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ORIGINAL ARTICLE - SPINE DEGENERATIVE

Intraoperative findings, complications, and short-term results after lumbar microdiscectomy with or without implantation of annular closure device

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Abstract

Background Standard microscopic lumbar discectomy (MLD) is a short operation with minimal blood loss, and a low rate of peri- and intraoperative complications. The objective of this study was to evaluate intraoperative findings, complications, and early postoperative neurological outcome (< 105 days) in patients undergoing MLD with or without implantation of an annular closure device (ACD).

Methods This study is based on data analysis of a post-marketing, prospective, multicenter RCT in Europe including patients undergoing standard MLD with or without implantation of an ACD (Barricaid®, Intrinsic Therapeutics, Inc., Woburn, MA). Enrollment of 554 patients in 21 centers in Europe (Germany, Switzerland, Austria, Belgium, The Netherlands, and France) started in 2010 and was completed in October 2014, with 276 patients randomized to the ACD group and 278 to the control group.

Results Mean operation time was 70 min in the ACD group and 52 min in the control group ($p < 0.0001$). Intraoperative fluoroscopy time was 24 s in the ACD group and 7 s in the control group ($p < 0.0001$). Average blood loss was 94.2 ml in the ACD group and 64.7 ml in the control group ($p = 0.0001$). Serious device- or procedure-related adverse events occurred in 3.7% (10/272) of the ACD group and 7.9% (22/278) of the control group. Dural injuries occurred in 13 (4.8%) patients in the ACD group and 7 (2.5%) in the control group. There was one device-related nerve root injury resulting in a nerve root amputation. Surgical complications included 3 hematomas in the ACD group and 4 in the control group; 3 infections occurred in both groups. Device migrations were documented in 3 patients in the ACD group. Patients in the ACD group ($n = 7$, 2.6%) underwent fewer reoperations compared with that in the control group ($n = 16$, 5.8%, OR = 2.3 (0.9–5.7)). Mean VAS leg pain at 3 months was 11.9 in the ACD and 15.1 in the control group, respectively.

Conclusion Short-term outcome after MLD with or without implantation of ACD was similar in both groups. Patients included in the ACD group underwent fewer reoperations in the first 3 months after surgery. Nevertheless, longer operation time, higher amount of blood loss, and risk of nerve root lesion during device implantation should be considered additional risks in patients undergoing ACD implantation after MLD.

Keywords Disc herniation · Intraoperative findings · Annular closure device

This article is part of the Topical Collection on *Spine degenerative*

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Introduction

Lumbar discectomy is one of most commonly performed elective spine surgery procedures in patients suffering from radicular pain due to a disc herniation [11]. Surgical treatment for carefully selected patients with sciatica due to lumbar disc prolapse is known to provide faster pain relief and improvement of neurological deficits [18]. Lumbar discectomy is a microsurgical, rather simple, standard operation with a short operation time, minimal blood loss, and low rates of peri- and intraoperative complications [27].

Various surgical approaches exist to treat herniated discs. Prior to the 1970s, a radical approach with curettage of the disc space and endplates was commonly performed [10]. Over time, less invasive methods became more popular. The subtotal discectomy was described and then an even less invasive technique, the limited discectomy, took over [41, 51, 52]. A limited discectomy described by Spengler [41] renounces the use of curettes and therefore recommends only removing extruded and loose fragments in the disc space. The excision of only the fragment was first described by Balderston et al. and Faulhauer et al., and is the appropriate treatment if there is only a sequestered fragment without a major annular defect [6, 15]. Currently, minimally invasive discectomy procedures such as endoscopic discectomies are being encouraged, but no clear advantage has been shown, and further research is necessary to define appropriate indications [13, 36].

Postoperative failures with increasing back pain due to acceleration of the degenerative process or recurrent disc herniation—particularly in patients with large annular defects—have been reported [2, 9, 22, 31, 47]. Implantation of an annular closure device (Barricaid® Intrinsic Therapeutics, Inc., Woburn, MA) might additionally reduce the risk of reherniation [50]. The opportunity to perform only a limited discectomy without increasing risk of reherniation by occluding the annular defect may help avoid segmental collapse and associated syndromes [7, 31].s

Two- and 3-year follow-up results of the current study have already been published in this journal and showed a lower recurrent herniation rate in the annular closure device group, compared with that in the control group (3 years 14.8% vs. 29.5%) [23, 43].

The aim of this study was to specifically investigate intraoperative findings, complications, and short-term outcomes in patients undergoing standard microscopic limited lumbar discectomy (MLD), with and without additional implantation of an annular closure device.

Materials and methods

Patient selection

This study is based on the analysis of data from a post-marketing, prospective, multicenter randomized controlled trial in Europe including patients undergoing standard lumbar limited discectomy with or without implantation of an annular closure device (Barricaid®, Intrinsic Therapeutics, Inc., Woburn, MA) (Clinicaltrials.gov NCT01283438). Enrollment of 554 patients in 21 centers in Europe (Germany, Switzerland, Austria, Belgium, The Netherlands, and France) started in December 2010 and was completed in October 2014. Ethics committee approval was received at each site. Informed consent was obtained from all individual participants included in the study. The study was overseen by an independent data safety monitoring board. Radiological findings throughout the study were analyzed by independent radiologists.

After enrollment in the study, patients were randomized to either standard discectomy (control group, or CG) or standard discectomy with implantation of an annular closure device (annular closure device group or ACDG). The 49 participating surgeons were experienced neurosurgeons or orthopedic surgeons and were trained in implantation of the device. Randomization 1:1 device-to-control was performed web-based and occurred intraoperatively during surgery, after measuring the defect of the annulus which had to be in the range of 4–6 mm in height and 6–10 mm in width. Adverse event severity and the relation between device and procedure were adjudicated by physicians acting as an independent data safety monitoring board (DSMB). This study is based on the analysis of intraoperative findings, perioperative complications, and postoperative outcomes over 105 days. In addition, a literature review was performed on studies reporting on intraoperative parameters and complications.

Annular closure device

The Barricaid® annular closure device (Intrinsic Therapeutics, Inc., Woburn, MA, USA) was designed for lumbar discectomies to prevent reherniation through blockage of the annular defect and preserves the nucleus within the disc space. The device received European Conformity (CE) marking in 2009 and FDA approval in 2019. It is composed of two parts: a flexible mesh that acts as a mechanical barrier to the annular defect and prevents movement of the nucleus out of the disc space, and a bone anchor which fixes it to the endplate of the adjacent vertebral body.

Surgical technique and intraoperative findings

Study design and methods have been published earlier [26]. Relevant intraoperative data such as duration of surgery, medications, and amount of blood loss was documented in each case. The herniated disc was inspected after fenestration, decompression of the dural tube, and identification of the nerve root. A limited nucleotomy as described by Spengler [41] was designated as standard for all patients in the protocol. The volume of removed nucleus pulposus was measured in cubic centimeters and the height and width of the annular defect were measured in millimeters using sizing paddles. Cases with a defect wider than 10 mm or higher than 6 mm were excluded from the trial before randomization. After randomization, no further nucleus removal was allowed. If the patient was assigned to the control group, the operation was considered to be complete. If the patient was randomized to receive an implant (ACD group), the device for annular closure was selected

according to the width of the defect as follows: an implant with an 8-mm wide mesh was used for patients with a defect of 6 to ≤ 8 mm; if the defect width was 9 mm or 10 mm, a 10-mm device was used. A trial sizing implant was used to confirm translaminar access and the correct angle to approach the disc space. To achieve best fit, the anchor could be placed either in the adjacent lower or upper endplate. The implant was then placed in proper position with the mesh reaching the disc space through the annular defect and the bone anchor affixed into the endplate using a surgical hammer. Appropriate position of the anchor and opening of the mesh into the disc was confirmed with intra- and postoperative anterior-posterior (AP)/lateral X-ray. Surgeons reported if there were any difficulties with device implantation, failure to implant, or device or delivery tool malfunctions. Epidural drainage was used according to the surgeon's preference. The time of surgery was defined as time from skin incision to the end of skin closure.

Complications/adverse events

Complications were recorded as adverse events (AEs) and tracked prospectively. Intraoperative AEs reported included (1) operation of wrong level or side, (2) dural injury, (3) cerebrospinal fluid (CSF) leak, (4) nerve root injury, (5) vascular injury, and (6) any blood product replacement intra- or postoperative due to excessive blood loss. Postoperative complications reported included (1) infection, (2) hematoma, (3) recurrent or persistent sciatica, (4) symptomatic reherniation, (5) device migration or loosening, (6) prolonged hospitalization or rehospitalization, and (7) reoperation for any reason or due to reherniation at index level.

Adverse events in both groups were classified as mild, moderate, severe, or serious (SAE). Assessment of relatedness to procedure or device was classified as definitely, probably, possibly, not related, or unknown. These classifications and assessments were adjudicated by the independent data safety monitoring board.

Follow-up

At discharge, patients were instructed with postsurgical guidance and activity restrictions according to the standard protocols of each site. Consultation at 6 weeks and 3 months included an AP/lateral X-ray, clinical examination, and assessment of current medication. Furthermore, patients completed the questionnaire for VAS leg and back pain, Oswestry Disability index (ODI), and Medical Outcomes Short Form-36 (SF-36) physical and mental component summary scales [20, 34].

Clinical outcome assessment

Scores for VAS leg and back pain (score range 0–100) as well as number of points in ODI (score range 0–100), SF-36 data (mental and physical components, score range 0–100) and clinical examination including neurological status were collected preoperatively at 6 weeks, 3 and 6 months, and annually thereafter. Current work status was recorded at every consultation. We assessed recurrent sciatica as documented by AE or by an initial decrease of VAS leg pain of minimum 20 points at 6 weeks followed by an increase ≥ 20 in VAS leg pain at 3 months. This did exclude patients with recurrent herniation. Persistent sciatica was defined as a decrease in VAS leg pain of less than 20 points. Worsening pain was defined as an increase in VAS leg pain of ≥ 20 points between 6 weeks and 3 months. New neurological deficits were reported as documented by AE or as reported in neurological exam at 6 weeks and 3 months. In order to provide a complete overview, we performed a post hoc analysis on the outcome of the five patients randomized for ACD implant but did not receive it due to technical issues during surgery.

Statistical analysis

Standard descriptive statistics of subject demographics, intraoperative parameters, and pain scores were calculated and tabulated. Correlations between variables were performed for the subjects implanted with the ACD as well as control subjects. Fisher's exact tests were used for categorical variables, and Wilcoxon rank-sum and Kruskal-Wallis tests applied to compare continuous variables. Correlations between continuous variables were investigated using linear regression analysis.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee (name of institute/committee) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This study was approved by the local ethics committee EKNZ, Switzerland (Nr. 2012/036).

Results

A total of 276 patients were randomized to the ACD group (ACDG) and 278 patients to the control group (CG) as shown in Fig. 1. Of the 276 patients in the ACDG, 3 patients (1.1%) had the device implanted on the second attempt, 5 patients (1.8%) had a failed implant attempt (mesh buckling with difficulties of mesh entry into the disc space), and in 4 patients, no implantation was attempted due to anatomical conditions, e.g., the position of the nerve root. In total, 272 patients had a

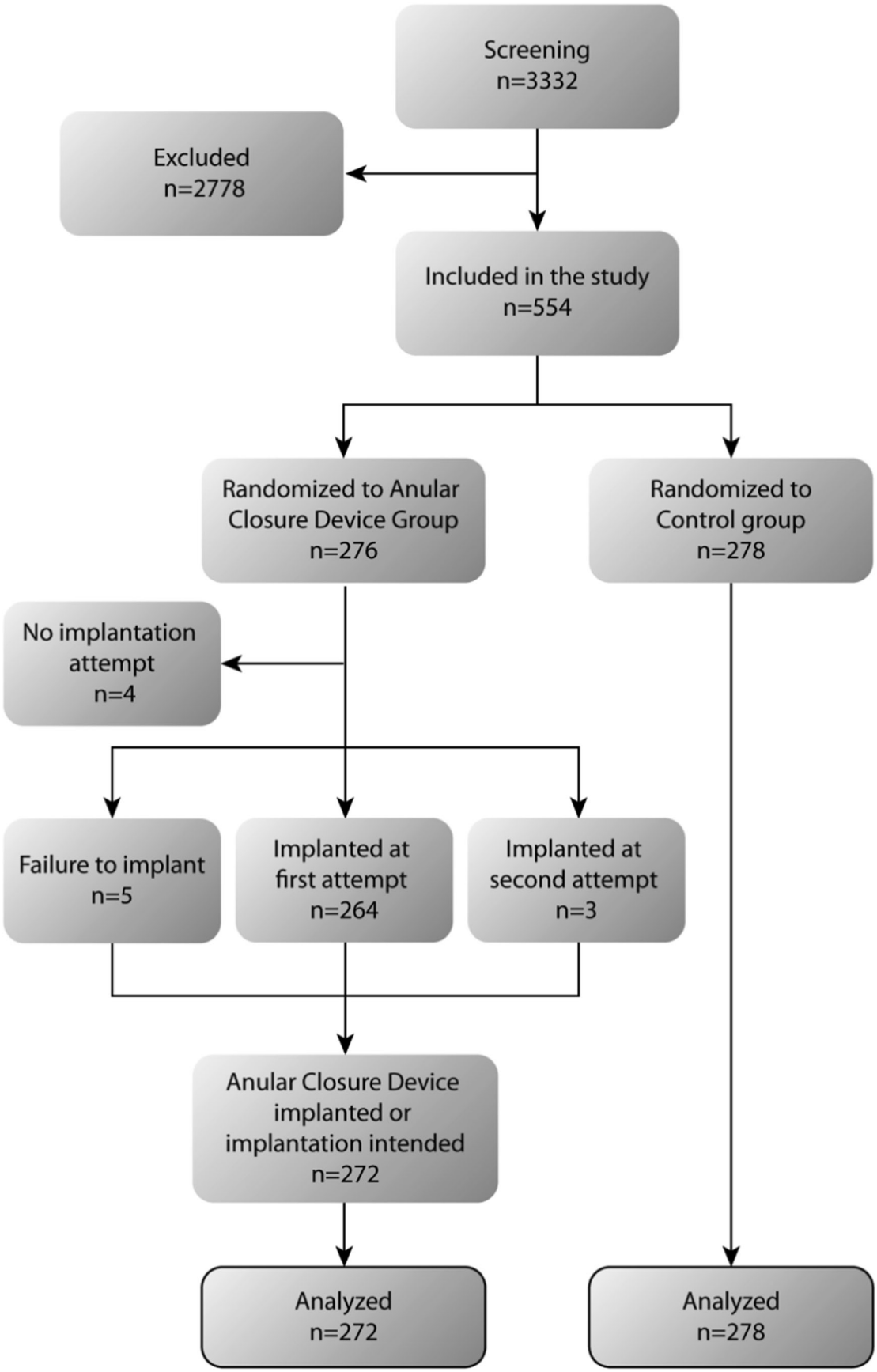

Fig. 1 Flow diagram of patient randomization in the trial and final data analysis

device implanted ($n = 267$) or an attempted implantation ($n = 5$) and were included in our analysis. We did not cross-over anyone to the CG.

Preoperative patient demographics

Preoperative demographic characteristics are shown in Table 1. There were no significant differences in any demographic parameters between the groups.

Operation time and duration of intraoperative fluoroscopy

The average operation time was 61 min (70 min in the ACDG and 52 min in the CG; $p < 0.0001$). We analyzed the influence of sex, hypertension, and BMI on operation time and found a significant correlation with BMI. The correlation was significant overall ($p < 0.001$, 1.37 min/BMI) and in the ACDG ($p < 0.001$; 2.11 min/BMI), and showed a trend in the CG ($p = 0.057$;

Table 1 Preoperative demographic characteristics for overall population, ACD, and control groups. There was no significant difference in any demographic parameter between the groups. For smoking, "yes" means the percentage of active smokers, and for working status, "yes" includes the percentage of patients working preoperatively

Preoperative demographic characteristics	All patients $n = 550$	ACD group $n = 272$	Control group $n = 278$	p value
Age (mean, range, SD)	43.5 (22–74) (10.7)	42.9 (22–71) (10.9)	44.0 (23–74) (10.4)	0.2337
Sex (female)	40.6% (223)	42.7% (116)	38.5% (107)	0.340
BMI (mean kg/m^2, SD)	26.3 (4.1)	26.3 (4.1)	26.3 (4.1)	0.8083
Smoking (yes)	44.4% (244)	44.5% (121)	44.2% (123)	1.000
VAS leg (mean, SD)	80.8 (14.9)	80.8 (15.1)	80.8 (14.6)	0.9696
VAS back (mean, SD)	56.1 (30.7)	56.6 (30.0)	55.7 (31.4)	0.7426
ODI (mean, SD)	58.6 (13.1)	59.0 (12.4)	58.2 (13.7)	0.4721
SF 36 PCS (mean, SD)	31.4 (5.6)	31.7 (5.5)	31.2 (5.7)	0.3653
SF 36 MCS (mean, SD)	42.2 (11.8)	41.5 (11.8)	42.9 (11.9)	0.1775
Sensory deficit	62% (340)	61% (166)	63% (174)	0.726
Motor deficit	37% (201)	39% (107)	34% (94)	0.185
Reflex decrease or loss	47% (256)	43% (117)	50% (139)	0.105
Positive straight leg raise	99.8% (549)	100% (272)	99.6% (277)	1.000
Working status (yes)	21.1% (116)	19.9% (54)	22.3% (62)	0.531
Homemaker, retired, student, unable to find work, not working by choice	8.6% (47)	7.7% (21)	9.4% (26)	0.543
Preoperative duration of symptoms (median months)	5.6	5.5	5.6	0.5967
Level of disc herniation				
L2/3	0.6% (3)	0.7% (2)	0.4% (1)	0.075
L3/4	2.4% (13)	2.9% (8)	1.8% 5)	
L4/5	40.7% (224)	45.2% (123)	36.3% (101)	
L5/S1	56.4% (310)	51.1% (139)	61.5% (171)	
Side of surgery (left/right)	298/252	142 / 130	156/122	0.392

VAS, Visual Analog Scale; ODI, Oswestry Disability Index; *BMI*, body mass index; *SF–36 PCS*, Short Form-36 physical component summary; *SF–36 MCS*, Short Form-36 mental component summary

0.70 min/BMI). In other words, if BMI increases by 1 point, operation time will increase 1.37 min overall and 2.11 min in the ACDG. The average intraoperative fluoroscopy time was 15 s (24 s in the ACDG and 7 s in the CG; $p < 0.0001$) Table 2.

Amount of blood loss

On average, 79.3 ml of blood was lost during discectomy (94.2 ml in the ACDG and 64.7 ml in the CG; $p = 0.0001$) (Table 2). The corresponding medians were 48 ml for the CG and 50 ml for the ACDG. The 54 patients (9.8%) who had hypertension lost significantly more blood (mean 96.6 ml) than patients without hypertension (77.4 ml); overall ($p = 0.0143$), and in the CG ($p = 0.0161$). Sex was a predictive factor overall (female 86.1 ml vs. male 74.6 ml; $p = 0.0244$) and blood loss increased by 1.07 ml per year of age in the CG ($p = 0.046$). The spinal level of surgery was another predictor (L2/3: 80 ml, L3/4: 208.8 ml, L4/5: 87.2 ml, L5/S1: 68.1 ml; $p = 0.0406$) and extruded or sequestered type of herniation showed approximately 20 ml more blood loss compared with contained fragment type; both overall ($p = 0.0038$) and in the ACDG ($p = 0.0056$).

Amount of removed bone and nucleus pulposus, defect size

The bony fenestration was divided into average, below average, and above average, as assessed subjectively by the surgeon. Above average was removed in 138 (50.7%) cases in the ACDG ($p < 0.001$) and 65 (23.4%) in the CG. The average amount of removed nucleus material was 1.3 cc and the mean defect area was 38.7 mm^2 (Table 2, Table 3, Table 4).

Implantation of ACD, device malfunction, and failures to implant

Surgeons reported that 63.8% of ACD implantations were easy, 28.4% acceptable, and 7.8% difficult. An intraoperative device delivery malfunction occurred in seven (2.6%) cases. Causes of device delivery limitations included mesh "buckling" and impossible access into the disc space ($n = 4$), device detachments from the delivery tool prior to attempting implantation ($n = 2$), and difficulty removing the delivery tool after finishing the implantation ($n = 1$) (Table 5).

Intraoperative complications

A total of 20 (3.6%) dural injuries occurred, 13 (4.8%) in the ACDG and 7 (2.5%) in the CG. Only three of the ACDG injuries were definitely device-related and two were documented as possibly related. There was one device-related nerve root injury resulting in a nerve root amputation. The patient developed postoperative hypoesthesia with absent tendon reflexes and severe leg pain. The patient was treated with various analgesics, opiates, and neuropathic pain medication. Repair techniques of the 20 dural injuries included suturing (ACDG: $n = 4$, CG: $n = 2$), suturing and fibrin glue (CG: $n = 2$), artificial dura (ACDG: $n = 2$), collagen sponge (ACDG: $n = 3$), muscle patch (ACDG: $n = 1$), none (ACDG: $n = 1$, CG: $n = 1$), and unknown (ACDG: $n = 2$, CG: $n = 2$).

Postoperative neurological deficits such as motor deficit, numbness, and reflex changes were allocated and reported as AEs. A total of 11 (2%) suspected nerve root injuries were reported in 10 patients (ACDG: 1.5% $n = 4$ vs. CG: 2.2% $n = 6$) and classified as possibly related to an intraoperative spinal nerve injury in absence of a clearly documented event (Table 6).

Postoperative complications

Hematomas In total, 7 (1.3%) hematomas occurred (3 = 1.1% in the ACDG, 4 = 1.4% in the CG). Three hematomas in the CG required surgical evacuation (Table 6).

Table 2 Intraoperative findings

Intraoperative findings				
	All patients $n = 550$	ACD group $n = 272$	Control group $n = 278$	p value
Operation time (min) ± SD	61 (31)	70 (33)	52 (26)	< 0.0001
Time of intraoperative fluoroscopy (s) ± SD	15 (19)	24 (23)	7 (7)	< 0.0001
Amount of blood loss (ml) ± SD	79.3 (114)	94.2 (130.4)	64.7 (93.1)	0.0024
Amount of nucleus removed (cc) ± SD	1.3 (0.9)	1.3 (1.0)	1.3 (0.8)	0.6906
Defect width in mm ± SD	7.9 (1.3)	7.8 (1.2)	8.0 (1.3)	0.0427
Defect height in mm ± SD	4.9 (0.7)	4.9 (0.7)	4.9 (0.7)	0.9209
Defect size in mm^2 ± SD	38.7 (8.9)	38.1 (8.6)	39.3 (9.1)	0.1334

min, minutes; *s*, seconds; *ml*, milliliter; *mm*, millimeter; *n/a*, not available

Table 3 Defect width and defect height

	All patients ($n = 550$)		ACD group ($n = 272$)		Control group ($n = 278$)		p value
	n	%	n	%	n	%	
Defect width							0.288
6 mm	93	16.9	49	18	44	15.8	
7 mm	120	21.8	65	23.9	55	19.8	
8 mm	173	31.5	88	32.4	85	30.6	
9 mm	82	14.9	37	13.6	45	16.2	
10 mm	82	14.9	33	12.1	49	17.6	
Defect height							0.934
4 mm	169	30.7	83	30.5	86	30.9	
5 mm	271	49.3	136	50.0	135	48.6	
6 mm	110	20.0	53	19.5	57	20.5	

Infections There were 6 postoperative wound infections, 3 in each group. We classified the infections as superficial and deep according to the thoracolumbar fascia relation. Antibiotics were the main treatment; 1 patient in each group required revision surgery. The patient with a deep infection in the CG required 4 revision surgeries. The first intervention was performed on day 20, but persisting infection required 3 further revisions performed at days 75, 92, and 99.

Device migration Device migration occurred in 5 patients in the ACDG (3× anchor: 2 symptomatic and 1 asymptomatic and 2× mesh: asymptomatic) (Table 6). The two symptomatic anchor migrations underwent device removal, and the asymptomatic cases did not require further treatment until the 3-month follow-up. The 3 anchor migrations occurred posterior. The first patient had a normal preoperative osteoporosis evaluation score. A dual-energy X-ray absorptiometry (DEXA) scan performed after the reoperation documented osteoporosis (T value − 3.3). As the patient was asymptomatic, initial treatment was conservative, but reoperation was performed at 1 year to remove the implant. The second patient was a heavy smoker (80 pack years) with a BMI of 37 kg/m^2 and type II diabetes. After a superficial wound infection and wound revision, anchor migration was seen at the routine 6-week follow-up. Following reoperation, a DEXA scan was performed, and the patient's bone quality was found to be osteopenic. The migration in this patient is thought to be related to comorbidity factors. The third patient who required reoperation had a normal DEXA scan and BMI, but the surgeon reported varying bone quality within the vertebra during implantation of the ACD. Histological investigation of tissues surrounding the explanted device revealed chronic inflammation with florid aspects probably due to micromotion of the implant.

Reoperations and recurrence rate

During the first 3 months, a total of 22 index-level reherniations occurred (4 in the ACDG, 18 in the CG). Overall, 20 reherniations were ipsilateral (3 in the ACDG, 17 in the CG) and 2 were contralateral (1 in each group). Of the 3 ipsilateral reherniations in the ACDG, 2 were found lateral of the ACD mesh. Within the initial 3 months, 12 patients required reoperation due to reherniation (3 in the ACDG, 9 in the CG) (Table 6).

Patients in the ACDG underwent fewer reoperations compared with that in the CG (OR = 2.3 (CI 0.9–5.7)). There were 7 reoperations in the ACDG (3 re-discectomies (1 sequestrectomy) due to reherniation, 2 implant removals, 1 nerve root decompression, and 1 wound revision due to superficial infection). One patient underwent 2 reoperations: nerve root re-decompression at day 16 and device removal and fusion at day 28. In the CG, 16 reoperations were performed: 9 repeat-discectomies due to reherniation, 3 hematoma evacuations, and 4 wound revisions.

Table 4 Amount of removed bone

Amount of removed bone				
	All patients $n = 550$	ACD group $n = 272$	Control group $n = 278$	p value
Below average	26 (4.7%)	5 (1.8%)	21 (7.6%)	< 0.001
Average	321 (58.4%)	129 (47.4%)	192 (69.1%)	
Above average	203 (36.9%)	138 (50.7%)	65 (23.4%)	

Table 5 Device implantation

Device implantation	
	ACD group $n = 272$
Easy	173 (63.8%)
Difficult	21 (7.8%)
Acceptable	77 (28.4%)
Device malfunction	7 (2.6%)
Failure to implant	5 (1.8%)
Implantation on second attempt	3 (1.1%)

Duration of hospital stay and other influencing factors

Median duration of primary and rehospitalization was 3 and 5 days, respectively (Table 7). We found a significant correlation between age and duration of hospital stay (0.02 days/year) in the CG ($p = 0.034$) and BMI and hospital stay in the ACDG (primary hospitalization: 0.17 days/BMI point, $p = 0.002$; rehospitalization: 1.1 days/BMI point, $p = 0.03$). Patients who were readmitted in the CG were older (average 51 years compared with 43 years without rehospitalization, $p = 0.0001$).

Serious adverse events

The device-related or procedure-related SAEs are shown in Table 8. SAEs were documented in 10 (3.7%) and 22 (7.9%) patients in the ACDG and CG, respectively.

Clinical outcome

Postoperative neurological findings and short-term outcomes are shown in Table 9. We performed a post hoc analysis on the outcome of 5 patients who were randomized to the ACDG and did not undergo implantation of ACD (failure to implant group = FG). Their postoperative leg pain (FG: 21.8, ACDG: 11.9, CG: 15.1) and ODI (FG: 22.5, ACDG: 16.5 CG: 17.4) at 3-month follow-up were slightly higher. Back pain in FG, however, was lower (FG: 10.8, ACDG: 19.2, CG: 18.9).

Discussion

The results of this study demonstrated that despite longer operation time and higher amount of blood loss in patients undergoing ACD, the postoperative outcomes were similar in patients undergoing MLD with or without additional ACD during the first 3 months after surgery. Complications such as nerve root lesions during ACD implantation should be considered serious adverse events and therefore a surgical risk. Current data revealed a good early postoperative outcome with major leg pain relief and only mild postoperative leg (VAS 13.6) and back pain (VAS 19). Other authors reported slightly higher residual mean leg (VAS range 13–40) [14, 29, 39, 42, 45] and back pain (VAS range 16–37) [39, 42]. No additional postoperative back pain was observed after ACD implantation. Thomé et al. reported good or excellent short-term outcome in 76% of patients undergoing MLD including a reduction in leg and back pain of > 80% [42]. At 3-month follow-up, only minimal disability persisted (ODI 17 points) which is in line with the study by Ashan et al. [1] (ODI 17 points, Mannion et al. [29] ODI 29.5). In the study by Hakkinen et al., major ODI improvement (up to 88%) after MLD was achieved during the first 6 weeks after surgery [21]. Furthermore, SF–36 scores for PCS and MCS improved to population norm (50 with SD of 10) [46].

Finally, we confirmed that patients with device implantation did not experience any increase in neurological deficits. Interestingly, other authors achieved a decrease of neurological deficits in more than 80% of patients [42]. Schick et al. obtained results similar to ours: 12.5% of patients had postoperative paresis (8.9% in our cohort) with a 28% decrease in motor deficits (27% in current study) [39].

This study showed that the ACDG had, on average, 35% longer surgery duration ($p < 0.0001$) which can be explained by the time needed for device implantation. Both groups probably also had minor delays compared with a routine MLD due to intraoperative randomization. Overall, the operation time in this study was in accordance with the literature (24 to 119 min), as showed in Table 10 [8, 12, 14, 17, 19, 35, 37, 40, 42, 48, 53]. Additional implantation of ACD after MLD took 2.2 times longer than a simple sequestrectomy. It should nevertheless be considered that an advanced learning curve could shorten the procedure. Our findings also supported previous results regarding the significant correlation of BMI with operation time [37, 53]. The need for intraoperative X-ray to confirm correct device placement may also have extended operation time. The time used for intraoperative fluoroscopy was on average 3.4 times longer (24 vs. 7 s) in the ACDG ($p < 0.0001$). Additional intraoperative fluoroscopy increases radiation exposure to the patient, surgeon, and staff. In a survey study by Wagner et al. from the Scoliosis Research Society, the authors noted an almost a 40-fold increase in thyroid cancer in spine surgeons compared with the average population. Members of the society had a 13% incidence of cancer and 30% incidence of cataract [44]. Mariscalco et al. reported that the mean radiation exposure outside the protective lead for the surgeon during open lumbar discectomy was 0.0016 mSv for thyroid/eyes, 0.0023 mSv for the chest, and 0.0020 mSv for the hands [30]. One limitation of the present study is that only fluoroscopy time without dose area product

Table 6 Intraoperative and postoperative complications

Intraoperative and postoperative complications								
	Operation of wrong level or side	Nerve root injury	Dural injury/CSF leak	Excessive bleeding intraop	Blood transfusion intra- or postoperatively	Vascular injury	Infection (deep)	Infection (superficial)
All patients $n = 550$	0	11 in 10 patients (1.8%)	20 (3.6%)	7 (1.3%)	1(0.2%)	0	3 in 2 patients (0.4%)	3 (0.5%)
ACD group $n = 272$	0	5 in 4 patients (1.5%)	13 (4.8%)	4 (1.5%)	0	0	1 in 1 patient (0.4%)	2 (0.7%)
Control group $n = 278$	0	6 in 6 patients (2.2%)	7 (2.5%)	3 (1.1%)	1 (0.4%)	0	2 in 1 patients (0.4%)	1 (0.4%)
p value	n/a	0.752	0.177	0.722	1.000	n/a	1.000	0.620

Intraoperative and postoperative complications								
	Hematoma	Seroma	Serious adverse events	Device- or procedure-related serious adverse event	Reoperation due to any reason	Rehospitalizations	Symptomatic reherniation	Reoperation due to reherniation
All patients $n = 550$	7 (1.3%)	3 (0.5%)	68 in 59 patients (10.7%)	34 in 32 patients (5.8%)	23 in 20 patients (3.6%)	59 in 51 patients (9.3%)	22 (4%)	12 (2.2%)
ACD group $n = 272$	3 (1.1%)	1 (0.4%)	30 in 25 patients (9.2%)	10 in 10 patients (3.7%)	7 in 6 patients (2.2%)	25 in 20 patients (7.4%)	4 (1.5%)	3 (1.1%)
Control group $n = 278$	4 (1.4%)	2 (0.7%)	38 in 34 patients (12.2%)	24 in 22 patients (7.9%)	16 in 14 patients (5.0%)	34 in 31 patients (11.2%)	18 (6.5%)	9 (3.2%)
p value	1.000	1.000	0.272	0.044	0.109	0.142	0.004	0.142

Excessive bleeding defined as blood loss ≥ 500 ml was measured in 4 patients in the ACDG and 3 patients in the CG. There was only 1 intraoperative blood replacement necessary in a CG patient with a blood loss of 200 ml and reinfusion of 100 ml

CSF, cerebrospinal fluid

Table 7 Duration of hospital stay for the primary stay and rehospitalization

Median duration of hospital stay				
	All patients ($n = 550$)	ACD group ($n = 272$)	Control group ($n = 278$)	Wilcoxon rank-sum p value
Median time of hospital stay	3 days	3 days	3 days	0.1752
Median time of rehospitalization	5 days (59 rehospitalizations, 10.7%)	4 days (25 rehospitalizations, 9.2%)	6 days (34 rehospitalizations, 12.2%)	0.2950

was reported. Nevertheless, we assume that implantation of ACD is safe for patients and surgeons if appropriate protection is used. Blood loss ranging from 56 to 185 ml has been reported by other authors [8, 17, 27, 37, 42, 48, 53] and is in agreement with our results (Table 10). Excessive bleeding (ACDG: 1.5%, CG: 1.1%) was described in 3.5% of cases by a group of very experienced surgeons [27].

The longer operation time and increased amount of blood loss may increase the risk of infection after device implantation [16, 28], and lead to economic burden, with higher cost and reduced turn-over in the operation room. The observations in this study regarding longer duration of surgery, higher amount of blood loss, and risk of root nerve lesion associated with the implantation of the ACD should be considered potential hazards for patients.

In comparison with our study, McGirt et al. removed an average of 40% more nucleus material (2 ± 1.1 cc, vs. 1.3 cc in both groups). This discrepancy can be explained by the limited discectomy approach in the current series [32]. Our results showed a significant difference in bone removal with a larger fenestration in the ACDG ($p < 0.001$). The proportion of procedures with an "above average" approach was assessed 2.2 times more often in the ACDG. The reason is more likely that enlargement of interlaminotomy after randomization was required in certain cases to free up enough space for device implantation. In contrast, the trend nowadays is toward minimally invasive approaches with less bone removal to maintain segmental integrity [45]. Long-term effects and incidence of segmental instability after increased bone removal have to be observed.

This study reported 3.6% dural injuries (DI) which is comparable with other findings (0.8 to 8.6%) (Table 10) [1, 8, 14, 27, 35, 38–40, 42, 48, 49, 53]. Due to the fact that the ACDG had a higher rate, the authors recommend adequate nerve root retraction and training in order to avoid DI. In 1.8% of patients, the cause of postoperative symptoms was suspected to be a nerve root injury. The source could not be clearly elucidated, and most likely involves excessive traction or heat during bipolar coagulation. Implantation of ACD might require forced retraction to protect the nerve root. In this regard, we were able to demonstrate that no additional postoperative nerve injury should be expected. One patient (0.4%) in the ACDG suffered a nerve root amputation during device implantation. The percentage of nerve root lesions after MLD has been predicted to be 0.2–1.7% in the literature [1, 8, 12, 14, 35, 39, 42, 48, 49] (Table 10). Although the rate was very

Table 8 Serious device- or procedure-related adverse events

Device or procedure-related SAE		
ACD group	Control group	p value
10 events in 10 patients (3.7%)	24 events in 22 patients (7.9%)	0.044
1 Nerve root amputation	16 Reherniations	
1 Infection	3 Hematomas	
1 Wound healing disorder	2 Seromas	
2 Implant dislocations	2 Infections (in one patient)	
3 Reherniations	1 Myocardial infarction	
1 Patient with low back pain		
1 Patient with radicular pain		

In the CG, 1 patient needed cardiopulmonary reanimation due to heart failure as a result of low potassium, and a cardioverter defibrillator was implanted during hospitalization. One patient in the CG suffered a myocardial infarction necessitating treatment with antiplatelet drugs and a coronary angiography. Finally, 1 patient in each group suffered temporary sexual dysfunction which resolved itself within 3 months. The overall mortality of the study until the 3-month follow-up was zero

AE, adverse event

Table 9 Postoperative neurological findings and outcome at 3-month follow-up

Postoperative neurological findings and outcome	All patients	ACD group	Control group	*p* value
Mean VAS leg pain (± SD)	13.6 (20.8) *n* = 525	11.9 (19.6) *n* = 260	15.1 (22) *n* = 265	0.0724
Mean VAS leg pain improvement	67.2 (83.2%) SD = 25.1 *n* = 530	69.0 (85.2%) SD = 24.9 *n* = 260	65.7 (81.3%) SD = 25.3 *n* = 265	0.1290
Mean VAS back pain (± SD)	19 (22.1) *n* = 525	19.2 (22.9) *n* = 260	18.9 (21.6) *n* = 265	0.8561
Mean VAS back pain improvement	37.1 (66.1%) SD = 33.6 *n* = 530	37.1 (65.5%) SD = 34.3 *n* = 260	37.0 (66.4%) SD = 33.2 *n* = 265	0.9685
Mean ODI (± SD)	17 (15.2) *n* = 525	16.5 (15.2) *n* = 260	17.4 (15.3) *n* = 265	0.5004
Mean ODI improvement	41.5 (70.9%) SD = 18.7 *n* = 530	42.5 (71.9%) SD = 18.8 *n* = 260	40.8 (70.1%) SD = 18.6 *n* = 265	0.2896
SF 36 PCS (mean)	46.5 (8.3) *n* = 530	47.1 (8.0) *n* = 260	45.9 (8.6) *n* = 265	0.1220
Mean PCS improvement	15.1 (47.9%) SD = 9.3 *n* = 530	15.4 (48.5%) SD = 9.4 *n* = 260	14.8 (47.3%) SD = 9.4 *n* = 265	0.4674
SF 36 MCS (mean)	51.2 (10.3) *n* = 530	51.9 (9.6) *n* = 260	50.6 (10.8) *n* = 265	0.1397
Mean MCS improvement	8.9 (21.1%) SD = 12.2 *n* = 530	10.3 (24.7%) SD = 12.4 *n* = 260	7.7 (18.0%) SD = 11.9 *n* = 265	0.0161
Sensory deficit	117/527 (22%)	63/262 (24%)	54/265 (20%)	0.346
Decrease in sensory deficit	220/532 (41%)	105/262 (40%)	113/265 (43%)	0.596
Motor deficit	54/527 (10%)	29/262 (11%)	25/265 (9%)	0.568
Decrease in motor deficit	153/532 (29%)	78/262 (30%)	74/265 (28%)	0.701
Patients with postoperative new neurological deficit #	46/515 (8.9%)	24/259 (9.3%)	22/256 (8.6%)	0.878
Rate of recurrent/persistent sciatica*	(62/519) 11.9%	(34/259) 13.1%	(28/260) 10.8%	0.420
Rate of worsening pain (3 months leg pain worse than 6 weeks by 20 points)	(42/517) 8.1%	(25/258) 9.7%	(17/259) 6.6%	0.202
Reflex decrease or loss	166/527 (31%)	82/262 (31%)	84/265 (32%)	0.926
Positive straight leg raise	54/527 (10%)	22/262 (8%)	32/265 (12%)	0.196
Working status	300/527(56.9%)	146/262 (55.7%)	154/265 (58.1%)	0.598

VAS leg pain, VAS back pain, ODI, SF–36 MCS, and SF–36 PCS improvements were defined as the difference between the preoperative score and the score at 3-month follow-up. Improvement in motor and sensory deficit was defined as the number of patients that showed an improvement of motor or sensory function at 3-month follow-up compared with the preoperative status. Working status defines the number of patients working at the 3-month follow-up

VAS, Visual Analog Scale; *ODI*, Oswestry Disability Index; *SD*, standard deviation; *SF–36 PCS*, Short Form-36 physical component summary; *SF–36 MCS*, Short Form-36 mental component summary

#Including any new sensory or motor deficit

*These patients exclude the patients with known reherniation

low in our cohort, nerve root amputation during an additional device implantation after MLD is a very serious adverse event (SAE) and might be considered unacceptable considering the low rate of serious complications reported during standard surgical treatment of lumbar herniated disc. Therefore, nerve root lesions associated with the implantation of the device was defined as serious. The long-term side effects and impact on quality of life after nerve root amputation cannot be underestimated by the medical community. Considering the findings of this study and the pending results of the ongoing long-term analysis of the patients included in this study, the commercial implantation of the ACD was paused in our site. According to the complications reported, the authors recommend the implantation of the ACD to be performed only under the operative microscope after preoperative measurement of the intervertebral space and size of the disc aperture.

The current incidence of hematoma (1.3%) is similar to the literature (0.1–3.8%) [5, 8, 12, 14, 27, 39, 40, 42, 48, 49]

Table 10 Literature review on intraoperative parameters/findings, intraoperative complications, postoperative complications and length of hospitalization

Literature review of intraoperative parameters/findings, intraoperative complications, postoperative complications, and length of hospitalization

	Intraoperative parameters/findings		Intraoperative complications		Postoperative complications		Hospitalization
Authors	Mean operation time	Mean amount of blood loss	Dural injuries	Nerve root injuries	Hematoma	Infection	Mean length (days)
Carragee et al. 1999 [8]	Range from 0.8 to 2.5 h with mean of 1.6 h	142 ml	4.4% (8/180)	1.7% (3/180)	0.6% (1/180)	0.6% (1/180)	1.5
Wenger et al. 2001 [49]	n/a	n/a	0% (0/104)	0% (0/104)	3.8% (4/104)	2.9% (3/104)	n/a
Fountas et al. 2004 [17]	70.8 ± 1.1 min range from 50 and 135 min	185.6 ± 0.8 ml Range from 25 to 275 ml	n/a	n/a	n/a	n/a	20.7 ± 0.2 h
Thomé et al. 2005 [42]	38.2 ± 10.3 min microdiscectomy 32.6 ± 13.8 min sequestrectomy	78 ± 61.6 microdiscectomy 67 ± 85.4 ml sequestrectomy never exceeded 400 ml	0% (0/84)	0% (0/84)	0% (0/84)	1.2% (1/84)	2.9 ± 1.3
Saxler et al. 2005 [38]	n/a	n/a	3.2% (41/1280)	n/a	n/a	n/a	n/a
SPORT trial 2008 [48]	79.1 ± 36.3 min	64.7 ml/2% blood replacement	4% (10/232)	0.4% (1/253) in randomized cohort 0.2% (1/545) in cross-over cohort	0.7% (4/545) cross-over cohort	1.6% (4/253)	discharged day of surgery: 27% ≤ One night: 83%
Schick et al. 2009 [39]	n/a	n/a	0% (0/200)	0% (0/200)	0.5% (1/200)	0% (0/200)	6.94
Pechlivanis et al. 2009 [35]	100 min < 2 years' experience 65 min > 10 years' experience	n/a	2.6% (31/1205)	0.2% (2/1205)	n/a	n/a	n/a
Shamim et al. 2010 [40]	99.3 ± 45 min	n/a	8.6% DI (43/501)	n/a	0.2% (1/501)	2% (10/501)	5
Arts et al. 2011 [5]	n/a	n/a	n/a	n/a	0.9% (3/325)	0% (0/325)	3.3 ± 1.1
Fakouri et al. 2011 [14]	32 min microdiscectomy 24 min sequestrectomy	n/a	1% (1/101)	0% (0/101)	0% (0/101)	4% (4/101)	1.17 ± 0.38
Ahsan et al. 2012 [1]	n/a	n/a	0.8% (3/398)	0.3% (1/398)	n/a	0.3% (1/398)	5
Patel et al. 2013 [33]	n/a	n/a	2.7% (15/546)	n/a	n/a	1.5% (8/546)	n/a
Rihn et al. 2013 [37]	Non-obese 72.3 ± 33.5 min Obese 86.5 ± 43.5 min	Non-obese 56.1 ± 90.8 ml Obese 83.2 ± 121.4 ml 1% blood replacement in non-obese	n/a	n/a	n/a	n/a	Non-obese 0.89 ± 0.8 Obese 1.2 ± 1.2
Yoo et al. 2014 [53]	Normal weight 99.3 min Overweight 110.2 min Obese 119 min	Normal weight 85.2 ml Overweight 116.1 ml Obese 177.5 ml	7% (9/129)	n/a	n/a	n/a	Normal weight 6.9 Overweight 7.4 Obese 6.5
NSQIP database 2014 [19]	81.4 ± 42.4 min	n/a	n/a	n/a	n/a	1% (65/6846)	Discharged day of surgery: 41% ≤ One night: 85%
Choi et al. 2015 [12]	Mean 50 min ranging from 30 to 90 min	n/a	n/a	0.03% (3/10,228)	0.1% (6/10,228)	n/a	Within 1 day

Table 10 (continued)

Literature review of intraoperative parameters/findings, intraoperative complications, postoperative complications, and length of hospitalization

	Intraoperative parameters/findings		Intraoperative complications		Postoperative complications		Hospitalization
Authors	Mean operation time	Mean amount of blood loss	Dural injuries	Nerve root injuries	Hematoma	Infection	Mean length (days)
Shousha et al. 2015 [54]	n/a	n/a	n/a	n/a	n/a	0.09% (4/4350)	n/a
Our RCT study	70 ± 33 min ACDG 52 ± 26 min CG	94.2 ml ± 130.4 ACDG 63.5 ml ± 91.6 CG	4.8% (13) ACDG 2.5% (7) CG	1.8% (5) ACDG 1.8% (5) CG	1.1% (3) ACDG 1.1% (3) CG	1.1% (3) ACDG 1.1% (3) CG	3

RCT, randomized controlled trial; *n/a*, not available

(Table 10). Only 3 symptomatic patients in the CG required evacuation. Postoperative symptomatic lumbar epidural hematoma is rare (0.22%) with a revision incidence of 0.1–3% [3, 4, 24]. An increase in systolic blood pressure of ≥ 50 mmHg after extubation and a high BMI were identified as risk factors [24]. Interestingly, only patients in the CG had epidural hematomas leading to revision surgery, although blood loss was higher in the ACDG. This could be due to better hemostasis when a tendency for higher bleeding was observed, or perhaps the surgeons decided to use a drainage after ACD implantation.

Readmission within 3 months occurred in 7.4% of the ACDG and 11.2% of the CG. Other authors reported readmission rates of 7% within 30 days [40]. We observed a significant correlation with BMI and length of hospital stay, which is supported by Rihn et al. [37].

Early recurrent symptomatic lumbar disc herniations (RLD) at the index level within the first 3 months occurred in 4% of patients, and 2.2% underwent reoperation. The CG had 4.3 times higher early reherniation rate (CG: 6.5%, ACDG: 1.5%) and a 3 times higher reoperation rate (CG: 3.2%, ACGD: 1.1%, OR = 2.3 (0.9–5.7)). Although the reoperation rate was lower in the ACD group, the 2 patients undergoing reoperations due to device anchor migration should be considered major failures. The early reherniation and reoperation rates in our study are similar to previous reports (1.1–5.9%) [2, 12, 14, 19, 25, 27, 33, 39, 40, 48, 49].

Conclusion

Short-term outcome after MLD with or without implantation of ACD was similar in both groups. Patients included in the ACD group underwent fewer reoperations in the first 3 months after surgery. Nevertheless, longer operation time, higher amount of blood loss, and risk of nerve root lesion during device implantation should be considered additional risks in patients undergoing ACD implantation after MLD. Patients undergoing ACD implantation after MLD had fewer early reherniations and reoperations.

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Compliance with ethical standards

This study was approved by the local EC (Ethikkommission Nordwest- und Zentralschweiz, EKNZ, Nr. 2012-036). All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus;

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