrasound examination of the lumbar spine was first described by Meire (1975) and Suarez et al (1975).

In both cases scanning was carried out through the abdomen. Meire (1975) mentioned the possibility of examining the spinal canal and the intervertebral discs. Suarez et al (1975) described a method using a realtime ultrasonic camera, using a mechanically scanned linear array (fig 15). The method however, was not suitable for showing sagittal sections of the lumbar spine, only coronal sections (fig 15).

Campbell et al (1975) were able to show spina

a

b

Fig. 15. (a) Realtime ultrasonic camera.
 (b) Coronal section through the lumbar spine showing the 12th rib (R) the lumbar spine (SP) and the transverse processes (TP).
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bifida of a foetus in utero.

Ultrasound examination of the low back from the posterior aspect was first described by Porter et al (1977, 1978a). They originally described measurement of the canal using an Escoline 20 A-scan machine and later using a Diasonograph 4102 B-scanner.

3.1.1 REPEATABILITY.

Porter et al (1977, 1978a), having measured the diameter of the lumbar canal in some 210 patients, reported that the results were repeatable within 0.02cm. Unfortunately they did not state whether this was a range, a mean error or give any indication of standard deviation, though from the results in section 5.2 it was generally considered to be the range.

spinal level	mean* mm	n	mean (mm) difference	S.D.	COV %
L1	16.4	30	0.34	0.24	1.46
L2	16.0	30	0.35	0.28	1.75
L3	15.6	30	0.37	0.35	2.24
L4	15.4	30	0.36	0.34	2.21
L5	15.6	30	0.52	0.35	2.24

TABLE 9

(* from Porter et al 1980)

Two years later in his M.D. thesis, Porter (1980) presented details of these and further measurements and produced figures for interobserver repeatability on 30 mining recruits with 2 examiners (table 9).

Hibbert et al (1981), co-workers of Porter calculated intra and interobserver repeatability. Intraobserver error was calculated from the mean absolute difference of paired readings at each lumbar level on 22 patients (table 10). Interobserver error was calculated from measurements on 100 subjects.

spinal level	mean mm	n	mean (mm) difference	S.D.	COV %
L1	15.8*	22	0.45	0.31	1.96
L2		22	0.44	0.30	1.90
L3		22	0.38	0.30	1.90
L4		22	0.40	0.21	1.33
L5		22	0.41	0.19	1.20

TABLE 10

Two observers made single measurements at each level. The mean absolute difference was calculated from the 2 readings at each level (table 11).

This same repeatability of approximately 0.4mm under clinical conditions has been reported by Ottewell and Howells (1981), also co-workers of Porter. Porter (1981) summarised their findings, stating that the mean repeatability is less than (* from Porter et al 1980)

0.05cm, but also added that the parameter measured for one patient may not be the same as for another, and any particular measurement may therefore have 1 or even 2mm error.

spinal level	mean mm	n	mean (mm) difference	S.D.	COV %
L1	15.8*	100	0.38	0.28	1.77
L2		100	0.41	0.30	1.90
L3		100	0.36	0.30	1.90
L4		100	0.37	0.32	2.03
L5		100	0.46	0.37	2.34

TABLE 11

Legg (1984) reported coefficients of variation for measurements within session and between sessions of 3.7% and 5.8% respectively.

3.1.2 PRECISION OF THE ULTRASOUND SYSTEM

The precision of the ultrasound system used by Porter and his colleagues was assessed by Langton (1981) using a vertebral body sample with a superimposed soft tissue mimicking material to provide some degree of scatter. He found an interobserver error using the system of 0.008cm and concluded that the precision of the system is obviously adequate and should not be a limiting

(* from Porter et al 1980)

factor in the determination of the 15 degree saggital diameter of the spinal canal. He suggested that this was further evidence that the echo recognition by the operator was the limiting factor of the technique.

Davies (1982) however, estimated the variability from physical sources to be at least 2.85mm, a quarter of which would be the expected standard deviation. He considered error arising from rectification of the received signal amounted to half a wavelength. The error associated with pulse length was stated to be 1.54mm. He noted other small contributions to error, one arising from the scale used, and another associated with setting up the pips on the peaks of the displayed echoes which are less well defined and wider than the leading edge. This he estimated from the 200 nanosecond rise time to be equivalent to a contribution to variability of 0.31mm.

3.1.3 OPERATOR ERROR

A critical appraisal of the technique was presented by Stockdale (1981) which was later published by Finlay et al (1981). One of the main criticisms was the implication that the incorrect selection of scanning plane could show artificificially high or low measurements. They were able to show

that the canal measurement could vary by several millimetres depending on the scanning plane selected. They considered the problem associated with choosing the appropriate scanning plane was one of the major factors determining the confidence to be placed in the in vivo procedure.

When considering the selection of A-scan peaks, they noted that the reflection from the more anterior edge of the lamina would be the one occurring latest in time and that the leading edge of this echo may be lost in the preceding composite echo.

They also mentioned that measuring from the trailing to the leading edge across changes in acoustic impedances could lead to errors in the recorded dimension. The magnitude of these errors would be a function of the electronic processing within the scanner and could not be reliably estimated, but may lead to a reduction in the measured dimension of possibly a few millimetres.

They considered however that the leading edge of the echo from the posterior surface of the body could be selected with adequate confidence.

The difficulty of selecting the reflection from the lamina had previously been noted by Hibbert (1980). She considered the accuracy of measurement depended on the operator's ability both to display and

recognise this echo, together with maximisation of its amplitude before final adjustment of the calipers.

Asztely (1983) investigated the reliability of measurement obtained at ultrasound examination, using 3 different scanners:- a digital static B-scanner (Searle, Pho/Sonic-SM) with a transducer frequency of 2.25 MHz, a dynamic B-scanner (Toshiba SAL-20) with a linear multi-element transducer frequency 3.5 MHz, and an analogue static B-scanner (Nuclear Enterprises Dasonograph 4200) with a transducer frequency of 1.6 MHz.

Unfortunately he did not present measurements for a specific population, but measurement errors were estimated with split unit analysis of variance. He concluded that both the dynamic scanner and the analogue static scanner consistently over-estimated measurements, and that the digital scanner appeared to be the best machine for measurement of the spinal canal.

3.1.4 ORIGINS OF ECHOES

Porter et al (1978a) originally described three major echoes, one from the posterior surface of the lamina, one from the anterior surface of the lamina

and one from the posterior surface of the vertebral body. Since their original publication they have carried out a number of further investigations and evaluations of echo origins.

Porter (1980) modified his original findings and suggested that the sound travelled only through the cranial tip of the lamina, and that some sound travelled through the ligamentum flavum.

He gave a number of reasons why the reflections were from the lamina and not from other surrounding tissues.

1. The lamina and body echoes are not staggered but in the same vertical plane on the B-scan, suggesting the sound goes through the lamina.
2. Reflections at 4cm depth, the approximate depth of the lamina, gave greater echoes than the soft tissues in the same field.
3. There was no difficulty in scanning patients with spinal stenosis who had overlapping lamina.
4. Flexing the lumbar spine to increase the interlamina space did not affect the relative

intensities of the ultrasound echoes.

5. There was widening of the spinal canal in patients with spondylolisthesis.

He postulated that if there was interlaminar transmission, there should be reflections from the intervertebral disc as this is found in the same transverse plane. He found no unilateral decrease in canal dimensions in patients with unilateral prolapsed intervertebral discs, demonstrated by radiculography.

He concluded that some sound is transmitted into the canal through a window of vertebral lamina at the cranial aspect, and some through the ligamentum flavum in the lamina region. He suggested that the echoes from within the canal were not reflected from the intervertebral discs, but from the central part of the posterior surface of the body.

These findings not surprisingly were supported by Hibbert and Langton (1981), co-workers of Porter, who suggested that peaks selected on the A-scan represented the cranial tip of the lamina and the vertebral body. From their investigations however, they concluded that the proportion of the echo travelling through the ligamentum flavum was greater

than that travelling through the lamina.

Kadziolka et al (1981) were the first to consider that significant reflections came from any other tissues than the bony elements of the lumbar spine. They made direct measurements of the lumbar canal on 10 fresh human lumbar spines. These measurements included ultrasonic measurement, measurement of a silicone rubber mould (containing a radiographic contrast media) injected into the dural sac, plain radiography with the mould intact and computerized axial tomography. The ultrasound technique was similar to that used by Porter et al (1978a), but they used a Searle, Pho/Sonic-SM ultrasound scanner. From direct comparisons of measurements using these techniques, they concluded that the strongest echoes during scanning of the lumbar spinal canal were from the cerebrospinal fluid/dural interface, and that the technique reveals the dimension of the dural sac at the level of the intervertebral disc and not the bony canal. They came to this conclusion because with few exceptions, the distance measured by ultrasound was smaller than the width of the dural sac, measured by the other techniques by 0.5 to 1mm.

These same conclusions were reported by Nachemson and Asztely (1981). Porter (1981) found

the suggestion that echoes arose from the dural interface an interesting concept, but one that was not supported by his experimental or theoretical work. He considered that the matter required urgent clarification.

3.2 SCANNING TECHNIQUE & SOURCES OF ERROR

3.2.1 SCANNING TECHNIQUE

Lumbar sonography like most diagnostic ultrasound techniques is essentially a pattern recognition procedure. The operator initially orientates the probe over the spine using the surface anatomy of the patient. The gantry of the scanner is inclined at 15 degrees to the sagittal plane because the bony spinouses do not permit transmission of the ultrasound signal into the lumbar canal.

Serial scans are used to select a "recognised" scanning plane. (The section through the body is in fact a slice several millimetres thick rather than a plane.)

Having selected the scanning plane which best depicts the spinal canal, measuring calipers are introduced onto the B-scan and A-scan (if available) to measure the canal at each level.

Selecting a scanning plane for each vertebra in turn, the calipers are positioned on the B-scan at the cranial end of the echoes representing the canal boundary. If only a B-scan is available then the measurement of the canal is made at this point. If

an A-scan is available, this is utilized for fine adjustment of the calipers. One caliper pip is placed half way up the leading edge on the reflection from the ventral echo (fig 16). The echo from the posterior aspect of the canal is less distinct, a part of a

FIG 16 Typical A-scan through the lumbar canal.
l = ripple on lamina complex echo.
b = leading edge of the body echo.

composite echo pattern from the entire lamina. A ripple is sought on the downward slope of this echo for the second caliper pip.

3.2.2 SOURCES OF ERROR

There are three main sources of error, the anatomy and positioning of the patient, operator

error and an inherent error introduced by the equipment used.

a. The anatomy and positioning of the patient.

The variations in anatomy of the subjects can affect the quality of the B-scan. The quality is reduced in older patients probably due to degenerative joint disease and also in the obese patient (or patients who have had previous spinal surgery) because of increased scatter and absorption (§ 2.1.4). Younger patients, especially children, provide very clear B-scans. The quality of the B-scan is also affected by patient movement. This is mainly due to respiration, but also due to elective movements by the patient, especially those suffering from back pain at the time of examination. Children also tend to move and fidget during examination more than adults making measurement more difficult. The positioning of the patient may cause slight rotation of the lumbar spine though this effect is negligible (Hibbert 1980). The measurement of the canal diameter at L5 appears to be more difficult than at other levels, probably due to the lumbosacral angle and the necessity to angle the probe.

b. Operator error.

This is dependent on the ability of the

operator to use the surface anatomy to position the probe and then to select a "recognised" scanning plane (§3.1.3 & 5.1). There is also an error in positioning the caliper pips on the B and/or A-scans.

c. The equipment.

Unfortunately there are many variables and an infinite number of combinations. These include:

(i) The probe. Probes vary tremendously in their frequency whether or not they are focused and their focal distance, the size of the acoustic beam (§ 2.1.5) as well as variations in their geometrical and acoustic axes.

(ii) Gantries usually come in two varieties, an XY gantry and an angle poise gantry. The XY gantry is considered to improve the accuracy of the technique (Hibbert et al 1981). Realtime probes rarely have a gantry, though one was constructed to hold the realtime probes during in vitro investigations (Chapter 4) and in vivo measurements of the spinal canal using a realtime scanner (§ 5.4).

(iii) Signal processing. Variables include (a) transmit power, (b) the slope of the time gain curve,

(c) the threshold setting, (d) the digitization of the signal, (e) the accuracy of the caliper settings, (f) the assumed speed of sound used to calibrate the caliper separation, (g) screen resolution and registration accuracy.

Having outlined the possible sources of error, and the infinite variations of equipment available, this may explain the differing opinions on the accuracy of ultrasound to measure the spinal canal (§ 3.1).

3.3 DISCUSSION

Spondylolysis occurs in approximately 6% of the European population (§ 1.3). It is associated with an increased incidence of both back pain and disc degeneration (§ 1.5). It is the commonest cause of low back pain and sciatica in children and adolescents and a major cause of spinal surgery under the age of 20 (§ 1.8). There is a strong hereditary predisposition (§ 1.7) with approximately a 1 in 4 chance that near relatives of patients with spondylolysis have a similar defect. With the early detection of this condition it has been shown that immobilisation of the spine in selected cases can result in reunion of the bony segments. Unfortunately preventative screening, using radiographic procedures, is considered unethical as it utilises the largest doses of ionizing radiation used in bone radiography (§ 1.6).

The object of this work was to determine if diagnostic ultrasound could be used for the early detection of this condition.

The proposed method of detecting spondylolysis was based on obtaining two canal measurements of the lumbar spine in prone and stressed positions (§ 1.6). The technique incorporates the method of lumbar canal

measurement using ultrasound, and is thus subject to the same errors (§ 3.2).

At the commencement of this work it was believed the published accuracy of $\pm 0.2\text{mm}$ (§ 3.1.1) represented the range of repeatability. The validity of such a low figure has been questioned and this has subsequently been revised (§ 3.1.1). The ability of the ultrasound system itself to provide such accurate results has also been disputed (§ 3.1.2).

The operator errors have been considered too great (§ 3.1.3), and even the origins of echoes from the structures within the canal from which measurements are taken have become a matter for debate (§ 3.1.4).

It therefore became necessary to clarify which tissues gave rise to echoes during lumbar sonography (§ 4.2), and how these tissues would be visualised with variations in scanning plane (§ 4.1). It was also necessary to clarify the precision with which an ultrasound system could measure between two interfaces (§ 4.3). The selection of scanning plane was considered to be the most likely cause of operator error (§ 3.1.3), and it was thus decided to determine what variations in scanning plane were possible (§ 4.1), and how precisely an experienced

operator could select a scanning plane in vivo (§ 5.1).

Spinal canal measurements were made using both realtime (§ 5.3) and compound scanners (§ 5.5) to determine repeatability for canal measurement before scanning in prone and stressed positions in an attempt to detect spondylolysis (§ 5.4 & § 5.6).

4.1 EXPERIMENTS TO DETERMINE THE BONY STRUCTURES VISUALISED DURING LUMBAR SONOGRAPHY AND THE GEOMETRICAL PARAMETERS FOR SCANNING.

Lumbar sonography is essentially a pattern recognition procedure (§ 3.2).

In order to clarify which structures of the lumbar vertebrae were probably being visualised during in vivo scanning, a series of B-scans were made of two human lumbar vertebrae immersed in a water bath. At the same time, the geometrical parameters for scanning the spinal canal were assessed.

METHOD AND MATERIALS.

Two dry human lumbar vertebrae were immersed in a water bath with their dorsal aspect uppermost. The bodies were separated by a plasticine insert which was shaped to simulate the intervertebral disc. A gantry was constructed (fig 17) over the water bath to hold a realtime probe at 15 degrees so that the scans depicted the 15 degree saggital oblique plane described by Porter et al (1978a). Serial B-scans were made with a realtime Roche Axiscan A using a 2 MHz probe. Scans were made moving medially in steps

FIG 17. Apparatus for realtime in vitro experiments.

of 2mm to 6mm, over a distance of 4cm, from a position just lateral to the transverse processes. The structures which were intersecting the beam were identified by carefully scratching the surface of the bone with a dissection needle introduced from the medial and lateral aspects. The experiments were repeated using a Nuclear Enterprises Diasonograph fitted with a 2.25 MHz probe and a realtime Roche Abdoscan using a 2.8 MHz probe. On the latter occasion however, a video recording was made whilst moving the probe very slowly backwards and forwards over the specimen.

Three scans were made of the lumbar canal, using the Diasonograph, with a variation in the sagittal angulation of the probe. The first scan was made with the probe perpendicular to the spinal axis, the second with the probe tilted 10 degrees cephalic, and the third with the probe tilted 10 degrees caudal. The three scans were then repeated having removed the posterior half of the plasticine insert, mimicking the intervertebral disc.

RESULTS

The serial B-scans using the Axiscan A are shown in fig 18, and the corresponding structures which

SECTION 1

SECTION 2

SECTION 3

SECTION 4

FIG 18. Serial B-Scans. t = transverse, a = articular column, o = body lat.aspect, p = sup art process.

SECTION 5

SECTION 6

SECTION 7

SECTION 8

FIG 18. Serial B-Scans. a = articular column,
b = body, l = lamina, o = body lat. aspect.

SECTION 9

SECTION 10

SECTION 11

SECTION 12

FIG 18. Serial B-Scans. b = body, l = lamina,
s = base of spinous, i = inf articular process.

SECTION NUMBER	READING (cm)	STRUCTURES VIEWED
	0.0	Transverse processes (TP's)
1	0.6	TP's, lateral aspect of bodies (1st quarter)
2	1.0	Proximal end of TP's, lateral aspect of bodies.
3	1.5	Sup. articular processes, lateral aspect of bodies
4	2.0	Articular column, lateral aspect of bodies
5	2.5	Articular column, some echoes from 2nd quarter of body but viewed from outside the canal
6	2.8	Articular column, 2nd quarter of body seen via the inter- lamina space. Note cephalic shift of body echoes
7	3.0	Articular column, lamina, 2nd quarter of body
8	3.2	Articular column, lamina, centre of body
9	3.4	Inf. articular processes, lamina, centre of body
10	3.6	Lamina, base of spinous, body (3rd quarter)
11	3.8	Lamina, base of spinous, body (3rd quarter)
12	4.0	Base of spinous, body (3rd quarter)

TABLE 12.

intersected the beam in table 12. Examples of the B-scans from the Abdoscan and the Diasonograph are shown in figure 19. They were similar in nearly all respects except for some minor differences probably due to variations in lateral resolution of the probes (§ 2.1.10).

The scans made of the lumbar canal with alterations in the sagittal angulation of the probe are shown in figure 20.

DISCUSSION.

Using the Axiscan the lamina and body echoes were depicted together in sections 7 to 11 (table 12). The scanning plane between these sections altered by 8mm. This figure was the same for the Abdoscan. Using the Diasonograph the body and lamina echoes were simultaneously displayed with a change in scanning plane of 9mm. Finlay et al (1981) were able to show simultaneous echoes from the lamina and body with a change in scanning plane of 8mm. On all occasions there was an acoustic dead space between the lamina and the body. During the video recordings using the Abdoscan it was interesting to note how two observers frequently picked the same scanning plane (within 1mm) as the section they would select for canal measurement.

a

b

FIG 19. Examples of B-scans from the Abdoscan (a) and the Diasonograph (b).
l = lamina, b = body.

a

b

FIG 20. B-Scans before (a) and after (b) removal of plasticine insert representing the intervertebral disc. = disc. W = A-scan line. (Probe axis perpendicular).

a

b

FIG 20. B-Scans before (a) and after (b) removal of plasticine insert representing the intervertebral disc. (Probe axis 10° cephalic).

a

b

FIG 20. B-Scans before (a) and after (b) removal of plasticine insert representing the intervertebral disc. (Probe axis 10° caudal).

The scans made before and after removal of the disc indicated which parts of the canal gave rise to reflections. Though there is some refraction of the ultrasound beam (§ 2.1.3), it largely depicts what the eye sees when looking at the inter-lamina space of a dry specimen (fig 21). In the scan made perpendicular to the spinal axis the posterosuperior aspect of the body below and the disc above was visualised. Tilting the probe 10 degrees caudally, a larger fraction of the body and a smaller part of the disc was seen. Tilting the probe 10 degrees towards the head introduced the postero-inferior aspect of the body above, the entire disc and a smaller proportion of the body below. This specimen was devoid of all soft tissues including the spinal cord, the reflections from which are discussed in section 4.2. The configurations of the B-scans however, obtained during these experiments, correlate well with those obtained during in vivo scanning.

The origin of bony echoes and the level from which they are obtained have been discussed by Porter (1980), Kadziolka et al (1981), and Hibbert & Langton (1981) section 3.4.

Porter (1980) mentioned that the lamina and body

a

b

FIG 21. Dry lumbar spine (a) 10° Caudal
(b) 10° Cephalic.

echoes are not staggered but in the same vertical plane on the B-scan, suggesting that sound goes through the lamina. If one looks at the B-scans published by Hibbert et al (1981), co-workers of Porter, it appears that the echoes are staggered, suggesting inter-lamina rather than intra-lamina transmission. Porter also found that flexing the lumbar spine to increase the inter-lamina space did not affect the relative intensities of the ultrasound echoes. This was not confirmed however, when scanning children in prone and flexed positions (§ 5.4). Indeed the lengths of the body echo increased significantly when flexing the spine, suggesting there was inter-lamina transmission.

Kadziolka et al (1981) concluded that the ventral echo represented the spinal canal just above and below the disc including the disc itself.

Hibbert & Langton (1981) concluded that there was both intra and inter-lamina transmission, though they suggested that inter-lamina transmission was greater.

It should be noted however, that the structures represented by an A-scan are dependent on angulation of the probe in the sagittal plane. It seems however, (fig 20) that unless the angulation is greater than

10 degrees, the ventral reflection on the A-scan represents the posterosuperior aspect of the same body as originally suggested by Porter et al (1978a).

It does not seem to represent the intervertebral disc though this may be dependent on beamwidth (§ 2.1.5).

CONCLUSIONS.

Scanning of the lumbar canal of two dry human lumbar vertebrae showed that reflections came from the posterior aspect of the lamina. There was an acoustic dead space below the lamina indicating that a proportion, if not all of the lamina, prevented transmission of the ultrasound beam.

Reflections from within the canal showed the posterosuperior aspect of the body below the intervertebral disc, and the postero-inferior aspect of the body above. In general the structures depicted were those which the eye could visualise when looking at a dry specimen. It was noted however, that this was dependent on any angulation of the probe in the sagittal plane. Reflections from the lamina and body were simultaneously depicted with a change in scanning plane of up to 9mm.

4.2 THE ORIGINS OF ECHOES DURING LUMBAR SONOGRAPHY.

Porter (1981) considered that his technique for measuring the lumbar canal revealed the dimension of the bony canal from the lamina to the body.

Kadziolka et al (1981) concluded that the strongest echoes during scanning of the canal were from the cerebrospinal fluid/dural interface, and that the technique revealed the dimension of the dural sac.

The object of this investigation was to clarify which structures gave rise to significant echoes during scanning of the lumbar spine. The experiments were initially carried out on porcine lumbar spine as a preliminary study to investigations on human lumbar spine.

MATERIALS AND METHODS.

Two scanners were used in this investigation. A Nuclear Enterprises Disonograph, model 4102A, using 1.5 and 5 MHz probes, and a realtime Roche Axiscan 5, using a 2 MHz probe. A mechanical gantry (fig 17) was constructed to hold the realtime probe over a water bath at 15 degrees to the vertical to simulate the same geometry reported by Porter et al (1978a).

The water bath was fitted with a steel baseplate to which was attached a steel toolmaker's vice. The base plate was an exact fit within the tank to ensure that there was no movement of the vice during the investigations.

Specimens of porcine lumbar spine of less than 2 days post-mortem were excised at an abattoir. On each occasion 3 lumbar vertebrae were divested of their surrounding soft tissues but leaving the ligamentous structures intact. The disc between the 2 most cranial vertebrae was severed with a scalpel, care being taken not to damage the dura and its contents. The ligaments at the same level were also severed and the cranial vertebra was prised away leaving the dura and spinal cord of that level intact. The remaining specimen consisted of 2 vertebrae with approximately 2.5cm of dura and spinal cord projecting from the cranial end.

Each specimen was immersed in degassed saline and placed in a vacuum of 0.0004mm of mercury for 30 minutes when only a few small bubbles were seen to be emerging from the specimen. The vacuum was removed and the contents allowed to equilibrate with the atmosphere for 5 minutes.

A degassing technique was used, as a number of initial experiments, using previously frozen, or non-degassed specimens, produced B-scans which were of insufficient quality to determine the structures being visualised.

The specimen was then transferred, without contact with the air, to a bath of degassed saline and clamped in a steel toolmaker's vice. On each occasion serial scans were made until the probe was in a position which would have been used for canal measurement. Confirmation that the sound beam intersected the canal was obtained by observing the introduction of a small dissection needle along the canal between the dural/lamina, and dural/body interfaces.

Using the compound scanner the A-scan was observed during gentle tugging of the dura and spinal cord which protruded from the cranial end. Photographs were taken of the A-scan with the dura intact and after the spinal cord and dura had been removed from the specimen. Using the realtime machine, video recordings of the A and B-scans were made, with gentle tugging of the dura and of the procedure of removing the dura and spinal cord from the canal.

It proved extremely difficult on all occasions to remove the dura from the canal and considerable force had to be used.

Similar experiments were carried out with human lumbar spine, the specimens being prepared in exactly the same way. Scanning was only carried out however, with the realtime machine during tugging of the spinal cord, with small variations in scanning plane across the lumbar canal.

RESULTS.

Photographs of the A-scans, before and after removal of porcine dura using the compound scanner are shown in fig 22. On most occasions it was possible to show that the dura gave significant reflections, but mainly from its dorsal aspect. On some occasions however, the dura only gave very small reflections (fig 22a). Photographs from the video recordings of the realtime B-scans of the porcine and human lumbar spines are shown in fig 23.

With the human specimens significant reflections arose from both the ventral and dorsal aspects of the dura.

a

BEFORE

AFTER

b

FIG 22. A-scans before and after removal of porcine dura.
 (a) using a 1.5 MHz and (b) using a 5 MHz probe.
 v=ventral echo, d=dorsal echo from the canal.

a

b

Fig. 23 Examples of realtime B-scans from video recordings of human (a) and porcine (b) lumbar spine.

(l = lamina, x = body, d = dura/cord)

DISCUSSION.

The initial results using porcine lumbar spine were confusing. Comparisons of the A-scan, before and after removal of the dura, showed varying results, some suggesting that the dura gave rise to significant echoes (fig 22b) and some suggesting the dura gave rise to very small reflections (fig 22a).

It was considered at one time that the amount of reflection from the dura may be dependent on the frequency of the probe used. The video recording of the realtime A and B-scans served to clarify the problem as it showed that the intensity of echoes from the dura was very dependent on small changes in the scanning plane.

The origins of echoes have been discussed by Porter (1980), Hibbert and Langton (1981) and Kadziolka et al (1981), (§ 3.4).

Kadziolka et al (1981) made direct measurements of the lumbar canal using four different methods: ultrasonic measurement, measurement of a silicone rubber mould (containing a radiographic contrast media) injected into the dural sac, plain radiography with the mould intact, and computerized axial tomography. They concluded by comparison of these

measurements that the dimension measured represented the size of the dural sac.

There are a number of factors however, in their techniques which if compounded could produce errors greater than the distance between the dural sac and the bony canal.

Measurements were made directly from the B-scan of their Pho/Sonic FM Searle. In the 30cm display field, the position registration accuracy of the B-scan is $\pm 1.5\text{mm}$. The electronic calipers have an accuracy of $\pm 1.5\text{mm}$ and the pixel resolution is 0.42mm (Siemens 1982). Also, as the signal is digitized errors of up to twice the sampling distance are possible. The ultrasound scanning of their specimens was carried out after the spinal cord had been removed, thus altering the dural/C.S.F./cord interface. They carried out no degassing procedure on the specimens, and it is possible that the dura contained air bubbles which would enhance reflections.

It is also incorrect for them to assume that the tissues which they considered gave rise to the strongest echoes, would be the same tissues selected for measurement by Porter et al (1978a).

Experiments by Langton (1982) showed no alteration in the A-scan across the lumbar canal with the introduction and removal of the dura, using a

Diasonograph. This was probably because the scanning plane selected did not optimize dural echoes.

Myelography shows that the dura is in contact with the lamina and thus the interface between the cranial tip of the lamina and the dura is likely to be represented by the same position on the A-scan (Porter 1983). The dural sac, ventrally however, is not directly adherent to the body or the intervertebral disc, but separated from it by an epidural space. This space is filled with fat areolar tissue and a plexus of blood vessels. There may be some error therefore in selecting the echo from the ventral reflection.

The fact that there is an acoustic dead-space below the lamina and not below the dura suggests that the sound is reflected more by the lamina than the dura. This is also supported by the fact that the impedance mismatch between collagen and saline is much less than the impedance mismatch between bone and muscle (§ 2.1.2).

A possible explanation of the dependence of bony and dural reflections on scanning plane is that the reflections are dependent on the geometry of the two structures (fig 24). The lamina and body are represented by the triangle, the dura by the circle. When the beam bisects the circle a strong reflection

Fig. 24. Schematic diagram of the spinal canal Δ and the dura O . When the beam (x) bisects the circle the reflections received are strong. If the scanning plane is changed slightly (y) the reflections received are weak or lost.

is received by the probe. If the probe is moved however, so that it is not perpendicular to the circle, the reflections are scattered. This can be compared to the so-called "red eye" in photography, where the retina, pupil, lens and flashgun are in line.

During in vivo examination of the spine in children using a realtime scanner (§ 5.4), small pulsations within the canal were visualised confirming that echoes came from the soft tissues. The frequency of these pulsations was similar to the

frequency of the patient's pulse.

The identification of soft tissue tumors within the cervical spinal cord using ultrasound has also been reported (Reid 1978).

CONCLUSIONS.

Echoes come from both the bony and soft tissue elements of the lumbar spine. The operator can accentuate or diminish echoes from these structures by making small alterations to the scanning plane, or by alteration of the signal processing.

4.3 EXPERIMENTS TO DETERMINE THE PRECISION OF THE ULTRASOUND SYSTEM.

There has been some disagreement on the precision with which an ultrasound system can measure between two interfaces (§ 3.1.2).

Two simple experiments were designed for testing the ability of different ultrasound systems:

- (a) to measure the distance between two interfaces
- (b) to register change in position of an interface.

METHOD AND MATERIALS.

Three scanners were used, a modified (§ 2.2.3) realtime Roche Axiscan A with a 2 MHz transducer, a realtime Roche Abdoscan with a 2.8 MHz transducer and a Nuclear Enterprises Diasonograph 4102 with a 1.5 MHz transducer.

Two lengths of nylon fishing wire were stretched around a U-shaped template (fig 25) which was immersed vertically in a water bath. On each occasion the probe was held vertically in a gantry over the template. Thirty serial measurements were made with each scanner. Before each measurement the caliper pips were reset to zero and the probe was moved away from the template.

In order to determine the ability of each system to measure change in range measurement a dissecting needle, attached to a micrometer, was immersed in a water bath. The needle was placed normal to the ultrasound beam and the distance from the transducer to the needle was measured using the calipers attached to the scanner. The needle was moved by varying amounts by the micrometer. The distal caliper was repositioned on each occasion, indicating the change in measurement recorded by the ultrasound system.

RESULTS.

The results for serial measurements between two wires are shown in tables 13, 14 and 15. The results for changes in range measurement using the three scanners are shown in tables 16, 17 and 18.

Fig. 25. Template used for serial measurements.
x = fishing wire.

Caliper reading (mm)

15.1	15.1	15.0	15.1	15.0	15.0
15.1	15.1	15.1	15.0	15.0	15.1
15.0	15.1	15.1	15.0	15.0	15.1
15.1	15.1	15.1	15.1	15.0	15.1
15.1	15.0	15.1	15.1	15.1	15.1

TABLE 13
SERIAL MEASUREMENTS BETWEEN
TWO WIRES USING A ROCHE AXISCAN A.
Mean 15.07mm (SD 0.05)
mean difference 0.043mm (SD 0.019) COV=0.13

Caliper reading (mm)

16.7	16.7	16.7	16.7	16.7	16.8
16.7	16.7	16.8	16.8	16.7	16.7
16.7	16.7	16.7	16.7	16.7	16.8
16.7	16.7	16.7	16.7	16.7	16.7
16.7	16.7	16.7	16.7	16.7	16.7

TABLE 14
SERIAL MEASUREMENTS BETWEEN TWO WIRES
USING A NUCLEAR ENTERPRISES DIASONOGRAPH.
Mean 16.71mm (SD 0.03)
Mean difference 0.021mm (SD 0.028) COV=0.17

Caliper reading (mm)

15	15	15	15	15	15
15	15	15	15	15	15
15	15	15	15	15	15
15	15	15	15	15	15
15	15	15	15	15	15

TABLE 15
SERIAL MEASUREMENTS BETWEEN TWO
WIRES USING A ROCHE ABDOSCAN.
Mean 15mm (SD 0)

Change in micrometer
reading
mm

Change in caliper
reading
mm

1.1
2.1
1.3
2.0
1.6
0.9
0.5
0.1
0.3
0.6

1.1
2.1
1.3
2.0
1.6
0.9
0.5
0.1
0.3
0.6

TABLE 16
VARIATIONS IN RANGE MEASUREMENT USING A ROCHE
AXISCAN A

Change in micrometer
reading
mm

Change in caliper
reading
mm

0.5
1.0
2.0
1.2
1.6
0.8
0.4
0.1
0.2
0.3

0.5
1.0
2.0
1.2
1.6
0.8
0.4
0.1
0.2
0.3

TABLE 17
VARIATIONS IN RANGE MEASUREMENT USING A
NUCLEAR ENTERPRISES DIASONOGRAPH.

Change in micrometer reading mm	Change in caliper reading mm
0.5	0
2.0	1
1.2	0
1.0	0
0.1	0
0.3	0
0.7	0
1.9	1
1.1	0
0.2	0

TABLE 18
VARIATIONS IN RANGE MEASUREMENT USING A
ROCHE ABDOSCAN

DISCUSSION

On first inspection of the three groups of serial measurements between two wires, it appears the results using the Roche Abdoscan (mean 1.5cm SD +/- 0) are superior to the results using the Diasonograph (mean 1.671cm SD +/- 0.003) or the Axiscan (mean 1.507cm SD +/- 0.005). However, on looking at the ability of the three systems to measure change in position of an interface (tables 16, 17 and 18), it can be seen that alterations of up to 1.2mm were not registered by the Abdoscan, whereas any change of more than 0.1mm was registered by both the Axiscan A and Diasonograph systems.

The poor precision for range measurement found with the Abdoscan system is mainly caused by two factors. Digitization of the signal introduces a large error as a sample spacing of 0.8mm is used with the 2.8 MHz probe. Also as the digital readout from the calipers is only given in millimetres there is a scale factor of 0.5mm, this being half the smallest division of the scale used. Because of this lack of precision this machine like the digital machines used by Kadziolka et al (1981), Asztely (1983) and Asztely et al (1983) is considered unsuitable for measurement of the lumbar spinal canal (§ 2.2.1). This may also explain why they consider the technique of canal measurement using diagnostic ultrasound is of limited value (Asztely et al 1983).

The precision of the ultrasound system to measure between two interfaces was assessed by Langton (1981). He found a mean interobserver error using the Diasonograph system of 0.08mm. This compares favourably with the mean intraobserver errors of 0.043mm and 0.021mm found in this study.

This precision has also been reported by McDicken (1976) who states that with perfectly flat surfaces and an unrectified display measurement can be made to one twentieth of a wavelength, and that the main factors which limit the accuracy are the

practicalities of making measurements not those of the basic physics.

Davies (1982) however, estimated the contribution to total (100%) variability from physical sources during scanning of the lumbar canal, using a Dasonograph, to be at least 2.85mm. He considered an error arose from the rectification of the received signal which amounted to half a wavelength and that there was also an error of 1.54mm associated with the pulse length. He noted other small contributions to error; one arising from the scale used (0.05mm) and another associated with positioning the calipers on the A-scan (0.31mm).

With the Dasonograph system however, there is no error arising from rectification of the received signal as there is full wave rectification.

When measuring between two interfaces, separated by a relatively large time interval (eg. twice the pulse length), there is no error due to pulse length (§ 2.1.11, fig 14). Positioning of the caliper pips on the leading edge of an A-scan does introduce a small error associated with the rise time but when measuring between two peaks of similar shape and amplitude, the delay in registering the position of each interface is the same (fig 14) and thus this systematic error is eliminated.

It seems Davies (1982) may have confused the

errors associated with range resolution (§ 2.1.10)
with those associated with range measurement.

CONCLUSIONS

The Roche Axiscan A and Diasonograph systems were able to measure movement of an interface in range with an accuracy of $\pm 0.05\text{mm}$. Repeated measurement between two interfaces using these systems did not vary by more than 0.1mm (Axiscan mean difference 0.043mm SD 0.019 COV 0.13 . Diasonograph mean difference 0.021mm SD 0.028 COV 0.17). The Roche Abdoscan system however, made errors in range measurement of more than 1mm and thus was not considered suitable for spinal canal measurement.

4.4 COMPUTER CONTROLLED SCANNING.

The main operator errors for measuring the lumbar canal using pulse-echo ultrasound are believed to be the selection of scanning plane and the positioning of the calipers on the A and B-scans (§ 3.1.3 & § 3.2.2).

It was considered that these errors could be reduced if scanning of the canal was automated using a computer and that all the B-scan sections across the lumbar canal, with their analogue A-scans, were permanently recorded. This would allow measurements to be made at a later date. The selection of a scanning plane could be standardized perhaps by selecting a midline scan through the canal.

A small feasibility study was carried out to determine if computer controlled scanning might be useful for this technique.

METHOD AND MATERIALS

Two dry human lumbar vertebrae were immersed in a water bath with their dorsal aspect uppermost (fig 26). The bodies were separated by a plasticine insert shaped to simulate the intervertebral disc. A gantry held a 2.25 MHz probe at 15 degrees so that the scans depicted the 15 degree saggital oblique

FIG 26. System for computer controlled scanning of the Lumbar Canal.

plane. The movement of the X-Y gantry was computer controlled. Six lines of 81 A-scans were recorded. The spacing between the lines was 0.975mm, as was the spacing between successive A-scans.

The exciting signal for the transducer was taken from the output of a Metrotek MP203 pulser triggered externally from a Thandar TG105 pulse generator (fig 26). The pulse repetition frequency was set so that successive A-scans did not overlap. The reflected signal from the specimen was amplified by a Metrotek MR101 receiver and fed into a Metrotek MD702 peak detector. The latter was used in the "delayed gate" mode and was externally triggered by the output from a Brookdeal 9425 scan delay generator. This was triggered synchronously with the pulser by the pulse generator. The position of the gate relative to the signal was controlled by the output from a 12 bit DAC. The signal was digitized using a combination of peak detector and a 12 bit ADC. The peak detector worked in such a way that its DC output was proportional to the maximum +ve or -ve signal within the gate at a particular time. In this case it was decided to digitize the negative part of the signal as the output from the pulser was a -ve spike.

The width of the gate was 100ns. Each scan contained 1000 data points and the sampling frequency was sufficient to recover all the salient features of

the raw signal.

The whole experiment was automated and controlled by a STWC 6809 Microprocessor. The data was stored on an 8 inch disc in binary form, converted into ASCII form and transferred to the University mainframe PRIME computer. Several routines from the graphics package GINOSURF were used to produce contour plots of the data. Unfortunately due to the enormous quantity of raw data a single contour map could not be produced. The limit of the system was about 2000 data points per plot, so the complete set of data had to be split into a series of smaller plots, each having approximately 2000 points. The collection of the data for the six scans of 2 lumbar vertebrae took 5 hours.

RESULTS

The six contour plots of the data are shown in figures 27 to 32. Each contour plot was made up of 40 smaller plots, an example of which is shown in fig 33.

DISCUSSION

Unfortunately it took over 5 hours to collect the raw data for six scans of two lumbar vertebrae.

FIG 27. Computer Scan 1. L = lamina, B = body.

FIG 28. Computer Scan 2. L = lamina, B = body.

FIG 29. Computer Scan 3. L = lamina, B = body.

FIG 30. Computer Scan 4. L = lamina, B = body.

FIG 31. Computer Scan 5. L = lamina, B = body.

FIG 32. Computer Scan 6. L = lamina, B = body.

X AXIS *10
Y AXIS *10

FIG 33. Example of a contour plot.

This time factor would have to be reduced to perhaps 5 to 15 minutes for in vivo scanning. This could be achieved with suitable apparatus (Chivers 1984).

This technique of storing serial sections may be useful for other ultrasound techniques which rely on the selection of scanning plane for their diagnostic value.

CONCLUSIONS

This study shows that it is possible to automate the procedure of lumbar canal scanning using pulse-echo ultrasound in vitro. Computer controlled scanning may be of value in reducing the operator errors associated with in vivo measurement of the lumbar spinal canal.

4.5 SUMMARY OF IN VITRO INVESTIGATIONS.

Lumbar sonography is essentially a pattern recognition procedure. In order to clarify which structures of the lumbar vertebrae were probably being visualised during in vivo scanning, a series of B-scans were made of two human lumbar vertebrae immersed in a water bath, using three different scanners. On every occasion there was an acoustic dead space below the lamina indicating that a proportion, if not all, of the lamina prevented transmission of the ultrasound beam.

In general the structures depicted were those which the eye could visualise when looking at a dry specimen from the posterior aspect. Reflections from the lamina and body were simultaneously depicted with changes in scanning plane of up to 9mm.

The origins of echoes during lumbar sonography were determined from experiments carried out on porcine and human lumbar spine. Echoes were found to come from both the bony and soft tissue elements of the lumbar spine, though it was found that the operator could accentuate or diminish echoes from these structures by making small alterations to the scanning plane.

The precision of the ultrasound system to measure between two interfaces was assessed and was found not to be a limiting factor for spinal canal measurement providing suitable analogue equipment was used. The digital equipment tested was considered unsuitable for spinal canal measurement as it introduced unacceptable errors.

A feasibility study was carried out to determine if automation of the scanning technique and storage of the raw data was possible. It was considered that with suitable equipment automated scanning may be possible in the in vivo situation and may help to reduce operator error.

5.1 INVESTIGATION TO DETERMINE AN EXPERIENCED
OPERATOR'S ABILITY TO SELECT SCANNING PLANE DURING
IN VIVO MEASUREMENT OF THE SPINAL CANAL.

INTRODUCTION

A method of measuring the diameter of the lumbar spinal canal using pulse-echo ultrasound was proposed by Porter et al (1978a). The number of possible scanning planes available has been reported as a potential source of uncertainty using this method (§ 3.1.3). The object of this investigation was to determine the variations in scanning plane during repeated in vivo canal measurement by an experienced operator.

METHOD AND APPARATUS

A linear displacement transducer (type D.C./150mm supplied by Sangamo Transducers, Bognor Regis, England.) was clamped to the gantry of a Nuclear Enterprises Diasonograph 4200 so that it could measure the lateral translation of the gantry, and hence identify the scanning plane chosen by the operator (fig 34). An ultrasonic transducer of nominal frequency 1.5 MHz (19mm diameter) type NE 4311 was used.

The slack in the angular movement of the gantry was reduced by inserting rubber wedges (fig 34) as the mechanical lock was considered insufficient for this experiment. In order to minimize any bending of the probe arm, the arm was retracted into the gantry housing as far as possible. Any further possible error due to slack between the probe arm and the gantry was reduced by standardizing the scanning procedure: when selecting the scanning plane the operator was allowed to move the gantry from a lateral to medial direction only. If she considered she had overshot the correct scanning plane the scanning procedure was repeated.

Fig. 34 Dasonograph gantry.
a = linear displacement transducer.
b = rubber wedge. c = probe arm.

The displacement transducer was supplied with a constant D.C. voltage from an Eagle International power supply model RP-124. Changes in the voltage with movement of the transducer were recorded on a digital multimeter. The displacement transducer was first calibrated by moving the gantry 20cm. and recording the voltage change. Ten consecutive in vivo measurements of the lumbar canal at L3 were made. The canal measurements and voltage readings were recorded (table 19).

Fig. 35. Variations in scanning plane.

A = range of possible scanning planes depicting spinal canal (in vitro).

B = range of possible scanning planes in vivo.

C = range of scanning planes selected in vivo.

D = mean deviation of scanning planes in vivo.

RESULTS

The variation in scanning plane was calculated from the voltage readings. The scanning plane selected by the operator was within $\pm 1\text{mm}$ on six out of ten occasions (fig 35). The selected plane was within $\pm 1.5\text{mm}$ on all ten measurements. The mean deviation of the scanning plane during ten consecutive scans was 0.9mm (SD 0.4).

canal measurement mm	voltage reading mv	deviation from mean mv	deviation of scanning plane mm
16.2	666	-3	0.2
14.9	690	+21	1.1
15.9	697	+28	1.5
16.0	687	+18	1.0
15.9	658	-11	0.6
15.7	652	-17	0.9
15.7	657	-12	0.6
15.9	690	+21	1.1
16.1	655	-14	0.8
15.8	642	-27	1.5

TABLE 19

mean voltage reading 669.4mv
displacement transducer calibrated at 18.5mv/mm .
mean deviation of scanning plane = 0.9mm (SD 0.4)
mean canal measurement 15.8mm (SD 0.36)
mean difference 0.23mm (SD 0.26) COV= 1.6

DISCUSSION & CONCLUSIONS

A critical appraisal of this technique was presented by Finlay et al (1981). One of their main criticisms was the implication that the incorrect selection of scanning plane could show artificially high or low measurements. They were able to show that the canal measurement could vary by several millimetres depending on the scanning plane selected. They considered the problem associated with choosing the appropriate scanning plane was one of the major factors determining the confidence to be placed in the in vivo procedure.

This study however, suggests that an experienced operator can repeatedly select a scanning plane during lumbar sonography with considerable precision (mean deviation 0.9mm SD 0.4).

The addition of an accurate measuring device to the gantry of a compound scanner, which indicates the scanning plane, may be useful when training operators for this and other similar scanning techniques.

5.2 PILOT STUDY.

AFFECTED PATIENTS VERSUS UNAFFECTED PATIENTS

A small pilot study was carried out to determine if it was possible to detect the instability of the posterior arch in patients with spondylolysis.

METHOD & MATERIALS

The canal dimensions were measured on 4 patients with spondylolysis (proven radiographically) and 4 control patients. The right side of the canal was measured at L3, L4 and L5 with the patient lying prone. The measurements were then repeated with the patients lying in the torqued position used to demonstrate the instability radiologically (Sandoz 1971, fig 5). The measurements were made using a Nuclear Enterprises Diasonograph 4200 fitted with an ultrasonic transducer of nominal frequency 1.5 MHz. When scanning the spine in torsion the angle of the gantry had to be altered for each vertebral level so that it approximated the 15 degree saggital oblique diameter. All measurements were kindly made by Mrs. C. Hibbert.

RESULTS.

The spinal canal measurements in prone and

stressed positions are shown in tables 20 & 21.

When comparing the canal measurements of unaffected vertebrae in the prone and stressed position the measurements did not vary by more than 0.3mm. This correlated well with the range for repeatability of 0.2mm reported by Porter et al (1978a).

PATIENTS		L.3	L.4	L.5
1	Prone	14.2	13.9	14.2
	Stressed	14.3	14.1	15.2
2	Prone	14.5	14.0	14.5
	Stressed	14.5	14.0	15.3
3	Prone	12.8	12.5	12.9
	Stressed	12.8	12.5	14.0
4	Prone	14.2	14.1	14.3
	Stressed	14.3	14.4	15.7

TABLE 20. PATIENTS WITH SPONDYLOLYSIS
canal measurements (mm).

CONTROLS		L.3	L.4	L.5
1	Prone	14.0	13.8	13.7
	Stressed	14.1	14.1	13.7
2	Prone	13.7	13.6	13.6
	Stressed	13.6	13.7	13.8
3	Prone	13.9	13.8	13.8
	Stressed	13.8	13.8	13.8
4	Prone	16.0	15.9	15.9
	Stressed	15.9	15.8	15.8

TABLE 21. CONTROLS WITHOUT SPONDYLOLYSIS
canal measurements (mm).

mean diff. unaffected vertebrae 0.1mm SD 0.09 COV 0.64
mean diff. affected vertebrae 1.1mm SD 0.25 COV 1.7

The mean canal measurement of unaffected vertebrae was 14.1mm. The mean difference between stressed and unstressed measurements was 0.1mm SD 0.09 COV 0.64. The mean canal measurement of affected vertebrae in the unstressed position was 14.0mm and in the stressed position 15.1mm. The mean difference between unstressed and stressed measurements of affected vertebrae was 1.08mm SD 0.25 COV 1.7. In the affected vertebrae the canal dimensions increased in the stressed position by an average of over 1mm (range 0.8mm-1.4mm).

Analysis of the results was carried out using a paired t test. The affected vertebrae of the patients showed a significant increase in canal dimension, in the stressed position, when compared to the change in canal diameter of the controls ($p < 0.01$). The difference between stressed and unstressed measurements in affected vertebrae versus the difference in unaffected vertebrae in the same patient was also significant ($p < 0.01$).

CONCLUSIONS

It was concluded that this ultrasound technique could detect the instability of the neural arch in patients with spondylolysis.

5.3 SPINAL CANAL MEASUREMENTS USING A REALTIME SCANNER TO DETERMINE REPEATABILITY

An initial survey was carried out to validate a method of spinal canal measurement using a realtime scanner, to calculate intraobserver error and to establish normal values for a population of young male children.

METHOD & APPARATUS.

A realtime Roche Axiscan A was used with a 2 MHz probe. The A-scan was taken from the TM socket at the rear of the machine, passed through a fast ADC (§ 2.2.3) and then displayed on a Hitachi V/302. 30MHz oscilloscope (fig 36). The B-scan on the scanner was set for a bistable display.

Canal measurements were made of the right side at L3, L4 and L5 of 44 boys (mean age 13.5 yrs, SD 1.06). Each child was examined prone with a small supporting cushion under the abdomen to reduce the lumbar lordosis. The probe was hand held at approximately 15 degrees to the sagittal plane. The scanning plane was varied, until the observer considered the B-scan best depicted the lumbar canal.

The A-scan line was moved until it bisected the

Fig. 36. Realtime apparatus for lumbar canal measurement. a = probe, b = scanner, c = ADC, d = oscilloscope.

superior tips of the echoes from the lamina and the body. The A-scan was frozen and the caliper pips were positioned on the peaks considered to represent the lamina and body. On the body peak, the pip was introduced half-way up the leading edge. On the lamina peak, the pip was positioned half-way down the descending edge or, if present, on a small ripple on the descending edge considered to represent the most cranial tip of the lamina (fig 16). Three measurements were taken of the right side of the canal at L3, L4 and L5 giving nine measurements on each subject.

RESULTS

The measurements taken are shown in Table 22. Permutations of the results obtained at each level gave 396 paired measurements (Table 23). The mean canal measurements at the three lumbar levels were L3 15.7mm (SD 2.0), L4 14.9mm (SD 2.0) and L5 14.4mm (SD 2.0).

The mean difference between canal measurements at the three lumbar levels were L3 0.97mm (SD 0.91 COV 5.8), L4 1.29mm (SD 1.04 COV 7.0) and L5 1.25mm (SD 1.17 COV 8.1). The mean absolute difference for the three levels was 1.16mm (SD 1.05).

PATIENT	AGE	L3			L4			L5		
1	10.5	131	131	129	141	144	145	106	118	106
2	12.5	161	169	164	152	142	138	133	146	143
3	12.5	171	151	137	167	144	133	169	152	143
4	12.5	172	149	163	147	150	159	147	155	174
5	12.5	156	146	138	149	149	135	143	139	137
6	12.5	128	159	126	127	165	131	116	130	136
7	12.5	145	113	125	145	119	117	148	106	167
8	12.5	181	181	169	174	141	123	151	152	151
9	12.5	132	149	136	161	147	141	143	151	121
10	12.5	175	182	178	152	173	179	162	134	149
11	12.5	181	164	173	201	188	202	184	185	139
12	12.5	150	151	163	159	169	132	126	158	124
13	13.5	169	166	168	158	144	149	157	154	147
14	12.5	122	133	135	119	147	133	135	136	122
15	12.5	176	177	176	176	164	166	154	165	160
16	12.5	162	174	176	163	176	178	179	166	164
17	13.5	185	198	198	154	166	149	137	136	153
18	13.5	172	191	161	150	157	153	139	134	134
19	13.5	161	165	167	159	160	155	151	135	152
20	13.5	150	168	157	150	156	120	165	153	134
21	13.5	142	140	156	136	113	145	118	128	159
22	13.5	139	149	111	138	145	127	136	140	138
23	13.5	179	136	172	123	156	126	123	131	128
24	13.5	161	161	156	158	148	147	151	137	147
25	14.5	169	156	152	132	144	156	155	154	160
26	13.5	147	143	144	134	134	123	104	102	126
27	13.5	183	197	189	194	205	191	212	175	220
28	13.5	146	160	140	148	139	122	169	141	138
29	13.5	174	173	175	161	171	185	157	146	147
30	14.5	185	173	179	165	149	154	161	155	168
31	14.5	147	145	144	104	106	106	143	111	122
32	14.5	138	110	127	141	108	124	140	155	146
33	13.5	140	136	133	141	144	140	120	135	130
34	13.5	156	144	144	131	159	149	148	140	145
35	14.5	149	155	147	131	123	157	115	098	090
36	14.5	149	149	151	143	153	153	153	149	147
37	15.5	188	167	181	152	165	165	167	162	168
38	14.5	181	184	186	166	153	146	135	128	133
39	14.5	169	158	164	146	138	140	136	128	132
40	15.5	134	158	132	154	159	141	162	128	148
41	15.5	153	152	148	145	149	148	162	164	152
42	14.5	194	185	186	172	166	166	156	138	141
43	13.5	116	125	129	122	123	104	115	128	127
44	15.5	169	167	166	181	166	178	150	151	157
		mean 15.7mm			mean 14.9mm			mean 14.4mm		
		(SD 2.0)			(SD 2.0)			(SD 2.0)		

TABLE 22. LUMBAR CANAL MEASUREMENTS
(units = 0.1mm)

PATIENT	L3			L4			L5		
1	0	2	2	3	1	4	12	12	0
2	8	5	3	10	4	14	13	3	10
3	20	14	34	23	11	34	17	9	26
4	23	14	9	3	9	12	8	19	27
5	10	8	18	0	14	14	4	2	6
6	31	33	2	38	34	4	14	6	20
7	32	12	20	26	2	28	42	61	19
8	0	12	12	33	18	51	1	1	0
9	17	13	4	14	6	20	8	30	22
10	7	4	3	21	6	27	28	15	13
11	17	9	8	13	14	1	1	46	45
12	1	12	13	10	37	27	32	34	2
13	3	2	1	14	5	9	3	7	10
14	11	2	13	28	14	14	1	14	13
15	1	1	0	12	2	10	11	5	6
16	12	2	14	13	2	15	13	2	15
17	13	0	13	12	17	5	1	17	16
18	19	30	11	7	4	3	5	0	5
19	4	2	6	1	5	4	16	17	1
20	18	11	7	6	36	30	12	19	31
21	2	16	14	23	32	9	10	31	41
22	10	38	28	7	18	11	4	2	2
23	43	36	7	33	30	3	8	3	5
24	0	5	5	10	1	11	14	10	4
25	13	4	17	12	12	24	1	6	5
26	4	1	3	0	11	11	2	24	22
27	14	8	6	11	14	3	37	45	8
28	14	20	6	9	17	26	28	3	31
29	1	2	1	10	14	24	11	1	10
30	12	6	6	16	5	11	6	13	7
31	2	1	3	2	0	2	32	11	21
32	28	17	11	33	16	17	15	9	6
33	4	3	7	3	4	1	15	5	10
34	12	0	12	28	10	18	8	5	3
35	6	8	2	8	34	26	17	8	25
36	0	2	2	10	0	10	4	2	6
37	21	14	7	13	0	13	5	6	1
38	3	2	5	13	7	20	7	5	2
39	11	6	5	8	2	6	8	4	4
40	24	26	2	5	18	13	34	20	14
41	1	4	5	4	1	3	2	12	10
42	9	1	8	6	0	6	18	3	15
43	9	4	13	1	19	18	13	1	12
44	2	1	3	15	12	3	1	6	7

(measurement units 0.1mm)

TABLE 23. ABSOLUTE DIFFERENCE OF PAIRED MEASUREMENTS

mean difference	L3 0.97mm	(SD 0.91	COV 5.8)
mean difference	L4 1.29mm	(SD 1.04	COV 7.0)
mean difference	L5 1.25mm	(SD 1.17	COV 8.1)

DISCUSSION & CONCLUSIONS.

The mean differences of 0.97mm, 1.29mm and 1.25mm were much greater than the mean difference of 0.1mm found in section 5.2 and the error reported by Porter et al (1978a). The coefficients of variation (L3 5.8, L4 7.0 and L5 8.1) were significantly greater than those reported (§ 3.1.1) by both Porter (1980) and Hibbert et al (1981). They were also significantly greater than the COV expected for affected vertebra (§ 5.2 & table 32).

The method therefore, was not considered accurate enough for either spinal canal measurement or the detection of spondylolysis. It was considered that the increased error may be due to the absence of a gantry for holding the probe in a steady position. Further modifications were thus made to the method and apparatus (§ 5.4).

5.4 SPINAL CANAL MEASUREMENTS OF CHILDREN IN STRESSED AND UNSTRESSED POSITIONS TO DETECT SPONDYLOLYSIS.

METHOD & APPARATUS.

A realtime Roche Axiscan A was used with a 2 MHz probe. The A-scan was taken from the TM socket at the rear of the machine, passed through a fast ADC (§ 2.2.3) and then displayed on an Hitachi V/302. 30MHz oscilloscope (fig 36). The B-scan on the scanner was set for a bistable display. A gantry was constructed to hold the realtime probe at 15 degrees to the sagittal plane (fig 37).

The canal was measured at the L4 and L5 levels on the right side on three occasions, twice with the patient lying prone with a small cushion placed under the abdomen to reduce the lumbar lordosis, and once in a stressed position sitting on a chair with the spine fully flexed. This position was used as the children were unable to sustain the torsion position used in section 5.2.

107 children were examined out of 122 who returned consent forms (8 absent due to illness, 5 considered too anxious for examination, and 2 not scanned as parents did not attend for their child's examination). The average age was 7.1yrs (SD 1.1).

FIG 37. Apparatus for spinal canal measurement.
(a) Gantry, (b) Probe, (c) Scanner

FIG 38. Saggital section of the spine showing
the Lumbar lordosis. S = Sacrum.

RESULTS.

The measurements taken are shown in tables 24 to 27. The mean canal measurements in the prone position were L4 15.0mm (SD 1.8), L5 14.0mm (SD 1.7). The mean absolute error was calculated from the two prone measurements at each lumbar level, (L4 0.62mm SD 0.56 COV 3.7), (L5 0.49mm SD 0.51 COV 3.6).

The average change in canal dimension in the flexed position was calculated by taking the average prone measurement at L4 and L5 and subtracting the measurement of the canal in flexion (tables 28 and 29). The average absolute change in canal dimension in the flexed position compared to the prone position was 1.07mm (SD 1.05) at L4 and 0.97mm (SD 0.8) at L5. Absolute differences of over 3mm occurred on 6 out of 214 occasions, five times at L4 and once at L5. Absolute differences between 2-3mm occurred on 18 out of 214 occasions, eight times at L4 and ten times at L5.

DISCUSSION & CONCLUSIONS

The canal measurements for the stressed position, were made in flexion rather than torsion,

case	age	L4					L5						
		1	2	1-2	av	F	av-F	1	2	1-2	av	F	av-F
1	6.5	137	124	13	130.5	140	9.5	118	121	3	119.5	130	10.5
2	7.5	146	151	5	148.5	145	3.5	120	130	10	125.0	124	1.0
3	5.5	150	150	0	150.0	150	0.0	130	131	1	130.5	131	0.5
4	7.5	135	134	1	134.5	141	6.5	137	136	1	136.5	143	6.5
5	6.5	150	143	7	146.5	158	11.5	149	150	1	149.5	144	5.5
6	5.5	136	136	0	136.0	136	0.0	130	128	2	129.0	134	5.0
7	8.5	173	174	1	173.5	166	7.5	140	139	1	139.5	115	24.5
8	6.5	131	126	5	128.5	130	1.5	135	135	0	135.0	129	6.0
9	7.5	173	156	17	164.5	151	13.5	151	151	0	151.0	131	20.0
10	6.5	154	159	5	156.5	136	20.5	141	147	6	144.0	144	0.0
11	7.5	137	137	0	137.0	137	0.0	130	125	5	127.5	121	6.5
12	7.5	132	154	22	143.0	137	6.0	152	143	9	147.5	135	12.5
13	8.5	151	163	12	157.0	149	8.0	139	134	5	136.5	124	12.5
14	6.5	133	132	1	132.5	120	12.5	135	131	4	133.0	137	4.0
15	6.5	152	153	1	152.5	154	1.5	145	150	5	147.5	156	8.5
16	6.5	147	161	14	154.0	125	29.0	151	148	3	149.5	129	20.5
17	6.5	138	144	6	141.0	131	10.0	125	121	4	123.0	121	2.0
18	7.5	150	157	7	153.5	165	11.5	158	157	1	157.5	154	3.5
19	7.5	152	151	1	151.5	156	4.5	131	146	15	138.5	126	12.5
20	5.5	121	120	1	120.5	127	6.5	109	109	0	109.0	110	1.0
21	7.5	148	149	1	148.5	150	1.5	126	125	1	125.5	131	5.5
22	7.5	113	115	2	114.0	108	6.0	108	109	1	108.5	107	1.5
23	8.5	158	165	7	161.5	147	14.5	146	142	4	144.0	137	7.0
24	8.5	165	159	6	162.0	150	12.0	157	146	11	151.5	141	10.5
25	6.5	154	152	2	153.0	145	8.0	143	141	2	142.0	144	2.0
26	7.5	139	145	6	142.0	144	2.0	134	129	5	131.5	153	21.5
27	8.5	163	150	13	156.5	147	9.5	149	150	1	149.5	149	0.5

TABLE 24. Canal measurements in prone and stressed positions.
(av = average prone measurement. F = measurement in flexion)
(measurement units 0.1mm)

case	age	L4					L5						
		1	2	1-2	av	F	av-F	1	2	1-2	av	F	av-F
28	6.5	175	175	0	175.0	157	18.0	165	165	0	165.0	167	2.0
29	7.5	149	149	0	149.0	159	10.0	134	137	3	135.5	129	6.5
30	6.5	135	144	9	139.5	101	38.5	120	119	1	119.5	120	0.5
31	5.5	128	111	17	119.5	161	41.5	122	133	11	127.5	144	16.5
32	6.5	163	147	16	155.0	150	5.0	142	142	0	142.0	130	12.0
33	6.5	141	146	5	143.5	146	2.5	139	138	1	138.5	127	11.5
34	6.5	152	149	3	150.5	152	1.5	139	138	1	138.5	143	4.5
35	5.5	136	134	2	135.0	130	5.0	141	146	5	143.5	131	12.5
36	8.5	161	167	6	164.0	158	6.0	140	130	10	135.0	148	13.0
37	7.5	169	183	14	176.0	156	20.0	145	141	4	143.0	126	17.0
38	5.5	121	135	14	128.0	140	12.0	133	136	3	134.5	123	11.5
39	6.5	185	182	3	183.5	165	18.5	166	168	2	167.0	167	0.0
40	8.5	128	123	5	125.5	135	9.5	121	121	0	121.0	100	21.0
41	6.5	150	148	2	149.0	141	8.0	152	138	14	145.0	134	11.0
42	7.5	131	154	23	142.5	153	10.5	128	131	3	129.5	139	9.5
43	7.5	126	131	5	128.5	126	2.5	130	131	1	130.5	116	14.5
44	5.5	155	167	12	161.0	151	10.0	134	139	5	136.5	132	4.5
45	5.5	138	128	10	133.0	124	9.0	109	107	2	108.0	100	8.0
46	5.5	175	175	0	175.0	174	1.0	172	171	1	171.5	152	19.5
47	5.5	144	151	7	147.5	147	0.5	139	141	2	140.0	137	3.0
48	7.5	140	142	2	141.0	158	17.0	130	147	17	138.5	138	0.5
49	8.5	180	179	1	179.5	190	10.5	132	126	6	129.0	121	8.0
50	8.5	175	160	15	167.5	143	24.5	156	166	10	161.0	150	11.0
51	6.5	158	154	4	156.0	159	3.0	157	156	1	156.5	162	5.5
52	7.5	192	192	0	192.0	197	5.0	177	181	4	179.0	182	3.0
53	8.5	156	163	7	159.5	134	25.5	152	165	13	158.5	140	18.5
54	7.5	174	171	3	172.5	153	19.5	168	162	6	165.0	157	8.0

TABLE 25. Canal measurements in prone and stressed positions.
(av = average prone measurement. F = measurement in flexion)
(measurement units 0.1mm)

case	age	L4					L5						
		1	2	1-2	av	F	av-F	1	2	1-2	av	F	av-F
55	7.5	128	118	10	123.0	107	16.0	110	125	15	117.5	101	16.5
56	10.5	111	109	2	110.0	117	7.0	106	104	2	105.0	96	9.0
57	8.5	159	169	10	164.0	166	2.0	157	159	2	158.0	156	2.0
58	5.5	155	147	8	151.0	143	8.0	128	141	13	134.5	129	5.5
59	6.5	118	125	7	121.5	121	0.5	117	122	5	119.5	129	9.5
60	8.5	152	155	3	153.5	123	30.5	187	187	0	187.0	175	12.0
61	7.5	155	164	9	159.5	167	7.5	158	149	9	153.5	152	1.5
62	5.5	157	153	4	155.0	149	6.0	154	153	1	153.5	147	6.5
63	7.5	148	147	1	147.5	145	2.5	128	134	6	131.0	147	16.0
64	6.5	185	164	21	174.5	174	0.5	186	179	7	182.5	181	1.5
65	5.5	142	149	7	145.5	149	3.5	137	142	5	139.5	121	18.5
66	5.5	129	143	14	136.0	138	2.0	145	145	0	145.0	122	23.0
67	7.5	134	130	4	132.0	132	0.0	129	132	3	130.5	155	24.5
68	7.5	130	145	15	137.5	135	2.5	138	127	11	132.5	143	10.5
69	7.5	160	160	0	160.0	153	7.0	150	147	3	148.5	155	6.5
70	8.5	167	164	3	165.5	162	3.5	128	125	3	126.5	118	8.5
71	6.5	160	159	1	159.5	148	11.5	165	167	2	166.0	150	16.0
72	6.5	164	174	10	169.0	162	7.0	154	155	1	154.5	142	12.5
73	5.5	118	118	0	118.0	118	0.0	104	105	1	104.5	123	18.5
74	7.5	129	148	19	138.5	150	11.5	142	141	1	141.5	158	16.5
75	6.5	125	124	1	124.5	141	16.5	126	117	9	121.5	133	11.5
76	7.5	137	137	0	137.0	114	23.0	128	114	14	121.0	178	57.0
77	8.5	180	187	7	183.5	170	13.5	166	167	1	166.5	154	12.5
78	5.5	162	163	1	162.5	145	17.5	136	130	6	133.0	131	2.0
79	5.5	154	156	2	155.0	158	3.0	151	156	5	153.5	141	12.5
80	7.5	136	128	8	132.0	118	14.0	125	128	3	126.5	139	12.5
81	7.5	130	129	1	129.5	147	17.5	158	135	23	146.5	145	1.5

TABLE 26. Canal measurements in prone and stressed positions.
(av = average prone measurement. F = measurement in flexion)
(measurement units 0.1mm)

Difference between canal measurements in prone and stressed positions at L4.
(mm)

TABLE 28.

Difference between canal measurements in prone and stressed positions at L5 (mm).

TABLE 29.

as the children found a torqued position uncomfortable and difficult to sustain. An increase in the canal dimension, in flexion, probably relies on producing a small amount of listhesis (as demonstrated radiographically by Wiltse 1969, Lowe et al 1971, Bailey 1947 and Meschan 1945). The increase in canal dimension in torsion however, seems to rely on distracting the posterior element away from the body. The difference in these methods for producing an increase in the canal dimension may be of significance.

The mean absolute errors (L4 0.62mm SD 0.56 COV 3.7, L5 0.49mm SD 0.51 COV 3.6) for paired measurements, in this study, were significantly less ($P < 0.001$) than the errors obtained using the realtime scanner without a gantry (§5.3). This was probably due to the introduction of the gantry, though the mean age of the children in this study (7.1yrs SD 1.1) was significantly less than the children examined without a gantry (13.5yrs SD 1.06) and may have been a contributory factor.

The differences in canal measurements in prone and flexed positions approximate a normal distribution at both vertebral levels (tables 28 & 29). At the L5 level however, there is a noticeable

increase, above that expected in a normal distribution, for differences of 1.15mm to 1.3mm. This may be due to a small group of affected patients superimposed on the normal distribution.

Spondylolysis occurs nine times more frequently at L5 than L4 (Roche and Rowe 1952). The frequency of absolute increase in canal measurement over 2mm, in the stressed position, was greater at L4 than L5. This method was thus unable to detect any significant changes in canal dimension at L5 compared to L4. It was therefore concluded that this method was unable to detect the instability of the posterior arch associated with spondylolysis, in children of this age group.

The coefficient of variation for the affected group in the pilot study was 1.7%. The coefficients of variation in this study ranged from 3.6% to 3.7%. This also suggests that the method is not sensitive enough to quantify the expected changes in canal dimension in affected vertebrae.

5.5 SPINAL CANAL MEASUREMENT USING A COMPOUND SCANNER TO DETERMINE REPEATABILITY.

In view of the poor repeatability figures for the realtime scanner (§ 5.3 & 5.4), compared to those found in the pilot study using a Diasonograph (§5.2), it was decided to assess the repeatability of canal measurement using a Diasonograph compound scanner.

METHOD

The lumbar canal was measured using the method (§ 3.2) reported by Hibbert et al (1981) except on this occasion a 2.25 MHz transducer was used. Twenty patients with low back pain were examined. The right side of the canal was measured from L1 to L5 on two different occasions, giving 100 paired measurements.

RESULTS

The results are shown in tables 30 and 31. The mean canal size for the five levels was 15.1mm (SD 2.23). The mean absolute error for the five levels was 0.94mm (SD 0.74 COV 4.9).

DISCUSSION AND CONCLUSIONS

The coefficient of variation (4.9%) for between session variability correlated well and was slightly less than the COV (5.8%) reported by Legg and Gibbs (1984). The mean error of 0.94mm (SD 0.74) was over twice the mean interobserver error reported by Hibbert et al (1981). This was statistically significant ($0.003 > P > 0.001$). The difference between the mean error for the compound scanner versus the realtime scanner with a gantry (§ 5.4) was not significant ($0.1 > P > 0.05$) but the results were significantly better ($P < 0.001$) than using a realtime scanner without a gantry (§ 5.3).

spinal level	mean (mm)	SD	n	mean (mm) difference	S.D.	COV %
L1	15.0	1.75	20	1.13	0.78	5.2
L2	15.4	1.62	20	0.99	0.88	5.7
L3	15.1	1.75	20	1.02	0.72	4.8
L4	14.7	1.76	20	0.66	0.58	3.9
L5	15.3	3.64	20	0.92	0.68	4.4

TABLE 30

The coefficients of variation found in this study and those reported elsewhere are summarised in table 32. It is difficult to draw conclusions from these results. The figures for repeatability of lumbar canal measurement reported by Hibbert et al

CASE NO	PAIRED CANAL MEASUREMENTS					DIFFERENCE				
	L1	L2	L3	L4	L5	L1	L2	L3	L4	L5
1	159	137	145	136	137	143	139	138	144	156
2	157	153	161	157	158	150	163	160	275	278
3	144	139	148	140	145	137	145	147	129	121
4	125	126	162	173	161	168	153	151	153	152
5	148	144	148	141	137	138	126	125	124	126
6	182	158	168	151	163	151	164	154	149	134
7	189	176	189	180	187	188	187	177	187	176
8	116	143	123	156	130	156	123	132	137	132
9	181	160	161	164	144	162	152	163	137	125
10	136	147	177	178	189	195	183	177	193	200
11	154	147	157	139	143	132	132	142	170	179
12	147	137	153	155	156	129	135	130	129	124
13	168	167	152	144	156	142	141	143	139	129
14	158	150	159	158	147	155	153	156	179	175
15	173	159	186	157	154	157	130	123	132	125
16	133	130	142	133	134	133	128	122	142	118
17	145	153	156	153	156	145	155	151	153	155
18	161	143	175	159	157	171	149	176	148	175
19	125	113	120	123	130	119	132	125	123	111
20	156	143	153	147	150	140	150	144	136	144

TABLE 31. PAIRED MEASUREMENTS USING A DIASONOGRAPH
(measurement units 0.1mm)

Author	Coefficient of variation %
Porter (1980) within session interobserver	1.46-2.24
Hibbert et al (1981) within session intraobserver	1.20-1.96
Hibbert et al (1981) within session interobserver	1.77-2.34
Legg & Gibbs (1984) within session intraobserver	3.7
Legg & Gibbs (1984) between session intraobserver	5.8
In vitro (§ 4.3) within session intraobserver	0.13-0.17
Compound scanner (§5.1) within session intraobserver	1.6
Pilot study (§ 5.2) within session intraobserver	0.64-1.7
Realtime scanner (§ 5.3) within session intraobserver	5.8-8.1
Realtime scanner (§ 5.4) with gantry within session intraobserver	3.6-3.7
Compound scanner (§ 5.5) between session intraobserver	3.9-5.7

Reported coefficients of variation for
measurement of the lumbar canal.

TABLE 32

(1981) are significantly less than those found in this study and reported by Legg and Gibbs (1984). This may be due to the vast experience that Porter and Hibbert have acquired over the past 7 years though Hibbert (1981) reports that non-medical operators can reach a similar degree of proficiency, with careful tuition, in 5 or 6 weeks.

5.6 SPINAL CANAL MEASUREMENTS OF AFFECTED AND
UNAFFECTED PATIENTS IN STRESSED AND UNSTRESSED
POSITIONS TO DETECT SPONDYLOLYSIS.

METHOD AND APPARATUS

Twenty patients with spondylolysis proven radiographically (mean age 43.5yrs SD 11.7) and twenty control patients without spondylolysis were scanned in prone and flexed positions. In the prone position a small cushion was placed under the abdomen to reduce the lumbar lordosis. In the stressed position the subject was seated with the spine fully flexed with the hands on the floor.

Measurements were made at the affected level of each patient (L4/2, L5/18) with spondylolysis and at the same level on a control patient using a Nuclear Enterprises Diasonograph 4200 fitted with a 2.25 MHz probe. The method of measurement is described previously (§ 3.2).

RESULTS

The results are shown in tables 32 and 33. Of the 20 patients with spondylolysis the canal dimension increased in the stressed position in 14 (mean 1.35mm SD 0.82) and decreased in six. Of the

20 controls the canal dimension increased in the stressed position in 12 (mean 1.28mm SD 0.89) and decreased in eight.

PATIENTS		CONTROLS	
Prone	Stressed	Prone	Stressed
15.7	16.3	16.1	16.9
16.8	15.5	12.6	14.2
19.3	20.1	15.5	15.2
13.7	15.5	17.7	19.5
12.5	14.1	13.5	15.4
18.1	18.2	16.3	15.2
15.3	15.9	13.5	16.2
14.8	17.4	15.2	17.8
16.3	16.0	14.8	16.0
18.5	20.7	15.3	15.5
16.0	17.0	19.2	19.4
13.0	14.1	17.7	13.8
15.1	17.8	13.5	13.0
16.3	13.7	18.6	17.5
15.9	16.6	14.5	13.2
13.9	13.8	16.1	16.4
14.3	16.4	15.7	15.4
16.2	15.1	12.8	12.7
13.8	14.8	12.9	13.4
14.2	13.7	16.3	17.9

TABLE 32.
Canal measurements of affected patients and
controls in prone and stressed positions.
(mm)

DISCUSSION

The canal measurements for the stressed position were made in flexion rather than torsion, as all the patients had low back pain and many complained of discomfort in the torqued position. Indeed, some

complained of discomfort in the flexed position, though to a lesser extent. An increase in canal dimension in the flexed position relies on producing instability in the form of an anterolisthesis. Bailey (1947) reported that 48% of candidates for the armed forces, who had spondylolysis, showed at least a few millimetres of forward movement of the involved vertebral body when the spine was flexed.

	mean canal measurement (mm)	SD	mean (mm) difference	SD	COV %
Patients prone	15.5	1.8			
stressed	16.1	2.0	1.24	0.84	5.4
Controls prone	15.4	1.9			
stressed	15.7	2.0	1.20	1.01	6.5

TABLE 33

The degree of this instability and listhesis is considered to decrease with age (Wiltse 1969). It is thus probably more difficult to demonstrate instability in this older group (mean age 43.5yrs SD 11.7) than in the younger group of patients (§ 5.4, mean age 7.1yrs SD 1.1). The quality of the B-scan is also reduced in the older patient (§ 3.2.2).

This may account for the slightly greater mean difference (1.2mm) found in this study compared to that found for the children (1.0mm, § 5.4).

It was generally more difficult to measure the canal in the flexed position than the prone position. This is supported by the observation that the mean errors are greater for the difference in measurements in prone and flexed positions, than for paired measurements in the prone position, using both realtime and compound scanners.

It is possible to calculate the maximum permissible mean error, standard deviation and coefficient of variation for the technique, in order to identify different degrees of instability. If one assumes a mean canal diameter of 15mm and that in affected vertebra the size of the canal increases by 1mm in the stressed position, for ($P < 0.001$) the mean error plus 3.291 standard deviations should be less than 1mm. Assuming the mean and standard deviations to be the same, a mean error of 0.23mm (SD 0.23) is required, which gives a coefficient of variation of 1.5%. Applying the same principles for ($P < 0.01$) the COV should be equal to or less than 1.86%. If the assumed increase in canal dimension is 2mm for affected vertebra the COV for ($P < 0.001$) should be less than 3% and for ($P < 0.01$) less than

3.7%. The coefficients of variation for the normal and affected groups in this study were 6.5 and 5.4 respectively.

This implies that the method is not sensitive enough to quantify the expected changes in canal dimension in an affected vertebra.

CONCLUSIONS

There was no significant difference between the patient and control groups. It was thus concluded that measurement of the spinal canal in prone and flexed positions, using lumbar sonography, could not detect the instability of the neural arch in patients (mean age 43.5yrs SD 11.7) with spondylolysis proven radiographically.

5.7 SUMMARY OF IN VIVO INVESTIGATIONS

An initial pilot study was carried out to determine if pulse-echo ultrasound could be used to detect the instability of the neural arch in patients with spondylolysis. The results indicated that the method was able to distinguish between affected and unaffected patients and between affected and unaffected vertebrae in the same patient ($p < 0.01$). The procedure was however time consuming, the equipment expensive and being non-portable made preventative screening in school children impractical.

A survey was therefore carried out to validate a method of spinal canal measurement using a portable realtime scanner. The lumbar canal of 44 boys was measured, the probe being hand held at approximately 15 degrees to the sagittal plane. The mean absolute difference was 1.16mm (SD 1.05 COV 7.0). This was much greater than the error of 0.2mm reported by Porter et al (1978a) and also greater than the expected difference in affected vertebrae.

The method was thus modified. A gantry was constructed to hold the realtime probe at 15 degrees to the sagittal plane. One hundred and seven children were examined between the ages of five and

ten years in an attempt to detect spondylolysis. Paired measurements were taken in the prone position to determine repeatability. The mean difference was 0.62mm (SD 0.56 COV 3.7) at L4, and 0.49 (SD 0.51 COV 3.6) at L5. The mean difference between the average canal measurement in the neutral position versus measurement in the stressed position was 1.07mm (SD 1.05) at L4, and 0.97mm (SD 0.8) at L5. Absolute differences of over 2mm occurred on 24 out of 214 occasions (L4-13 / L5-11).

As the frequency of increase in canal measurement over 2mm was greater at L4 than L5, and spondylolysis occurs nine times more frequently at L5 than L4, it was concluded that this method was unable to detect any significant changes at L5 compared to L4. The coefficients of variation were also greater than the COV expected for affected vertebrae. It was therefore concluded that this method was unable to detect the instability of the posterior arch, associated with spondylolysis, in children of this age group.

It was thus decided to re-establish if spondylolysis could be detected using a compound scanner. Paired measurements were made of the canal in 20 patients with low back pain to calculate the mean intraobserver error. The mean absolute error

was 0.94mm (SD 0.74 COV 4.9). These figures were significantly greater than those reported by Hibbert et al (1981) but correlated well with those reported by Legg and Gibbs (1984).

In order to determine if a compound scanner could detect the instability of the neural arch, the spinal canal was measured in prone and flexed positions in 20 patients with spondylolysis, proven radiographically, and compared to changes in the canal dimension of 20 controls. In the patient group the canal dimension increased in 14 (mean 1.35mm SD 0.82) and decreased in six. In the control group the canal dimension increased in 12 (mean 1.28mm SD 0.89). There was no significant difference between the two groups. It was concluded that the instability of the neural arch in patients with spondylolysis could not be detected using lumbar sonography.

The selection of scanning plane was considered to be one of the greatest potential sources of operator error. An experienced operator however, was able to repeatedly select a scanning plane in vivo with considerable accuracy (mean deviation 0.9mm SD 0.4).

CONCLUSIONS & SUGGESTIONS FOR FURTHER WORK.

The object of this thesis was to determine if diagnostic ultrasound could be used for the early detection of spondylolysis. The method was dependent on the accuracy of canal measurement using the method reported by Porter et al (1978a). The validity of the technique was subsequently debated and a number of further questions arose:

1. Was it possible for an ultrasound system to provide such accurate results?
2. How could the operator errors affect repeatability?
3. What were the origins of echoes from the structures within the canal from which measurements were taken?
4. Were the published figures for repeatability representative for the technique?

The precision of different ultrasound systems was found to vary, but providing suitable analogue equipment was used the accuracy of the equipment was more than adequate for the technique.

The main operator errors were considered to be the selection of the scanning plane across the canal

and the positioning of the caliper pips on the A and B-scans. It was shown that in vitro, echoes from the lamina and body could be simultaneously depicted with changes in scanning plane of up to 9mm. An experienced operator however, was able to select the scanning plane across the canal with a mean deviation of 0.9mm (SD 0.4). The selection of scanning plane therefore, was not considered to be a major source of error.

Echoes were found to come from both the bony and soft tissues of the lumbar spine, though it was found that the operator could accentuate or diminish echoes from these structures by making very small alterations to the scanning plane.

The figures for repeatability for the pilot study correlated well with the published accuracy at that time (Porter et al 1978a). These were subsequently revised (Hibbert 1982) and it was considered that their earlier results were subject to observer bias. The coefficients of variation found in this study, using realtime and compound scanners, were significantly larger than those published by Porter (1980) and Hibbert et al (1981) but slightly less than those published by Legg and Gibbs (1984).

Subsequent investigations to detect spondylolysis in children gave greater errors than the variations expected in an affected subject. The method was also unable to distinguish between an affected and an unaffected group, and thus it was concluded that pulse-echo ultrasound was unable to detect the instability of the neural arch associated with spondylolysis.

A feasibility study for computer control scanning of the spinal canal indicated that this method may be useful for in vivo scanning. This method may possibly reduce the errors associated with this technique and warrants further investigation.

Lumbar sonography will be of benefit in the analysis of the lumbar lordosis and the assessment of gross lumbar movement (appendix 1), conditions where the errors associated with the technique are small in relation to the variations expected.

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APPENDIX 1

Pulse-echo ultrasound will possibly be of benefit in identifying a number of conditions associated with low back pain and may be useful for the assessment of gross lumbar movement. More significant results will be obtained when the errors associated with the technique are small in relation to the variations expected.

LUMBAR SWAYBACK.

It has been concluded that the apophyseal joints of the lumbar spine resist a substantial percentage of the intervertebral compressive force whenever the normal lordosis is increased, and that this possibly leads to low back pain and facet degeneration (Adams and Hutton 1981). Lumbar sonography could be used to analyse the lumbar lordosis and select patients with increased compressive forces of the facet joints before the onset of symptoms (fig.38). Repeated analysis could be used to determine the effect of remedial exercises or any prescribed treatment.

LUMBAR MOVEMENT.

Gross lumbar movement can be assessed using lumbar sonography (fig.39). A number of goniometers

FIG 39. Sagittal sections of the lumbar spine
 (a) in flexion, (b) in extension.
 S = Sacrum, L = L3 body.

for measuring movement of the lumbar spine have been assessed (Reynolds 1975). They all however, rely on taking measurements from the surface anatomy of the patient rather than from the lumbar spine itself. The use of ultrasound to measure lumbar spinal movement certainly warrants further investigation.

LUMBAR CANAL STENOSIS.

The diagnosis of lumbar canal stenosis is usually based on myelography and more recently with computerized axial tomography (Asztely 1983) and diagnostic ultrasound (Porter et al 1978). The pulsations which were found to come from the soft tissues of the spinal canal (§ 4.2) are probably from the cerebrospinal fluid and/or dura. It is possible to demonstrate these pulsations, using a Doppler ultrasound technique, at each interlamina level of the lumbar spine in normal patients. A decrease in, or the absence, of these pulsations may indicate a relative or absolute canal stenosis and may prove to be a useful primary diagnostic tool.

LEG LENGTH INEQUALITY.

Leg length inequality is considered to be a potential cause of both back pain (Rush & Steiner 1946) and hip degeneration (Gofton & Trueman 1971).

Most non-radiological methods for measuring leg length have large errors (Hammond 1975). Pulse-echo ultrasound may be of use in measuring leg length and may possibly provide a preventative screening procedure.

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