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ORIGINAL ARTICLE

Outcome of L5 radiculopathy after reduction and instrumented transforaminal lumbar interbody fusion of high-grade L5–S1 isthmic spondylolisthesis and the role of intraoperative neurophysiological monitoring

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Abstract
Purpose To evaluate the incidence and course of iatrogenic L5 radiculopathy after reduction and instrumented fusion of high-grade L5–S1 isthmic spondylolisthesis and the role of intraoperative neurophysiological monitoring (IONM).
Methods Consecutive patients treated for high-grade spondylolisthesis with IONM from 2005 to 2013 were screened for eligibility. Prospectively collected clinical and surgical data as well as radiographic outcomes were analyzed retrospectively. Patients completed the multidimensional Core Outcome Measures Index (COMI) before and at 3, 12, and 24 months after surgery.
Results Seventeen patients were included, with a mean age of 26.3 (±9.5) years. Mean preoperative L5–S1 slip was 72% (±21%) and was reduced to 19% (±13%) postoperatively. Mean loss of reduction at last follow-up [mean 19 months (±14, range 3–48 months)] was 3% (±4.3%). Rate of new L5 radiculopathy with motor deficit (L5MD) after surgery was 29% (five patients). Four patients fully recovered after 3 months, one patient was lost to neurologic follow-up. IONM sensitivity and specificity for postoperative L5MD was 20 and 100%, respectively. COMI, back pain and leg pain scores showed significant ($p < 0.001$) improvements at 3 months postoperatively, which were retained up to 24 months postoperatively.
Conclusions Transient L5 radiculopathy after reduction and instrumented fusion of high-grade spondylolisthesis is frequent. With IONM the risk of irreversible L5 radiculopathy is minimal. If IONM signal changes recover, full clinical recovery is expected within 3 months. Overall, patient-reported outcome of reduction and instrumented fusion of high-grade spondylolisthesis showed clinically important improvement.

Keywords Spondylolisthesis · Intraoperative neurophysiological monitoring · Lumbar fusion · Complication · Patient-rated outcome

Introduction

Surgery remains the treatment of choice for patients with high-grade L5–S1 isthmic spondylolisthesis who have persistent low back pain and radicular pain refractory to multimodal conservative therapy, marked slip progression or neurologic impairment [1]. The literature reports a wide spectrum of recommended surgical techniques for these challenging deformities, such as uninstrumented anterior [2–5], posterior or posterolateral in situ fusion [2, 6–12], combined approaches with in situ fusion [13] or posterior pedicle screw reduction [3, 4, 14–19]. There is, however, a paucity of high-quality evidence pertaining to the optimal surgical management of high-grade spondylolisthesis [20]. With all operative methods, complications are common and comprise pseudarthrosis, slip progression and neurologic injury presenting as L5 radiculopathy with moderate to severe palsies and sacral root dysfunction [21]. The

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reported rates of clinically evident neurologic complications associated with slip reduction essentially range from 0 to 45% [22–26]. Little is known about the clinical course and outcome of iatrogenic L5 radiculopathy after instrumented reduction of high-grade spondylolisthesis and to the best of the authors' knowledge no detailed and quantitative reports have been published to date.

Intraoperative neurophysiological monitoring (IONM) is well established and widely used during spine surgery, allowing real-time monitoring of nerve function and alerting the surgeon to impending nerve root damage [27–29]. The precise role of IONM during surgery for high-grade spondylolisthesis, especially during reduction, and its impact on the incidence of postoperative L5 radiculopathy, has scarcely been examined. In our experience, L5 nerve root palsy with foot drop may occur instantly or with some delay after instrumented reduction of high-grade spondylolisthesis, even in cases with uneventful IONM.

In this article, we describe the incidence and clinical course of new-onset L5 radiculopathy in a series of patients who had undergone reduction and instrumented fusion for high-grade spondylolisthesis. Secondly, we analyze the role of IONM and its impact on iatrogenic L5 radiculopathy.

Materials and methods

Inclusion criteria

We conducted a retrospective single-center study that analyzed prospectively collected data. Consecutive patients who had been operated on with transpedicular screw placement for high-grade L5–S1 isthmic spondylolisthesis at our Spine Center from 2005 to 2013 were screened for study eligibility (Fig. 1). Patients with a history of prior spinal surgery at the L5–S1 level were excluded.

Imaging studies

Standing anteroposterior and lateral radiographs of the lumbar spine were routinely obtained preoperatively, postoperatively and at each follow-up visit. In addition, flexion and extension radiographs, and magnetic resonance imaging of the lumbar spine were carried out before surgery. If indicated, based on the surgeon's judgment, computed tomography (CT) was also ordered. Spinopelvic parameters such as the pelvic and L5 incidence were measured on lateral radiographs of the lumbar spine. For grading we used the Meyerding classification of spondylolisthesis [30]; accordingly, grade 3 or a slip of 50% or greater was considered a high-grade deformity. The degree of spondylolisthesis was determined using standing lateral radiographs of the lumbar spine.

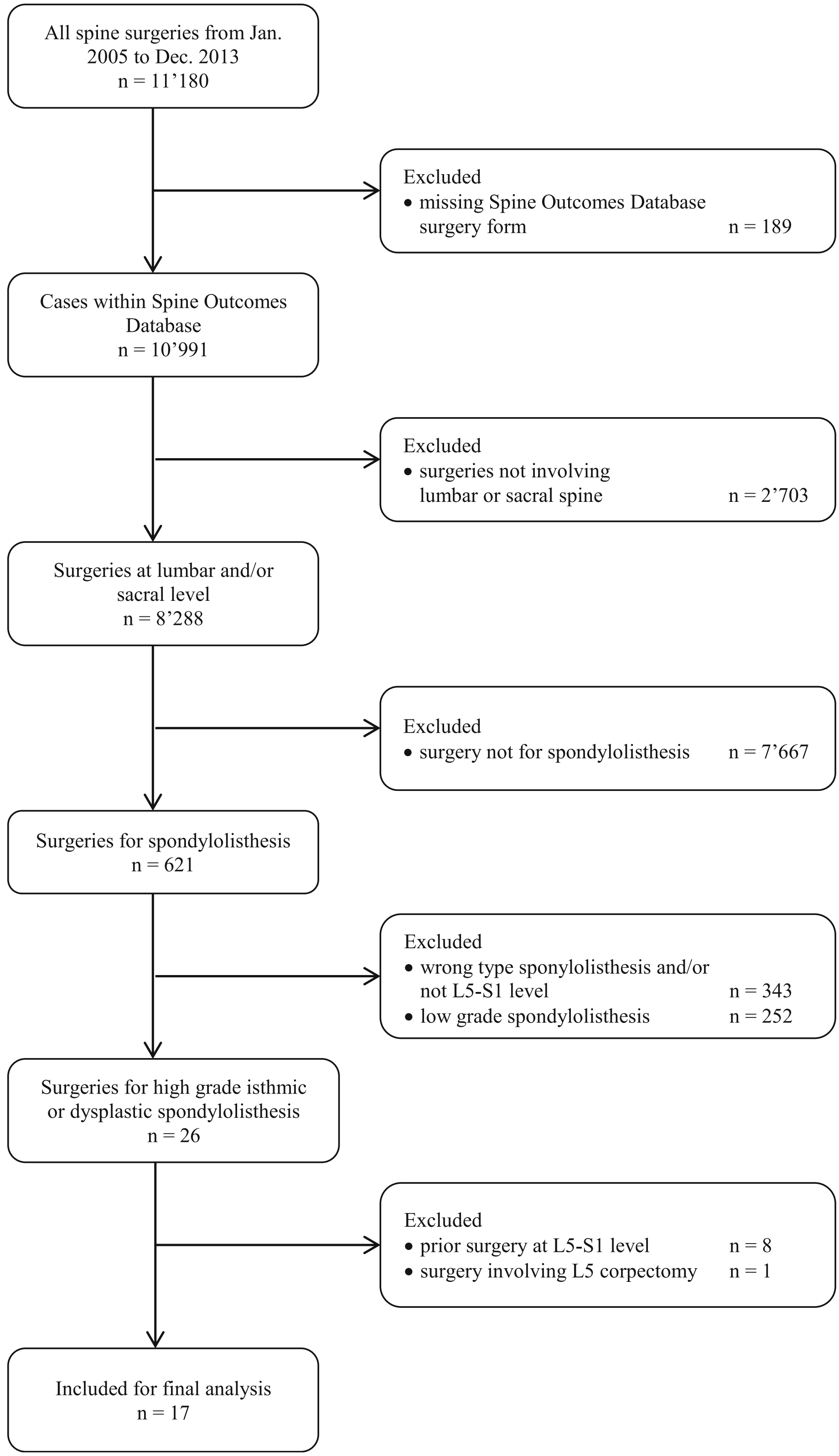
Data acquisition system and patient-orientated questionnaires

Clinical, surgical and radiologic data on all spine surgery cases are documented prospectively in our Spine Center using a customized, in-house database linked to the EUROSPINE Spine Tango registry system (http://www.eurospine.org/spine-tango.htm) [31]. The relevant data extracted from the database were verified or completed by cross-checking with data in our local medical information and documentation system. The Spine Tango surgical documentation form, which was completed by the surgeon at each stage from admission through to discharge, contains questions about pathology, previous treatment, patient morbidity status, surgical details, and surgical complications. Patients were requested to complete a questionnaire before and at 3, 12 and 24 months after surgery. This form contained the multidimensional Core Outcome Measures Index (COMI) [32, 33]. The COMI comprises a series of questions covering the domains of pain [back and leg/buttock pain intensity, each measured separately on a 0–10 graphic rating scale (GRS)], and function, symptom-specific well-being, general quality of life, social disability, and work disability (each on a 5-point scale). The preoperative questionnaire was sent to the patient at home, and they were asked to complete it and hand it in during admission. The follow-up questionnaires were sent out by and returned to the hospital's research unit by post.

Materials for intraoperative neurophysiological monitoring

For IONM, Keypoint® 8-channel workstations (Dantec Keypoint® Focus system, Natus Medical Inc., CA, USA) were used with integrated electrical stimulators and custom software. Neuroline 720 surface electrodes (Ambu A/S, Ballerup, Denmark) were used for the stimulation of peripheral nerves for obtaining somatosensory evoked potentials (SEP) and recording of compound muscle action potentials for motor evoked potentials (MEP), triggered electromyography (EMG) and EMGs. For transcranial motor stimulation and the recording of cortical SEP, Dantec monopolar needle electrodes were placed at C3′ and C4′ according to the international EEG 10-20 System. The placement of stimulating and recording electrodes and extension cables was carried out during the induction of anesthesia. This prolonged the pre-surgical procedure by 5–15 min.

Fig. 1 Flow diagram of patients included



Anesthesia protocol

Total intravenous anesthesia by propofol (4–8 mg/kg/h) and remifentanil (0.3–0.8 µg/kg/min) was used. Muscle relaxants were only used for intubation.

Method and principles of intraoperative neurophysiological monitoring

The IONM methods have been described previously [34]. All monitoring was performed by two experienced neurologists with clinical experience in neurophysiology and IONM (MS, AE). Transcranial electrical (tce) MEP were evoked by 100–200 mA with a train of five single stimuli of 0.5 ms duration and a 2.5 ms interstimulus interval. The compound muscle potentials of five trains repeated at 1 Hz were averaged and used for diagnostic analysis. Pedicle screw stimulation was carried out using a single stimulus of 0.5 ms duration, repeated at 5.9 Hz, and gradually increased from 0 mA to threshold values, with a maximum of 30 mA. M. abductor digiti minimi (input control), vastus medialis (L4/plexus), M. tibialis anterior or M. peroneus longus (L5) and M. abductor hallucis (S1) were recorded for tceMEP, tMEP and EMG. L5-Dermatome SEPs involved stimulation of the distal plantar medial nerve or peroneal nerve. IONM alerts were defined as a reduction of tceMEP or SEP amplitudes greater than 50%, neurogenic discharge in EMG for more than 10 s and threshold values of pedicle screws less than 5 mA. All of these IONM alerts were communicated and discussed immediately with the surgeon and recorded in a database. Amplitudes in single muscles that were reduced by less than 50% at the end of surgery were not expected to be significant in predicting postoperative clinical findings.

True positive cases were considered to be those in which IONM was able to correctly identify a postoperative new or aggravated neurologic deficit. False positive cases were those where IONM incorrectly predicted a neurologic complication. True negative cases were those where IONM correctly predicted no neurologic complication and false negative cases, those where IONM did not identify any postoperative new or aggravated neurologic deficit.

Surgical technique

The surgical techniques used are shown in Table 1. All patients underwent posterior lumbosacral fusion with transpedicular instrumentation and rod fixation. Reduction was performed in all patients. In 14 patients, surgery included a complete discectomy and interbody fusion at the L5–S1 segment by a transforaminal lumbar interbody fusion (TLIF) technique [35]. Accordingly, a total facetectomy was performed by removing the inferior and superior facet and thereby creating an open foraminotomy and decompression of the exiting L5 nerve root. Excessive fibrocartilaginous tissue at the pars interarticularis defect was removed as required for nerve root decompression. In our series usually a bilateral TLIF approach with visualization and decompression of the L5 nerve root was performed. If necessary for anterior support either a unilateral TLIF cage or two Harms cages were inserted bilaterally into the disc space (Fig. 2). Both the disc space and the cage were filled with autologous bone graft after thoroughly removing the intervertebral disc. Posterior instrumentation alone without the use of an interbody cage was used in three patients. In all patients, autologous bone graft was locally procured at the decompression site and, depending on the surgeon's judgment, also from the iliac crest for intervertebral fusion.

Clinical and radiographic follow-up and definition of neurologic complication (injury)

All patients were routinely followed up clinically and radiologically with standing anteroposterior and lateral plain radiograph films at 6 weeks, 3 months, and 1 year postoperatively. Depending on the surgeon and/or the patients, follow-up continued at 1-year intervals.

A neurologic complication was defined as any new sensorimotor deficit or worsening of a pre-existing deficit that occurred after surgery, and was either of a transient or permanent nature. A neurologist carried out the final clinical evaluation. Neurologic motor deficits were quantified using the Medical Research Council (MRC) scale for muscle strength, grading the patient's output on a scale of 0/5–5/5 [36]. A mild motor deficit was defined as a paresis of 4/5, a moderate deficit as a paresis of 3/5 and a severe deficit as 2/5 or worse. An L5 motor deficit was identified clinically as a muscle weakness of the tibialis anterior (TA) and or extensor hallucis longus (EHL) muscle.

Statistical analysis

Descriptive data are presented as mean ± standard deviation (SD). The significance of any differences for the proportions of two nominal variables was analyzed using Fisher's exact test of independence. For comparing the difference in COMI, back pain, and leg pain over time in groups with and without postoperative L5 radiculopathy, two-way repeated measures analyses of variance were used (ANOVA), with one between factor (group) and one within factor (time of assessment). Where data were missing for a given follow-up time, but available for another (either

Table 1 Surgical techniques, complications and revisions

No.	Sex	Age (years)	Grade	Instrumentation	Technique	Complication	Revision
1	F	30.5	4	L4–S1	Cage L4/5 and L5/S1		No
2	M	15.2	3	L5–S1	Cage L5/S1, temp. L4 screws intraop.		No
3	F	20.1	5	L4–S1	No cage, temp. L3 screws intraop.; L4/5 release after 6 months	Moderate L5MD	No
4	F	14.0	4	L5–S1	No cage, temp. L4 screws intraop.	Moderate L5MD	No
5	F	26.4	5	L5–S1	No cage, temp. L4 screws intraop.		No
6	F	41.3	3	L5–S1	Cage L5/S1, temp. L4 screws intraop.		No
7	F	19.7	4	L5–S1	Cage L5/S1; L4/5 release	Pedicle fracture with implant failure	Lengthening L4–S2 after 6 days; removal of S2 screws after 6 months
8	F	38.3	3	L5–S1	Cage L5/S1, HWR after 17 months	Mild L5MD	No
9	F	21.8	4	L4–S1	Cage L5/S1; L4/5 release after 7 months		No
10	F	26.9	3	L4–S1	Cage L5/S1; L4/5 release after 6 months, HWR after 31 months	Mild L5MD	No
11	F	22.8	3	L5–S1	Cage L5/S1, temp. L4 screws intraop.		No
12	F	39.4	3	L4–S1	Cage L5/S1; L4/5 release after 11 months	Implant failure: S1 screw fracture and pseudarthrosis	Exchange of screws after 21 months
13	M	34.6	3	L4–S1	Cage L5/S1; L4/5 release after 8 months		No
14	F	38.5	3	L5–S1	Cage L5/S1, temp. L4 screws intraop.	Mild L5MD	No
15	M	28.1	4	L4–S1	Cage L4/5 and L5/S1		No
16	F	14.3	3	L5–S1	Cage L5/S1		No
17	M	15.2	3	L5–S1	Cage L5/S1, temp. L4 screws intraop.		No

F female, *HWR* hardware removal, *L5MD* L5 nerve root motor deficit, *M* male, *w* weeks

before or after it), the value from the available follow-up was used; where multiple alternatives were available (e.g., 12-month follow-up missing, but 3 and 24 months available) the worse of the two values (i.e., 3 or 24 months) was used. A reduction in COMI score of at least 2.2 points was set to indicate minimal clinically important difference for individual improvement [32]. Statistical significance was defined at a p value <0.05.

Results

A total of 17 patients (13 women, 4 men) were included in the study. The average age at time of the index surgery was 26.3 years (SD ± 9.5, range 14–41 years).

Radiologic findings

Table 2 shows preoperative and postoperative radiologic findings on standing lateral radiographs of the lumbosacral spine. Reduction of the spondylolisthesis was performed in all patients with a mean absolute slip reduction of 54% (±17, range 27–99%) with minor loss of reduction at the last radiologic follow-up. The mean radiologic follow-up was 19 months (±14, range 3–48 months). One patient was lost to radiologic follow-up after 3 months.

Intraoperative neurophysiological monitoring

Clinical and IONM findings are shown in Table 3. A total of 25 intraoperative IONM alerts occurred in 15 out of 17

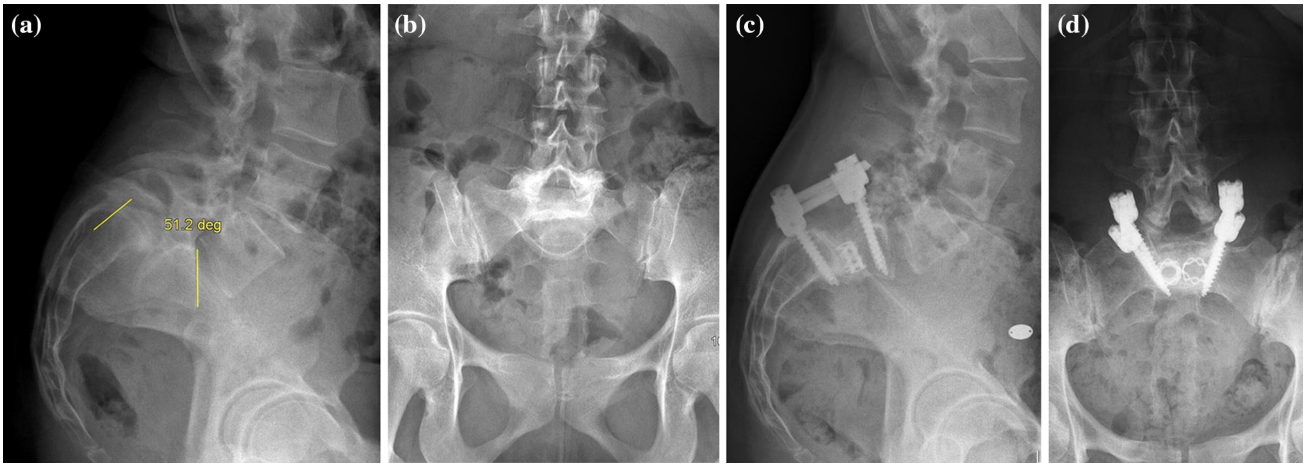


Fig. 2 Lumbar spine radiograph series of a 21-year-old female patient with grade 4 L5–S1 spondylolisthesis. Preoperative lateral (a) and anteroposterior (b) radiographs demonstrating severe slip and segmental kyphosis. Postoperative lateral (c) and anteroposterior (d) radiographs with partial slip reduction with pedicle screws and anterior support with two Harms cages

Table 2 Radiological findings on standing lateral X-ray films

No.	Sex	Age (years)	Grade	Preoperative			Postoperative		
				Slip (%)	PI	L5I	Slip (%)	ASR (%)	Slip last FU (%)
1	F	30.5	4	81	90	77	34	47	34
2	M	15.2	3	57	83	62	5	52	5
3	F	20.1	5	121	75	96	22	99	22
4	F	14.0	4	70	77	61	19	51	19
5	F	26.4	5	117	75	126	48	69	58
6	F	41.3	3	51	77	51	18	33	20
7	F	19.7	4	88	81	85	18	70	33
8	F	38.3	3	66	84	64	17	49	19
9	F	21.8	4	80	92	116	23	57	29
10	F	26.9	3	67	90	77	16	51	21
11	F	22.8	3	61	101	69	2	59	4
12	F	39.4	3	65	90	70	2	63	7
13	M	34.6	3	54	92	65	11	43	13
14	F	38.5	3	60	87	57	3	57	7
15	M	28.1	4	87	93	83	36	51	33
16	F	14.3	3	51	78	59	24	27	25
17	M	15.2	3	53	88	86	20	33	21
Mean		26.3	3.5	72	85	77	19	54	22
SD		9.5	0.7	21	8	21	13	17	13

ASR absolute slip reduction, *FU* follow-up, *L5I* L5 incidence, *PI* pelvic incidence, *SD* standard deviation

index surgeries (88.2%). Surgical actions triggering IONM alerts were screw placement, distraction, decompression and reduction (Table 3). In response to these alerts the surgeon changed the positioning of pedicle screws, reduced segmental distraction, performed additional foraminal decompression, or reduced the amount of reduction.

Based on partial or complete recovery of IONM signal changes which triggered an IONM alert by the end of surgery, one new neurologic deficit was correctly predicted intraoperatively in one patient (true positive IONM prediction). This patient had a postoperative tibialis anterior muscle (TA) and extensor hallucis longus muscle (EHL) 3/5 paresis on the left side. Four additional patients with IONM alerts and only partial recovery of the signals had postoperative L5 motor deficits that were not predicted (false negative IONM prediction). Based on early postoperative clinical findings, the IONM prediction had a sensitivity of 20% and specificity of 100%. With recovery of

Table 3 Pre- and post-operative neurologic and MIOM findings

No.	Sex	Age (years)	Grade	Preoperative		Surgical action triggering IONM alerts				Postoperative L5 nerve root motor deficit			
				RP	L5MD	CMEP	sMEP	EMG	SEP	Postop.	Postop. 6 weeks	Postop. 3 months	Postop. 12 months
1	F	30.5	4	No	No	1 Di	–	–	–	No	–	–	–
2	M	15.2	3	No	No	1 S	–	–	–	No	–	–	–
3	F	20.1	5	No	No	–	–	1 R	–	Moderate	No FU	–	–
4	F	14.0	4	No	No	2 R	–	–	–	Moderate	Mild	No	–
5	F	26.4	5	No	No	–	–	1 R	–	No	–	–	–
6	F	41.3	3	Yes, L	Mild	–	–	1 S	–	No	–	–	–
7	F	19.7	4	Yes, L + R	No	–	1 S	–	–	No	–	–	–
8	F	38.3	3	No	No	1 Di	–	–	–	Mild	Mild	No	–
9	F	21.8	4	Yes, R	No	–	–	1 De	–	No	–	–	–
10	F	26.9	3	Yes, L > R	No	–	2 S	1 De	–	Mild	No	–	–
11	F	22.8	3	Yes, L	No	–	–	–	–	No	–	–	–
12	F	39.4	3	No	No	–	2 S	1 Di	–	No	–	–	–
13	M	34.6	3	No	No	–	–	–	–	No	–	–	–
14	F	38.5	3	Yes, L	No	1 R	1 S	–	–	Mild	No	–	–
15	M	28.1	4	Yes, L < R	No	2 Di	–	1 Di	–	No	–	–	–
16	F	14.3	3	Yes, L	Mild	1 Di, 1 R	1 S	–	–	No	–	–	–
17	M	15.2	3	No	No	–	–	1 R	–	No	–	–	–

cMEP cortical motor evoked potential, *De* decompression, *Di* distraction, *F* female, *FU* follow-up, *L* left, *M* male, *m* months, *R* right, *sMEP* spinal motor evoked potential, *R* reduction, *RP* radicular pain, *S* screw placement

all deficits after 3 months, the IONM had 100% specificity. The patient with the true positive prediction was lost to follow-up, and thus no sensitivity could be calculated.

We did not see any diagnostic value of dermatomal SEP monitoring for L5 radiculopathy with stimulation of the plantar medial nerve and cortical recording.

Association between new-onset postoperative L5 motor deficit and slip reduction

There was a tendency for greater deformity and greater slip reduction in those patients who developed postoperative L5 radiculopathy, but the differences were not statistically significant. Mean preoperative slip of patients with new L5MD after surgery was 77% (±25%) compared to a mean slip of 70% (±30%) in patients without L5MD ($p = 0.59$). Absolute slip reduction was 61% (±21%) and 50% (±15%) ($p = 0.22$), respectively.

Clinical findings and L5 radiculopathy

The main presenting symptom before surgery in all patients (100%) was chronic low back pain refractory to conservative treatment, in most cases for many years. Additionally, eight patients (44%) complained of accompanying L5 radicular pain in one leg (five patients) or both legs (three patients). Preoperatively, mild L5 motor deficits were detected in two patients (11%) (Table 3).

Postoperatively, both patients with mild pre-existing L5 motor deficits had normal neurologic findings. However, new-onset L5 motor deficits were noted in 5 of 17 patients (29.4%) after surgery. These deficits were mild in three and moderate in two of the patients. Postoperative imaging with radiographs and CT excluded malposition of the pedicle screws. The 3 patients (No. 8, 10 and 14) with mild new-onset L5 motor deficits all had grade 3 spondylolisthesis. They developed MRC grade 4 paresis of TA or EHL function. Full recovery was noted in all patients either at their first or second follow-up visit at 6 weeks (one patient) or at 3 months (two patients). The first case of moderate L5MD (No. 3) was seen in a 20-year-old woman without any pre-existing paresis with L5–S1 spondyloptosis. She developed a new MRC grade 3/5 paresis of the TA and a grade 4/5 paresis of the EHL muscle on the left. Since she was a foreign patient living abroad, no clinical follow-up data were available beyond discharge 9 days after surgery. The second patient (No. 4) with new-onset L5MD postoperatively was a 14-year-old girl operated on for a grade 4 spondylolisthesis who developed MRC grade 3 paresis of the EHL muscle on the left postoperatively. However, full neurologic recovery was recorded upon her second clinical follow-up visit at 4 months.

With the exception of the 1 patient (No. 3) lost to clinical follow-up, none of the 16 patients who attended clinical follow-up visits suffered a permanent L5 motor deficit. The four patients with postoperative de novo L5 motor deficits who were clinically followed up had full neurologic recovery after a mean period of 12 weeks.

New-onset postoperative radiculopathy without motor deficits developed in two female patients. One patient (No. 9, age 21 years at index surgery) complained of persistent paraesthesia in the L5 dermatome dominant in the right leg. This sensation faded over time and was significantly better at 3-month follow-up and shifted to a slight hypaesthesia on the lateral calf on the right after 1 year. The second patient (No. 12, age 39 years) suffered from postoperative pain in the left leg. This pain subsided only gradually after release of the L4–5 segment 11 months after the index surgery. At the 2-year follow-up the pain had further decreased.

Patient-rated outcome

Over the course of the study, questionnaires were missing for three patients (one patient each at 3, 12 months' and 2 years' follow-up). The course of change in COMI, back pain and leg pain scores over time is shown in Fig. 3. Compared with preoperative values, the whole group showed significant ($p < 0.001$) improvements in all scores at 3 months postoperatively, which were maintained up to 24 months postoperatively, with no significant differences ($p > 0.21$) between the groups (those with and without new postoperative L5 motor deficits) for the pattern of change over time. The reduction in COMI score up to 24 months after surgery also surpassed the minimal clinically important difference in both groups. Three of four patients with preoperative leg pain and who had postoperative L5 radiculopathy with a motor deficit reported little or no improvement in leg pain by 3 months. At 1-year follow-up leg pain had considerably reduced in all but one patient (No. 10).

Surgical complications and revision surgery

Surgical revision was required in 2 cases (11.7%) (Table 1). The first (No. 7) was a grade 4 slip in a 19-year-old female patient who had reduction and fusion of L5–S1 with placement of an interbody cage. She suffered an L5 pedicle fracture with loosening of the screws and radicular pain in the left leg. Revision and lengthening of the instrumentation to L4 was performed on the sixth day after the index surgery. In the second case, a 39-year-old female

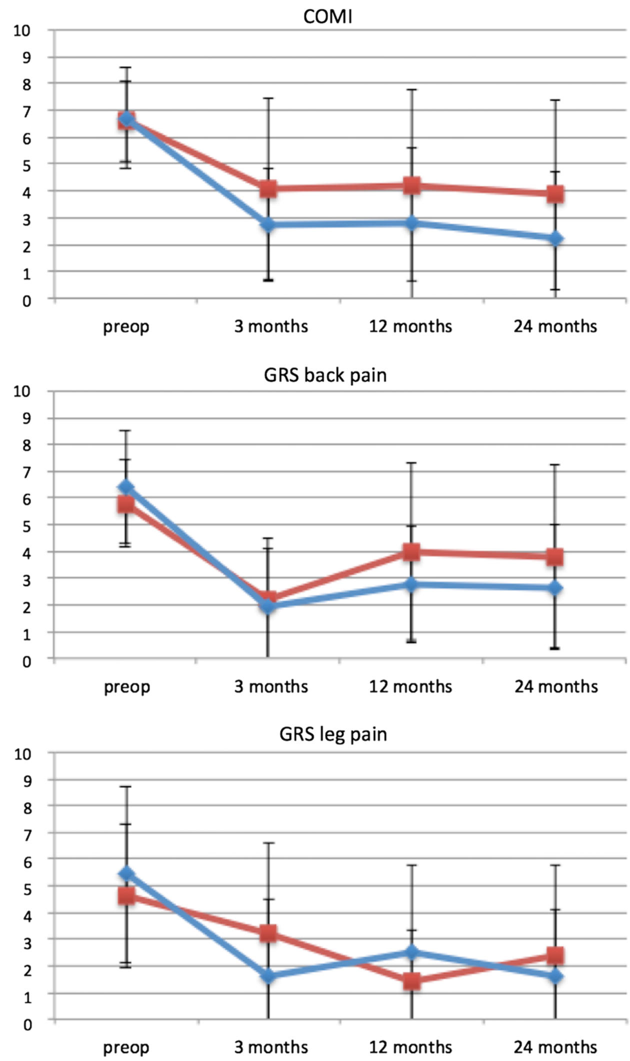


Fig. 3 Comparison of patient-rated outcome with and without postoperative L5 motor deficits. COMI and GRS scores shown as mean values ± standard deviation. The *red graph* (plotted with *square markers*) represents patients with postoperative L5 radiculopathy ($n = 5$) and the *blue graph* (*diamond markers*), patients without deficits ($n = 12$). For the whole patient group there was a significant improvement ($p < 0.001$) from preoperatively to all follow-ups, with no significant difference between the two groups in the pattern of change over time (repeated measures ANOVA)

patient (No. 12) with a grade 3 slip suffered from new-onset lumbosacral pain 21 months after the index surgery due to fracture of the S1 screws and subsequent pseudarthrosis requiring revision surgery to be performed.

Discussion

In situ fusion and reduction procedures have both been shown to lead to good clinical outcomes in the treatment of high-grade L5–S1 isthmic spondylolisthesis [16, 37, 38]. However, no randomized clinical trials comparing reduction with in situ fusion have been published and the question as to whether reduction offers a better long-term clinical outcome remains unclear [4, 37]. Iatrogenic L5 nerve root injury after surgical reduction and instrumented fusion of high-grade spondylolisthesis is a major concern. This complication is one of the many arguments used in the ongoing debate on reduction versus in situ fusion. For this reason many authors advise against reduction of high-grade spondylolisthesis for concern of L5 nerve root stretching and a potentially higher risk of iatrogenic nerve root injury [39]. Support for this hypothesis is found in an anatomic study by Petraco et al. who demonstrated that the greatest strain to the L5 nerve root occurs during the second half of reduction [40]. Hence a partial reduction might seem less likely to result in stretch injury of the L5 nerve root.

While for low-grade spondylolisthesis there is evidence from a recent prospective study that slip reduction has no influence on clinical outcome [41], there is no consensus in the literature in this regard for high-grade spondylolisthesis. In theory, slip reduction and instrumented fusion has some advantages, including alteration of the overall sagittal spinal profile, allowing normalization of spinopelvic parameters and protection of the adjacent L4–L5 segment, and indirect L5 nerve root decompression. Furthermore, posterolateral in situ fusion of high-grade spondylolisthesis may be associated with a higher incidence of pseudarthrosis and postoperative progression of the deformity [42]. As a result, many surgeons advocate complete slip reduction in high-grade spondylolisthesis [18]. A recently published meta-analysis of 8 eligible studies comparing 165 reduction and 101 in situ fusion procedures for high-grade spondylolisthesis showed that reduction potentially improves overall spine biomechanics, is not associated with a greater risk of developing neurologic deficits than in situ fusion (7.8 versus 8.9%), and has a significantly lower rate of pseudarthrosis; both procedures have a good clinical outcome [37].

Opinions regarding the surgical techniques proposed to avoid postoperative L5 radiculopathy are somewhat discordant. Whereas some are opposed to posterior decompression of neural elements to minimize L5 nerve root manipulation and increase fusion rates [19], Ruf et al. highlight the importance of decompressing and exposing the nerve roots far laterally [18]. With high-grade spondylolisthesis the optimal choice of fusion technique remains controversial. Posterior lumbar interbody fusion (PLIF) using two cages as well as TLIF using a single cage are both widely used. A main advantage of TLIF is the transforaminal approach to the disc space with less retraction of the dural sac and nerve root. In our series we chose a bilateral TLIF approach in most cases with the use of two Harms cages for optimal anterior support if necessary. By using the TLIF technique we were able to achieve a mean absolute slip reduction of 54% with only minor loss of reduction at the last follow-up. A recent randomized controlled trial comparing PLIF and TLIF for reduction of low- and high-grade adult isthmic spondylolisthesis showed that both techniques provide good clinical and radiological outcomes [43].

Although postoperative L5 radiculopathy with motor deficits has long been acknowledged [22], its true incidence after slip reduction or in situ fusion remains unclear. Detailed reports are scarce and based on relatively small case series. Also, published rates of postoperative neurologic complications vary substantially, as stated earlier, and make no mention of the use of IONM. Sailhan et al. reported a rate of 9% de novo postoperative neurologic deficits in their surgical series of 44 patients with high-grade spondylolisthesis, with 1 patient suffering a persistent L5 motor deficit [19]. A retrospective review of 165 pediatric and adult patients showed the occurrence of new neurologic deficits after surgery to be the most common complication, with a rate of 11.5% [25]. Seitsalo et al. reported an incidence of 6% in their series of 44 patients with new L5 motor deficits requiring reoperation [11]. In a consecutive series of 27 patients with reduction and monosegmental fusion, 6 patients (22%) showed symptoms of L5 nerve root lesions after surgery, with 1 patient suffering a permanent deficit [18]. DeWald et al. reported an overall incidence of 45% of new postoperative neurologic symptoms in a series of 20 patients [26].

Our data confirm that new-onset L5 radiculopathy with motor deficits constitutes a common complication after decompression, reduction and instrumented fusion of high-grade spondylolisthesis. Although the overall rate in our series was high (29%), outcome was very good with full recovery being seen within 3 months. Transient neurologic deficits had no significant impact on overall patient-rated outcome. Rather, COMI scores showed clinically important difference in both patient groups with and without L5MD.

Higher grades of spondylolisthesis and greater absolute slip reduction seemed to pose a higher risk of developing a postoperative L5 motor deficit, although in the present study the sample size limited the validity of the statistical analyses of the association. Such a (plausible) correlation has long been acknowledged [19, 40]. Further (long-term) studies will show whether slip reduction and the potentially higher risk for transient postoperative L5 palsy is outweighed by correction of the lumbosacral profile, with the accompanying functional advantages and protection of the adjacent L4–5 segment.

The value of IONM for intramedullary spinal cord tumors has long been recognized [44]. Yet, there is no thorough account of its impact specifically in the setting for high-grade spondylolisthesis apart from a report of two cases [45]. In the present study a decrease of MEP amplitude greater than 50% was defined as an IONM alert. With this regime our sensitivity for postoperative L5 radiculopathy with motor deficits was only 20%, whereas specificity was 100%. Two of five patients with L5MD had only EHL weakness. Additional MEP and EMG monitoring of this muscle together with the tibialis anterior muscle might further increase our IONM sensitivity. Although most studies have suggested a decrease of MEP amplitude of 50–80% [34, 46], other authors relied on a complete loss of signal [47]. Evidently, defining these thresholds directly influences sensitivity and specificity. Currently, there is no generally accepted alert level for MEP amplitude decrease owing to a lack of evidence from prospective multicenter studies. Recently, Kobayashi et al. recommended an alarm point of a 70% decrease in transcranial MEP during spinal deformity surgery based on their prospective multicenter study that included 959 patients with spinal deformity [48]. This new definition provided a sensitivity of 95% and a specificity of 91%. We found no diagnostic value for SEP by stimulation of the plantar medial nerve for sensory L5 radiculopathy, which supports our earlier findings [29]. SEP by stimulation of the distal peroneal nerve might be the preferred method to evaluate in future studies. Regardless of the surgical technique used in cases of high-grade spondylolisthesis, IONM of MEPs, and triggered and continuous EMG play an important role. During surgical manipulation, IONM recorded alerts during almost all surgical procedures, allowing the surgeon to react accordingly, e.g., to reduce distraction and reposition or correct screw placement. Whereas all postoperative L5 radiculopathy cases had at least 1 intraoperative alert, IONM may have prevented further deficits by alerting the surgeon promptly, since there were 16 alerts in 10 cases without the occurrence of neurologic sequelae.

Limitations

Although data were collected prospectively, the retrospective nature of the analyses is a limitation of the study. The sample size of 17 patients is relatively small and at each of the 3 follow-ups one (different) patient did not return the questionnaire. This compromised the repeated measures statistical analyses, reducing the effective sample size to 14. In this observational series there was no control group without intraoperative neurophysiological monitoring. Therefore, we have no means of directly evaluating the impact of IONM on neurologic outcome.

Conclusion

The risk of new-onset transient L5 radiculopathy with motor deficit after reduction and instrumented fusion of high-grade L5–S1 isthmic spondylolisthesis is high. However, the outcome is favorable, with most patients having fully recovered within 3 months. IONM is not able to avert postoperative L5 radiculopathy. However, by providing instant alerts to the surgeon, IONM might help prevent a possibly higher incidence of potentially irreversible postoperative L5 motor deficits. Recovered IONM potentials indicate a good prognosis with respect to postoperative neurological deficits. Overall, patient-rated outcome is good up to 2 years postoperatively.

Compliance with ethical standards

Conflict of interest The authors report no conflict of interest concerning the materials and methods used in this study or the findings specified in this paper.

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