■ SPINE

Scoliosis in patients with Friedreich's ataxia

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We reviewed 31 consecutive patients with Friedreich's ataxia and scoliosis. There were 24 males and seven females with a mean age at presentation of 15.5 years (8.6 to 30.8) and a mean curve of 51° (13° to 140°). A total of 12 patients had thoracic curvatures, 11 had thoracolumbar and eight had double thoracic/lumbar. Two patients had long thoracolumbar collapsing scoliosis with pelvic obliquity and four had hyperkyphosis. Left-sided thoracic curves in nine patients (45%) and increased thoracic kyphosis differentiated these deformities from adolescent idiopathic scoliosis. There were 17 patients who underwent a posterior instrumented spinal fusion at mean age of 13.35 years, which achieved and maintained good correction of the deformity. Post-operative complications included one death due to cardiorespiratory failure, one revision to address nonunion and four patients with proximal junctional kyphosis who did not need extension of the fusion. There were no neurological complications and no wound infections. The rate of progression of the scoliosis in children kept under simple observation and those treated with bracing was less for lumbar curves during bracing and similar for thoracic curves. The scoliosis progressed in seven of nine children initially treated with a brace who later required surgery. Two patients presented after skeletal maturity with balanced curves not requiring correction. Three patients with severe deformities who would benefit from corrective surgery had significant cardiac co-morbidities.

Friedreich's ataxia (FA) is the most common progressive spinocerebellar degenerative disorder characterised by ataxia and was first described by Nikolaus Friedreich in the late 19th century.¹ It is inherited by an autosomal recessive trait, although autosomal dominant inheritance patterns have also been described.² Linkage mapping techniques have identified the defective region to be on the long arm of chromosome 9 at 9q13-q21, within the *Frataxin* gene, with no evidence of genetic heterogeneity, and FA exhibits an accumulation of mitochondrial iron stores and free radical formation ultimately leading to cell death.³ A marked loss of large and a limited loss of small myelinated fibres in the peripheral nerves is observed. The severe loss of large myelinated fibres also affects the posterior columns of the spinal cord while the anterior horns and cranial motor nerves are preserved.

Scoliosis has a prevalence of 63% to 100% in patients with FA.^{2,4-8} Early reports may have confused FA with other similar ataxic syndromes prior to the development of strict diagnostic criteria,⁹ which is why previous studies have quoted a less than 100% prevalence of scoliosis. A study using DNA analysis to

establish the neurological diagnosis has reported a 63% prevalence of scoliosis,⁵ which may be due to DNA analysis identifying children with FA at an early stage of growth before they have developed a spinal deformity.

Information is limited regarding the natural history and treatment of scoliosis in patients with FA due to the rarity of the condition.^{4-8,10-12} The purpose of this study is to evaluate the demographics, progression of spinal deformity and the effect of bracing and surgical treatment in patients with FA.

Patients and Methods

Medical records and spinal radiographs of all patients with typical FA who presented in our scoliosis clinic between 1978 and 2008 were reviewed. The diagnosis was made by paediatric neurologists using the Geoffroy criteria.⁹ The medical records were analysed for the age of the patient, size and type of scoliosis at presentation, treatment and outcome. Serial spinal radiographs were measured using the Cobb method from the same anatomical landmarks.¹³ The site of the main curve was classified using the Scoliosis Research Society criteria¹⁴: cervicothoracic (apex C7-T1);

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Table I. Curvatures in the 31 patients with Friedreich's ataxia and scoliosis

Type of curvature (n, %)	
Thoracic	12
Left-sided	2 (17)
Right-sided	10 (83)
Thoracolumbar	11
Left-sided	7 (64)
Right-sided	4 (36)
Double major (thoracic/lumbar)	8
Left thoracic/right lumbar	7 (87.5)
Right thoracic/left lumbar	1 (12.5)

thoracic (apex between T2-T11); thoracolumbar (apex at T12 or L1); lumbar (apex between L2-L4); and lumbosacral (apex at L5 or caudal).

MRI of the whole spine was not performed in any patient. Management of the scoliosis included observation, bracing and surgical treatment with instrumented fusion.

Results

Over the 30-year period, 31 patients with FA and scoliosis were identified. There were 24 males and seven females. The mean age at presentation was 15.5 years (8.6 to 30.8) with mean curve size of 51° (13° to 140°). There were 12 thoracic, 11 thoracolumbar and eight double major (thoracic/lumbar) curves (Table I). Seven patients (22.6%) who presented at a mean age of 20 years (10.1 to 30.8) were wheelchair-dependent; two (6.5%) had a long C-shaped thoracolumbar collapsing scoliosis with marked associated pelvic obliquity. There was thoracic hyperkyphosis (> 50°) in four patients (12.9%).

Within this cohort we identified five distinct groups: 1) patients observed to skeletal maturity; 2) patients under brace treatment; 3) patients under surgical treatment; 4) patients unfit for scoliosis surgery; and 5) patients who presented at skeletal maturity.

Group 1: observation to skeletal maturity (seven patients, 22.6%). Seven patients (22.6%, all male) presented at a mean age of 14.7 years (12.9 to 17.4) with Risser grades¹⁵ between 0 and 4. They were followed for a mean of 26 months (12 to 34) to the end of spinal growth (Risser 5) but received no treatment; three patients had thoracic (two right, one left), three had left thoracic and right lumbar, and one a right thoracolumbar curve. The mean scoliosis at presentation was 41.2° (15° to 58°) in the thoracic curves, 40.6° (16° to 53°) for the lumbar, and 33° for the thoracolumbar curve. The mean scoliosis at maturity was 47° (25° to 59°) for the thoracic curves, 55.3° for the lumbar (30° to 68°), and 35° for the thoracolumbar curve. The mean scoliosis progression during observation was 5.84° (2.6°/year) for thoracic, 14.7° (6.7°/year) for lumbar, and 2° (2°/year) for thoracolumbar curves.

Group 2: brace treatment (nine patients, 29%). Five male and three female patients presented at a mean age of 10.9 years (8.6 to 15.1) with Risser grade 0 or 1. They were

braced for a mean of 40.1 months (12 to 132) using a custom-moulded Boston-type thoracolumbosacral orthosis; full-time wearing of the brace was recommended and compliance was good with no child discontinuing treatment due to poor brace tolerance. One male patient was treated in a brace until skeletal maturity (Risser 5) and discharged with small and balanced thoracic/lumbar curves. The remaining ninth patient was female with a left thoracic scoliosis measuring 27°. She had been treated since the age of 6.9 years in an underarm brace; 70 months after starting bracing her curvature measured 30° out of brace while she was still premenarchal at Risser grade 1.

The scoliosis progressed substantially in seven of the nine patients (77.8%), and they later underwent posterior spinal fusion.

Four patients had thoracolumbar (three left, one right), two had right thoracic, and two thoracic and lumbar curves (excluding the patient who is still under brace treatment). The mean scoliosis at the beginning of bracing was 37.2° (13° to 52°) for thoracolumbar, 36° (27° to 41°) for thoracic, and 39° (28° to 50°) for lumbar curves. The mean scoliosis at surgery or discharge was 55.75° (42° to 90°) for thoracolumbar, 43° (37° to 49°) for thoracic, and 46.5° (38° to 55°) for lumbar curves. The mean scoliosis progression during bracing was 18.55° (5.5°/year) for thoracolumbar, 7° (2°/year) for thoracic, and 7.5° (2.3°/year) for lumbar curves.

Group 3: surgical group (17 patients, 54.8%). There were twelve male and five female patients who underwent posterior instrumented spinal fusion; seven of these (41%) had previously been treated in a brace. The fusion extended from the upper thoracic (T2-T4) to the lumbar spine (L2-L5) in 16 patients depending on the extent of the curve and from T3 to the sacrum with pelvic fixation of the rods in one wheelchair-bound patient. Instrumentation used included Harrington rods in two, Luque rods in six (both Harrington and Luque rods now discontinued), hybrid construct (hooks/screws/wires) in six, and all-pedicle screw fixation in three patients (Figs 1 and 2). Locally harvested autologous bone was used and was supplemented by allograft bone (fresh-frozen femoral heads) at the levels of the instrumentation. Intra-operative spinal cord monitoring was not used and neurological integrity was assessed at completion of instrumentation with the Stagnara wake-up test.¹⁶ Post-operative spinal support through bracing/casting was used in patients who underwent fixation with Harrington rods. None of the patients had anterior spinal surgery.

The mean age at surgery was 13.4 years (9.1 to 16.9) with Risser grade 0 to 4. The mean post-operative follow-up was 4.5 years (0 to 7), excluding one patient who died following surgery, giving a minimum three-year follow-up at least to skeletal maturity (Risser grade 5). Eight patients had thoracolumbar (seven left, one right), six had right thoracic, and three left thoracic and right lumbar curves. The mean pre-operative scoliosis was 62.6° (42° to 93°) for thoracolumbar, 60.55° (40° to 116°) for thoracic, and 55°

Fig. 1a

Fig. 1b

Fig. 1c

Fig. 1d

Pre-operative posteroanterior (a) and lateral (b) radiographs of a female patient with a right thoracic scoliosis and associated increased thoracic kyphosis. The patient presented at age 11.1 years with a 40° thoracic curve and was braced for 26 months. Her scoliosis progressed despite brace treatment to 60°. Following posterior spinal fusion from T4-L2, correction of the scoliosis from 60° to 15° was achieved (c). Proximal junctional kyphosis developed above the fusion but this did not progress and no treatment was required (d) at latest follow-up 60 months after surgery.

Fig. 2a

Fig. 2b

Fig. 2c

Fig. 2d

Posteroanterior (a) and lateral (b) radiographs of a male patient with a severe left thoracolumbar scoliosis who presented at age 13.8 years. The patient underwent posterior spinal fusion from T3-L4, which corrected the scoliosis from 95° to 25° and achieved a balanced spine (c and d) at latest follow-up three years after surgery.

(42° to 68°) for lumbar curves. This was corrected to a mean of 21.3° (12° to 40°, 66%) for thoracolumbar, 31.2° (5° to 80°, 48.5%) for thoracic, and 24.3° (20° to 31°, 55.8%) for lumbar curves.

Complications. There was one post-operative death early in the series (in 1978), which occurred one week after surgery

due to cardiorespiratory failure; this was a female patient aged 9.1 years who had a severe right thoracic scoliosis measuring 116° treated with posterior fusion (T3-L3) using Harrington rods. The pre-operative assessment had indicated left ventricular dysfunction but she was considered fit for surgery. The only patient who underwent fusion

extending to the sacrum/pelvis with Luque rods due to severe pelvic obliquity developed nonunion at the thoracolumbar junction with breakage of the rods; revision posterior surgery involved a hybrid construct 18 months after the original procedure and he had a good outcome. There were no neurological complications and no wound infections in this group. Proximal junctional kyphosis occurred in four patients who were fused proximally to T4 (23.5%) but this was non-progressive and required no extension of the fusion. Two of these patients had Luque rods and two had a hybrid construct with proximal fixation using concave pedicle hook and convex pedicle and transverse process hooks in a claw configuration. The intraspinal ligaments were sacrificed in the patients with the Luque rods to facilitate placement of sublaminar wires which might have destabilised the upper thoracic spine and precipitated kyphosis. However, junctional deformity did not occur in any of the remaining eight children with Luque rods and hybrid constructs or among the three patients in whom pedicle screw constructs were used with the fusion extending proximally to T2 or T3.

Group 4: patients unfit for spinal surgery (3 patients, 9.7%). Three patients (9.7%, two male and one female) presented at a mean age of 22.6 years (15.1 to 28.3) with significant thoracolumbar (two patients) and thoracic (one patient) scoliosis measuring a mean of 84° (50° to 140°). One had an associated thoracic hyperkyphosis measuring 88° and one had pelvic obliquity measuring 40°. All three were considered unfit for surgery due to severe hypertrophic cardiomyopathy with associated marked left ventricular dysfunction.

Group 5: presentation at skeletal maturity (two patients, 6.4%). There were two male patients who presented at the age of 17.4 and 30.8 years, respectively, following completion of growth (Risser 5). One had a right thoracic curve measuring 58° and the other had a balanced left thoracic/right lumbar scoliosis measuring 37° and 35° respectively. Both patients had no spinal symptoms and received no treatment. They were observed for two years after presentation and their scoliosis progressed by only 2° and 3°, respectively.

Discussion

FA is a rare condition with an estimated prevalence of 0.13 to 4.7/100 000 in Western Europe.^{17,18} Males and females are equally affected. Children appear to have normal neurological function at birth and achieve normal developmental milestones. Initial findings include ataxia associated with weakness of the proximal muscles, particularly the gluteus maximus. The diagnosis is generally made in mid-childhood or early adolescence based upon clinical criteria defined by Geoffroy et al.⁹

Primary and secondary features required for diagnosis include the onset of symptoms before the age of 20 to 25 years, progressive ataxia, dysarthria, decreased proprioception and vibratory sense, absent knee and ankle reflexes, muscle weakness, extensor plantar responses, decreased upper limb motor nerve conduction velocity, absent

reflexes in the upper limbs, cavus foot deformities, scoliosis, cardiomyopathy in up to 90% of patients, optic atrophy and diabetes. The level of function gradually deteriorates with the patients becoming wheelchair-dependent by the second or third decades of life, at which time most patients die due to severe cardiomyopathy.¹⁹⁻²¹

Scoliosis develops within a few years of the onset of ataxia. Labelle et al⁴ reported a significant correlation between the progression of the scoliosis and the age at onset of the disease or age at recognition of scoliosis, with most curves that develop before puberty requiring surgical treatment. In contrast, they found no correlation between the progression of scoliosis and the degree of muscle weakness or ability to walk, type of curve with or without pelvic obliquity, age, gender, and duration of disease. The pattern of deformity is suggested to resemble adolescent idiopathic scoliosis (AIS).²² In our series, we recorded almost equal distribution of curves between single thoracic, thoracolumbar and double thoracic/lumbar with only two patients having long C-shaped collapsing scoliosis associated with pelvic obliquity, which is consistent with previous reports showing that 14% to 25% of patients with FA develop C-shaped thoracolumbar curves.^{4,7,12} Hyperkyphosis has also been described with a frequency of 24.5% to 66%,^{4,5,7} and was noted in four of our patients. The presence of increased thoracic kyphosis and left-sided thoracic curves, which are common in neuromuscular conditions and occurred in nine of our 20 patients with thoracic or double major curves (45%), as well as the male predominance (77%) differentiate scoliosis in FA from the typical lordoscoliosis seen mainly in females with AIS. Milbrandt et al⁵ reported that 22% of their patients with thoracic scoliosis had left-sided curves. The male predominance among our 31 patients has not been previously reported and we believe is due to the fact that we did not have access to the whole population of patients with FA in our area. Therefore, we are unable to draw conclusions in terms of a gender difference when it comes to prevalence of scoliosis. In addition, there were no confounding factors that could justify this gender discrepancy for a condition that genetically affects males and females in equal distribution nor for the increased rate of left-sided thoracic scoliosis, as our cohort represents an ethnically uniform population of patients seen as part of a National Health Service.

We did not perform MRI of the spine as previous series have not reported intraspinal anomalies that could contribute to the development of the scoliosis or affect surgical management.²³⁻²⁵ MR images of the cervical spinal cord have shown thinning of the cord and intramedullary changes indicating spinal atrophy in the cranial portion of the cord, consistent with degeneration of posterior and lateral white matter tracts in FA.²³⁻²⁴ Wessel et al²⁶ suggested that MRI exploration of the cranial spinal cord may be recommended as an additional diagnostic marker in FA.

Scoliosis in FA is not always progressive and in our series 29% of patients did not require treatment (Groups 1 and 5).

The diagnosis of ataxia before the age of ten years and the development of scoliosis before the age of 15 years has been associated with significant progression.⁴ Bracing has a limited role as it does not change the natural history of scoliosis, and progression of 11° per year has been reported during brace treatment.^{4,6-8} In our study, only one patient (12.5%) who was braced did not require surgical correction while a second patient is currently under review. Comparison of the rates of progression of scoliosis between Groups 1 and 2 showed less deterioration of lumbar curves during bracing and similar degrees of change for thoracic curves. Thoracolumbar scoliosis progressed more rapidly despite bracing when compared with the one child under observation (age at presentation 14.9 years) probably because the patients in Group 2 were younger and prepubertal (mean age at presentation 9.8 years) with more remaining growth. Bracing in our series did not affect the prognosis of the deformity or prevent the need for surgical treatment. A few patients presented after completion of growth with balanced curves and did not require surgical treatment (Group 5). In addition, some patients with severe deformities who would benefit from surgery often had cardiac co-morbidities which precluded surgery (Group 4).

Surgical treatment has been indicated for curves > 60° or curves 40° to 60° in patients with early-onset disease and progressive scoliosis.⁴ Pre-operative assessment should include cardiac and respiratory tests as these patients suffer from cardiomyopathy and often have restrictive lung disease.²⁷ Severe hypertrophic cardiomyopathy and left ventricular dysfunction, especially if this is poorly controlled with medication, may be considered a contraindication for corrective surgery. Fusion to the sacrum/pelvis is not needed except for long thoracolumbar curves with marked pelvic obliquity and this occurred in only one of our patients. Intra-operative spinal cord monitoring might be possible, recording motor evoked potentials as the somatosensory evoked potentials are usually markedly reduced or absent.^{4,5,28} In this series, we tried intra-operative spinal cord monitoring, recording cortical, epidural and cervical somatosensory potentials, which were inconsistent and poorly reproducible. We are currently attempting to record motor evoked potentials, which have been present and reliable in some but not all of our patients. Correction of deformity by 33% and 41% has been reported^{6,8}; our mean correction of 48.5% to 66% depending on the type of curve, and achieved following a posterior fusion, compares favourably to those results. Our complications included one early post-operative death due to cardiomyopathy and one nonunion requiring revision surgery but no re-operations for progressive junctional kyphosis, which occurred in four of our patients. Proximal junctional kyphosis developed in patients who were fused proximally to T4 but in no patient in whom the fusion extended more cephalad. We, therefore, recommend that instrumented fusion is to T2/T3, as patients with FA are at high risk for developing a junctional kyphotic deformity probably due to inherent poor muscular control.

We applied post-operative braces or casts only to patients early in the series in whom Harrington rods were used. Using hybrid and all-pedicle screw constructs, adequate stability can be maintained without the need for post-operative support. Modern segmental spinal instrumentation allows for better correction and would limit the need for anterior surgery which is associated with increased morbidity and potential mortality.

In conclusion, patients with FA who have scoliosis can have a variable prognosis with patterns of spinal deformity distinct from those of AIS. Long thoracolumbar collapsing scoliosis with pelvic obliquity is not common in contrast to other neuromuscular conditions. Progression is likely to occur in children with early onset of disease and early development of deformity. In our experience, almost one third of patients have non-progressive or slowly progressive curves and they do not require surgical treatment. Bracing has been generally unsuccessful in controlling the deformity and is of limited value, but it may be used in very young and compliant patients in order to slow down progression of the scoliosis and delay surgical correction. Posterior spinal fusion has achieved and maintained satisfactory correction of the deformity with a relatively low rate of complications and re-operations. The presence of cardiomyopathy and respiratory compromise will determine life expectancy, as well as the patients' suitability for surgery. The decision to operate should be made on an individual basis taking into account the severity of the deformity, the severity of the symptoms, the risk of progression, as well as the possible adverse effect that a long spinal fusion could have on the patients' mobility in the presence of ataxia causing disturbance of balance, gait and posture.

Supplementary material

A table detailing the demographic data and results of each of the 31 patients is available with the electronic version of this article on our website www.jbjs.boneand-joint.org.uk

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References

1. **Friedreich N.** Ueber degenerative atrophie der spinalen Hinterstränge. *Virchows Arch Pathol Anat* 1863;26:391-419 (in German).
2. **Shapiro F, Bresnan MJ.** Orthopaedic management of childhood neuromuscular disease. Part II: peripheral neuropathies, Friedreich's ataxia, and arthrogryposis multiplex congenita. *J Bone Joint Surg [Am]* 1982;64-A:949-953.
3. **Alper G, Narayanan V.** Friedreich's ataxia. *Pediatr Neurol* 2003;28:335-341.
4. **Labelle H, Tohmé S, Duhaime M, Allard P.** The natural history of scoliosis in Friedreich's ataxia. *J Bone Joint Surg [Am]* 1986;68-A:564-572.
5. **Milbrandt TA, Kunes JR, Karol LA.** Friedreich's ataxia and scoliosis: the experience at two institutions. *J Pediatr Orthop* 2008;28:234-238.
6. **Cady RB, Bobechko WP.** Incidence, natural history, and treatment of scoliosis in Friedreich's ataxia. *J Pediatr Orthop* 1984;4:673-676.
7. **Daher YH, Lonstein JE, Winter RB, Bradford DS.** Spinal deformities in patients with Friedreich's ataxia: a review of 19 patients. *J Pediatr Orthop* 1985;5:553-557.

8. Hensinger RN, MacEwen GD. Spinal deformity in heritable neurological conditions: spinal muscular atrophy, Friedreich's ataxia, familial dysautonomia and Charcot-Marie-Tooth disease. *J Bone Joint Surg [Am]* 1976;58-A:13-24.
9. Geoffroy G, Barbeau A, Breton G, et al. Clinical description and roentgenologic evaluation of patients with Friedreich's ataxia. *Can J Neurol Sci* 1976;3:279-286.
10. Allard P, Dansereau J, Thiry PS, et al. Scoliosis in Friedreich's ataxia. *Can J Neurol Sci* 1982;9:105-111.
11. Allard P, Dansereau J, Duhaime M, Geoffroy G. Scoliosis assessment in Friedreich's ataxia by means of intrinsic parameters. *Can J Neurol Sci* 1984;11(Suppl):582-587.
12. Labelle H, Fossier F. Scoliosis and Friedreich's ataxia: update. *Rachis* 1991;3:423-426 (in French).
13. Cobb JR. Outline for the study of scoliosis. In: American Academy of Orthopaedic Surgeons, ed. *Instructional course lectures*. Ann Arbor: JW Edwards, 1948:261-275.
14. No authors listed. The Terminology Committee of the Scoliosis Research Society: a glossary of scoliosis terms. *Spine (Phila Pa 1976)* 1976;1:57-58.
15. Risser JC. The iliac apophysis: an invaluable sign in the management of scoliosis. *Clin Orthop Relat Res* 1958;11:111-119.
16. Vauzelle C, Stagnara P, Jouvinroux P. Functional monitoring of spinal cord activity during spinal surgery. *Clin Orthop Relat Res* 1973;93:173-178.
17. Juvonen V, Kulmala SM, Ignatius J, Penttinen M, Savontaus ML. Dissecting the epidemiology of a trinucleotide repeat disease: example of FRDA in Finland. *Hum Genet* 2002;110:36-40.
18. Polo JM, Calleja J, Combarros O, Berciano J. Hereditary ataxias and paraplegias in Cantabria, Spain: an epidemiological and clinical study. *Brain* 1991;114:855-66.
19. Hewer RL. Study of fatal cases of Friedreich's ataxia. *Br Med J* 1968;3:649-652.
20. Johnson WG. Friedreich ataxia. *Clin Neurosci* 1995;3:33-38.
21. De Michele G, Di Maio L, Filla A, et al. Childhood onset of Friedreich ataxia: a clinical and genetic study of 36 cases. *Neuropediatrics* 1996;27:3-7.
22. Aronsson DD, Stokes IA, Ronchetti PJ, Labelle HB. Comparison of curve shape between children with cerebral palsy, Friedreich's ataxia, and adolescent idiopathic scoliosis. *Dev Med Child Neurol* 1994;36:412-418.
23. Mascalchi M, Salvi F, Piacentini S, Bartolozzi C. Friedreich's ataxia: MR findings involving the cervical portion of the spinal cord. *AJR Am J Roentgenol* 1994;163:187-191.
24. Wüllner U, Klockgether T, Petersen D, Naegel T, Dichgans J. Magnetic resonance imaging in hereditary and idiopathic ataxia. *Neurology* 1993;43:318-325.
25. DeMichele G, DiSalle F, Filla A, et al. Magnetic resonance imaging in "typical" and "late onset" Friedreich's disease and early onset cerebellar ataxia with retained tendon reflexes. *Ital J Neurol Sci* 1995;16:303-308.
26. Wessel K, Schroth G, Diener HC, Müller-Forell W, Dichgans J. Significance of MRI-confirmed atrophy of the cranial spinal cord in Friedreich's ataxia. *Eur Arch Psychiatry Neurol Sci* 1989;238:225-230.
27. Bureau MA, Ngassam P, Lemieux B, Trias A. Pulmonary function studies in Friedreich's ataxia. *Can J Neurol Sci* 1976;3:343-346.
28. Pelosi L, Lamb J, Grevitt M, et al. Combined monitoring of motor and somatosensory evoked potentials in orthopaedic spinal surgery. *Clin Neurophysiol* 2001;113:1082-1091.