ELSEVIER

The Spine Journal 8 (2008) 570–577

THE SPINE JOURNAL

Fusion assessment of posterior lumbar interbody fusion using radiolucent cages: X-ray films and helical computed tomography scans compared with surgical exploration of fusion

Guy R. Fogel, MD*, John S. Toohey, MD, Arvo Neidre, MD, John W. Brantigan, MD

South Texas Orthopedic and Spinal Surgery Associates, 9150 Huebner Road, San Antonio, TX 78240, USA

Received 29 October 2006; accepted 19 March 2007

Abstract

BACKGROUND: Plain radiographic assessment of posterolateral fusion has been reported as accurate in only two thirds of patients who were found to be healed at surgical exploration. Plain radiographic techniques for fusion assessment of interbody fusion with radiolucent cages are reported to be accurate. A helical computed tomography (CT) scan shows a high sensitivity for pseudarthrosis compared with plain radiography.

PURPOSE: To determine the accuracy of fusion assessment with plain X-ray films and helical CT scans by comparison to results of surgical exploration of fusion.

STUDY DESIGN/SETTING: The accuracy and interobserver agreement of plain X-ray films and thin-cut helical CT scans were compared with fusion assessment by surgical exploration in patients with posterior lumbar interbody fusion using a radiolucent carbon fiber reinforced polymer cage (CFRP) and iliac crest bone graft.

PATIENT SAMPLE: A review of 90 patients who had surgical exploration of the lumbar fusion.

OUTCOME MEASURES: All patients had plain X-ray films including Ferguson anteroposterior parallel to the interbody space. Fifty-four patients had thin-section helical CT scans.

METHODS: Fusion assessment by exploration was compared with blinded assessment by plain X-ray films and CT scans.

RESULTS: Ninety patients had surgical exploration of 172 lumbar interbody and posterolateral fusion levels. At the time of exploration, fusion was determined to be successful in 87 of 90 patients and 168 of 172 (97%) fusion levels. X-ray assessment showed healed interbody fusions in 87% and posterolateral fusion healed in 75%. CT grading of the interbody fusion found healed interbody fusion in 77%, and the posterolateral fusion was fused in 68%. Plain X-ray films and CT scans had a sensitivity of 100% for pseudarthrosis and a negative predictive value of 100% for healed fusion. Specificity was almost 90% and was not significantly different between X-ray films and CT scans.

CONCLUSIONS: Fusion assessment with plain X-ray films and helical CT scans showed equal accuracy after posterior lumbar interbody fusion confirmed by surgical exploration. Our results indicate that when plain X-ray films show strong evidence of fusion or pseudarthrosis, the helical CT is unlikely to provide useful new information.

Keywords: Spinal fusion; Evaluation methods; Outcome; Lumbar vertebrae; Radiography; Surgery; Tomography; X-ray computed

Introduction

Modern techniques combining posterolateral fusion (PLF) with interbody fusion (PLIF) using radiolucent interbody cages have increased the fusion rate to nearly 100% by plain radiographic assessment [1–5]. Nevertheless, 10% to 15% of patients may remain symptomatic. Accurate radiographic assessment of fusion success is important to

FDA device/drug status: approved for this indication (Lumbar I/F Cage and the VSP Spinal Fixation System).

Dr. Brantigan has a financial interest in the Lumbar I/F Cage.

* Corresponding author: South Texas Orthopedic and Spinal Surgery Associates, 9150 Huebner Road, San Antonio, TX 78240. Tel.: (210) 561-7234; fax: (210) 561-7240.

E-mail address: gfogel@satx.rr.com (G.R. Fogel)

1529-9430/08/$ – see front matter
doi:10.1016/j.spinee.2007.03.013

identify patients who might benefit from further surgery. Physicians have continued to struggle with the correct interpretation of radiographic methods. To date, the ‘‘gold standard’’ of fusion determination has been surgical exploration [6–8]. Comparison of plain radiographic assessment of posterolateral fusion does not correlate with surgical exploration in a third or more of patients [6,9,10]. Plain radiographic techniques for fusion assessment of PLIF with radiolucent cages have been compared with surgical exploration and have been reported to be accurate [1,2].

Improvement in computed tomography (CT) scanning has increased accuracy in fusion assessment. Early studies used only axial images, and, when compared with surgical exploration, they showed noncorrelation in up to 43% of cases [6]. More recently, thin-section 1 mm axial helical CT scans with sagittal and coronal reconstructions provide high-quality images with exquisite bone detail. Several helical CT studies have shown a high specificity for detection of pseudarthrosis compared with plain radiography particularly in evaluation of the interbody fusion [11–16].

From a single surgical cohort, we have performed a retrospective chart and radiographic review of 90 consecutive patients who had surgical exploration of the fusion after posterior lumbar interbody fusion at one or more levels. Our purpose was to show the accuracy of plain X-ray films and helical CT scans in fusion assessment. To our knowledge, a comparison of plain X-ray films and helical CT scans to surgical exploration in evaluation of PLIF with radiolucent cages has not been previously reported.

Materials and methods

Clinical study design

From February 1999 to October 2003, we performed PLIF using the Lumbar I/F Cage (DePuy Spine, Raynham, MA) with pedicle screw and plate fixation in our practice. Iliac crest bone autograft was used for the interbody fusion and local bone for the posterolateral fusion. Inclusion criteria included patients with disabling back pain because of degenerative disc disease at one or more lumbar levels and included patients with primary degenerative disc disease, failed discectomy, spondylolisthesis, failed fusion, and degenerative spondylolisthesis. During the spring of 2005, we conducted a retrospective chart review of all patients. From this group, 90 patients were identified who had surgical exploration of the lumbar fusion. There were 48 men and 42 women. The average age was 43 years (range, 27-70). The average time from the index fusion operation to the exploration of the fusion was 27.2 months (12-65 months). The indications for exploration of the fusion were persistent nonspecific low back pain in 63, adjacent-level operation for indications of instability or stenosis in 18, and radiographic pseudarthrosis in 10. The minimum follow-up after the index fusion operation was 24 months (mean, 38 months [median, 35 months; range, 24-68 months]).

Radiographic assessment of fusion

All patients underwent X-ray assessment of 172 levels of fusion before the surgical exploration using plain static X-ray films including anterior-posterior, lateral, and individual Ferguson views of each interbody fusion level. The Ferguson view is an anterior-posterior X-ray directed parallel to the end plates of the vertebral body designed to visualize the interbody fusion. Two of the authors (GRF and JST), blinded to the names of the patients and the results of the surgical exploration, independently graded the X-ray films for evidence of interbody and posterolateral fusion.

Fifty-four patients with 109 levels of fusion had thin-section helical CT scans with sagittal and coronal reconstructions before the exploration of fusion at an average of 30 months (range, 10-60 months) after the index surgery. These patients underwent 1-mm thin-section helical CT scanning of the involved lumbar segments performed on a high-speed helical scanner (Sensation 4; Siemens). Reconstructed images were generated in sagittal plane and coronal planes exactly perpendicular to the plane of each cage. Each helical CT scan was interpreted by one of three radiologists who were blinded with regard to the clinical history and the plain radiographic findings.

The interbody and posterolateral fusion were graded by two methods. Each level and each side was judged individually. Interbody fusion was graded by the method of Brantigan and Steffee [17] as modified to describe the Fraser definition of locked pseudarthrosis (BSF scale) [14] outlined in Table 1. The posterolateral fusion was graded by the method of Lenke et al. [18] outlined in Table 2.

Surgical exploration of fusion

At the time of exploration, the pedicle screws were removed. All soft tissue was removed from the fusion mass. The fusion mass, facet joints, and intertransverse areas

Table 1
Classification of interbody fusion success: Brantigan, Steffee, Fraser (BSF)

BSF-1: *Radiographical pseudarthrosis* is indicated by collapse of the construct, loss of disc height, vertebral slip, broken screws, displacement of the carbon cage, or significant resorption of the bone graft, or lucency visible around the periphery of the graft or cage.
BSF-2: *Radiographical locked pseudarthrosis* is indicated by lucency visible in the middle of the cages with solid bone growing into the cage from each vertebral endplate.
BSF-3: *Radigraphical fusion:* bone bridges at least half of the fusion area with at least the density originally achieved at surgery. Radiographical fusion through one cage (half of the fusion area) is considered to be mechanically solid fusion even if there is lucency on the opposite side.

Table 2
Lenke classification of posterolateral fusion success

Grade A: Definitely solid with bilateral trabeculated stout fusion masses present
Grade B: Possibly solid with a unilateral large fusion mass and a contralateral small fusion mass
Grade C: Probably not solid with a small fusion mass bilaterally
Grade D: Definitely not solid with bone graft resorption or obvious pseudarthrosis bilaterally

were carefully explored. Motion was evaluated by one or more methods. Where significant portions of the adjacent spinous processes remained, a Kocher clamp was used to apply distraction or compression; direct compression was placed on the fusion mass and facets with a large punch. Long pedicle probes were placed in each pedicle screw hole and used to apply compression and distraction. A solid posterolateral fusion was indicated by observation of a solid bridge of cortical bone bridging the posterolateral area. Posterolateral pseudarthrosis was indicated by either an observed defect in the bridging bone or by visible motion in the posterolateral fusion area. Each side of the posterolateral fusion was graded separately. Solid interbody fusion was indicated by total rigidity and lack of motion between the manipulated pedicle probes. Interbody pseudarthrosis was indicated by any relative motion between the manipulated pedicle probes.

Statistical methods

The sensitivity, specificity, positive predictive value, and negative predictive value for detecting pseudarthrosis were calculated for all plain X-ray films and the helical CT scans by comparing the results of the independent interpretations of those studies with the results of surgical exploration. The threshold for fusion was set at interbody radiographic fusion BSF-3 (Table 1) and posterolateral fusion at Lenke-A (Table 2). The values for the plain X-ray films were compared with those values for the helical CT scan, with use of the normal distribution to approximate the difference between any two percentages. Interobserver agreement for X-ray film interpretation was assessed with the chi square test, Fischer exact test, and the McNemar's test. Statistical analysis was performed by using SPSS 6.1.3 (SPSS Inc, Chicago, IL).

Results

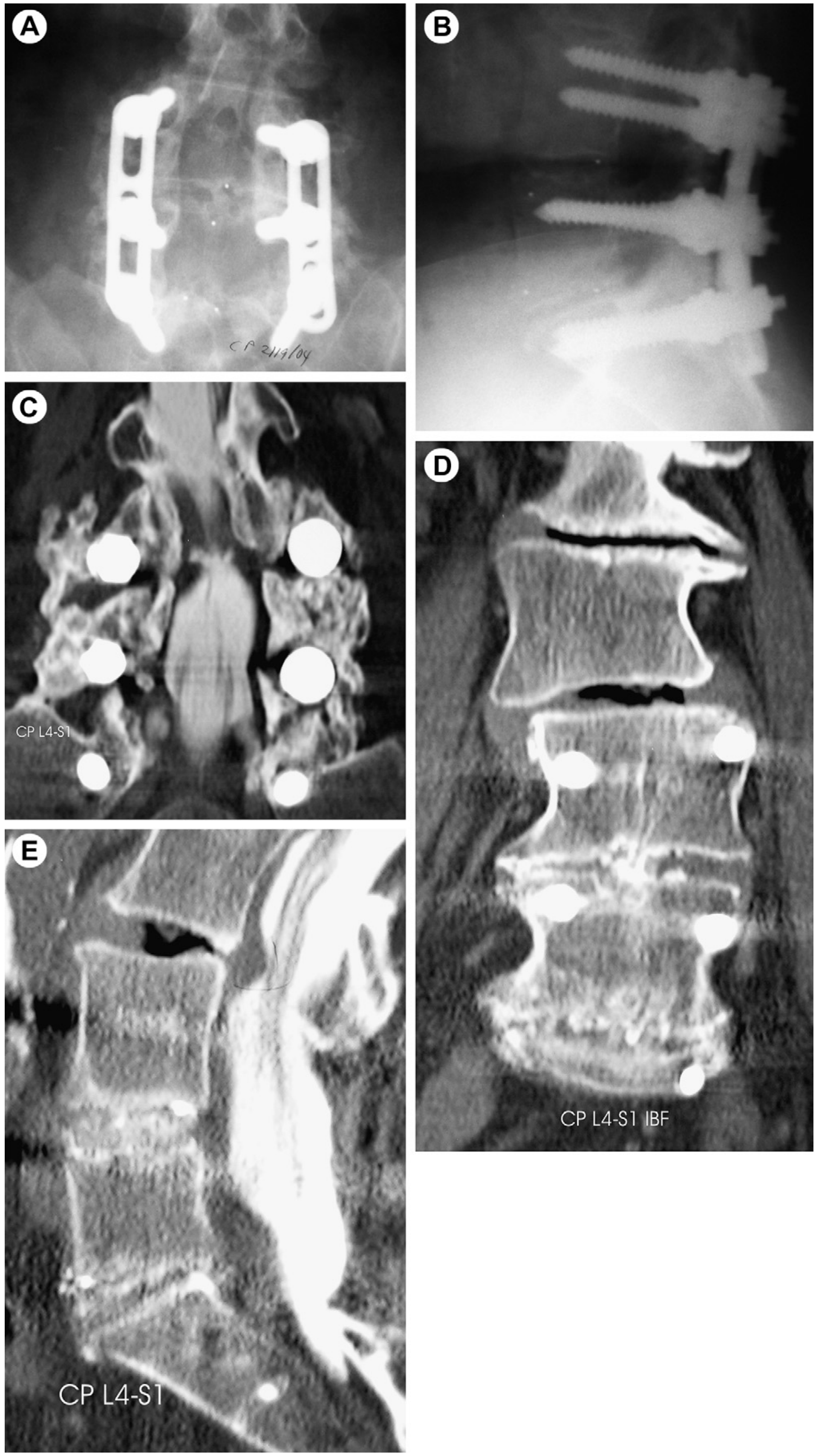
Ninety patients had surgical exploration of 172 lumbar interbody and posterolateral fusion levels (Table 3). At the time of exploration, fusion was determined to be successful in 87 of 90 patients and 168 of 172 (97%) fusion levels (Fig. 1). Surgical exploration revealed four pseudarthroses (4/172, 2.3%). Two of the four pseudarthroses occurred at L5–S1, one at L4–5, and one at L1–2. Because all pseudarthrosis levels were relatively stable, the pedicle screws were left out and augmentation of the posterolateral fusion was performed with a combination of supplemental local bone chips, demineralized bone graft, and/or bone morphogenic protein. The patient with L1–2 pseudarthrosis had two revision procedures. The first included removal of pedicle screws and augmentation of the posterior-lateral grafting. The second included reinstrumentation with pedicle screw fixation and augmentation of the posterior-lateral bone grafting (Fig. 2).

X-ray assessment showed healed interbody fusions in 87%, and the posterolateral fusion was healed bilaterally in 75% (Table 3). Interobserver agreement for X-ray interpretation was not significantly different comparing

Table 3
Fusion assessment of interbody fusion (BSF) and posterolateral fusion (Lenke)

		L5–S1 # (%)	L4–5 # (%)	L3–4 # (%)	L2–3 # (%)	L1–2 # (%)	Total levels (%)	Matched XR to CT (%)
Explored		69 (40)	69 (40)	23 (13)	9 (5)	2 (1)	172	
Pseudarthrosis		2	1	0	0	1	4 (2)	
Levels with CT		38	45	16	8	2	109	
BSF-3	XR	58 (84)	61 (88)	21 (91)	8 (89)	1 (50)	149 (87)	
	CT	28 (74)	39 (87)	15 (94)	7 (88)	1 (50)	90 (77)	86 (96)
BSF-2	XR	11 (16)	8 (12)	1 (4)	1 (11)	0	21 (12)	
	CT	9 (24)	6 (13)	1 (6)	1 (13)	0	17 (16)	9 (53)
BSF-1	XR	0	0	1 (4)	0	1 (50)	2 (1)	
	CT	1 (3)	0	0	0	1 (50)	2 (2)	1 (50)
Lenke-A	XR	57 (83)	48 (70)	17 (74)	6 (67)	1 (50)	129 (75)	
	CT	28 (74)	26 (58)	13 (81)	6 (75)	1 (50)	74 (68)	63 (85)
Lenke-B	XR	7 (10)	14 (20)	3 (13)	2 (22)	0	26 (16)	
	CT	1 (3)	10 (22)	2 (13)	0	0	13 (12)	6 (46)
Lenke-C/D	XR	5 (7)	7 (10)	3 (13)	1 (11)	1 (50)	17 (9)	
	CT	9 (24)	9 (20)	1 (6)	2 (25)	1 (50)	22 (25)	2 (40)

There were 172 levels explored. Four of 172 were pseudarthroses at surgical exploration. All levels had X-ray films, and 109 levels had helical CT scans. The image grading is reported as the number of levels with that grade and a percentage of levels with X-ray film or CT scan. Matching image grading is reported as number of X-ray films to CT scan matches as a percentage of levels with CT scans.


A
B
C
CP L4-S1
D
CP L4-S1 IBF
E
CP L4-S1

interbody and posterolateral fusion level by level and overall (chi-square test=0.5595, p=.455, Fischer exact test=.046, and McNemar's=5.400, p=.02). The proportion of overall agreement between observers was 98.6%.

CT grading of the interbody fusion found solidly healed interbody fusion in 77%, and the posterolateral fusion was solidly fused bilaterally in 68% (Table 3). When the CT scan showed a healed interbody or posterolateral fusion, the X-ray film was also healed in 96%. If the CT scan showed a healed posterolateral fusion, the X-ray film was also healed in 85% (Table 3).

Table 4 presents the data to calculate the sensitivity, specificity, positive and negative predictive values for plain X-ray films, and CT fusion assessment confirmed at exploration. The incidence of pseudarthrosis at the time of surgical exploration was 4/172 levels or 2.3%. Sensitivity refers to how good a radiographic test is at correctly identifying fusion levels with pseudarthrosis. When calculating sensitivity, we are therefore interested in only the fusion levels with pseudarthrosis. The sensitivity of both CT and plain X-ray films was 100% in correctly identifying pseudarthrosis. Specificity, on the other hand, is concerned with how good the radiographic test is at correctly identifying fusion levels that are healed and do not have a pseudarthrosis. Specificity was almost 9 of 10 and was not significantly different between X-ray film and CT scan at the chosen threshold for fusion. The positive predictive value refers to the chance that a positive radiographic test for pseudarthrosis will be correct (ie, the chance was less than one in four that there was a pseudarthrosis at exploration when the X-ray films were interpreted as below the threshold for fusion). The negative predictive value is concerned only with the radiographic tests negative for pseudarthrosis. When the radiographic test was solidly healed (negative for pseudarthrosis), 100% of the levels were healed at exploration.

The plain X-ray findings of the CT group were compared with that of those patients who did not have a CT scan. The incidence of solid fusion was not significantly different in the two groups. However, the incidence of pseudarthrosis was significantly greater in the CT group. All of the patients with obvious plain radiographic pseudarthrosis did have adjunctive CT scanning. All cases of surgical pseudarthrosis had both plain X-ray and helical CT studies.

Discussion

The accuracy of distinguishing posterolateral fusion success from PLIF fusion success by surgical exploration is based on observations made over many years. Numerous authors have noted that a solid posterolateral fusion has flexibility of motion up to 4° or 5° [19–22]. Unlike a posterolateral fusion, a successful interbody fusion creates a totally rigid motion segment [23–25]. Luk et al. [24] evaluated 52 cases of anterior lumbar interbody fusion 5 years after surgery and noted there was an average of 1° of motion measured in the fused segment and 12° to 15° in the adjacent nonfused segments. The authors attributed the 1° of motion to artifact and rotational and measurement variations.

The possible errors in each surgical determination should be considered individually. Failed PLIF and failed PLF should be the easiest and most accurate category to evaluate surgically because there is a definite gap in the posterolateral fusion mass. Axial compression and distraction shows definite motion in the posterolateral area, and flexion forces on the pedicle probes show motion in the interbody area. With healed PLIF and failed PLF, the pedicle probes show no motion on flexion or extension forces; however, there is a visible discontinuity in the posterolateral fusion mass. With failed PLIF and healed PLF, there will be a solid bridge of bone bridging the posterolateral fusion area. Axial distraction or compression produces no motion in the posterolateral area, but flexion forces on the pedicle probes produces a slight motion or "springiness." Admittedly, this category provides the greatest possibility of misinterpretation. With experience, healed PLIF and healed PLF category can be accurately determined because there is solid bridging posterolateral bone with no motion on either axial or flexion forces. A locked pseudarthrosis should appear to be a healed PLIF because, by definition, this type of segment is stable. Although this result is correctly described as "pseudarthrosis," it should not be considered a noncorrelation in the two-by-two analysis or surgical exploration.

In this study, both the helical CT scans and plain radiography were found to be highly accurate with high sensitivity for pseudarthrosis and high negative predictive value for healed fusion. Helical CT scans did not miss a single pseudarthrosis. Plain X-ray films missed one pseudarthrosis at L5–S1 that was diagnosed with a helical CT scan. The negative predictive value was the most important measure of accuracy. For both X-ray films and CT scans, the negative predictive value was 100% when either the interbody fusion or the posterolateral fusion was solidly healed. The only difference between X-ray films and CT scans was the number of false-positive readings for pseudarthrosis, reflected by the positive predictive value. The X-ray films

Fig. 1. True-negative healed fusion at L4–S1 graded 3A on plain X-ray films and 3B on CT scan and confirmed to be healed by exploration. (A) An anteroposterior view parallel to L4–5 end plates shows a single interbody cage with bridging bone at L4–5 (BSF-3) and bridging bone bilateral in posterolateral fusion (Lenke "A"). (B) A lateral view with bridging bone across the L4–5 interspace. (C) A CT coronal view through posterolateral graft bridging bone across transverse processes bilatrally (Lenke "A"). (D) A CT coronal view through interspace (BSF-3). (E) A CT sagittal view through interbody spaces showing bridging bone (BSF-3").


A
B
C
EN 5-28-04
D
E

Table 4
True-and false positive and-negative findings of surgical exploration to X-ray films and CT scan fusion assessment

X-ray	TP	FN	FP	TN
Interbody fusion	4	0	19	149
Posterolateral fusion	4	0	39	129
CT Scan				
Interbody fusion	4	0	15	90
Posterolateral fusion	4	0	31	74

TP=True-positive represents pseudarthrosis at exploration and by radiographical criteria. FN=False-negative or pseudarthrosis at exploration and BSF-3 by radiographical criteria, FP=false-positive is healed fusion at exploration and less than BSF-3 by radiographic criteria, TN=true negative is healed fusion at exploration and BSF-3 by X-ray film criteria.

falsely predicted pseudarthrosis in 6% and the CT scans in 8%. The false-positive test result was not significantly different between the two modalities in assessment of either interbody fusion (chi-square test=.4624, p=.4965) or posterolateral fusion (chi-square test=.012, p=.9609).

The plain radiographic diagnosis of a successful interbody arthrodesis was enhanced by a radiolucent implant filled with cancellous iliac crest graft and standardized radiographic technique including the Ferguson view of the interbody space. In other studies, accuracy in determining fusion was diminished because of the metallic posterior and anterior interbody instrumentation obscuring the bone graft. Metallic implants obscure the bone graft within, making it difficult to see remodeling or trabeculations that have formed across the interspace between the end plates. When cortical bone chips or synthetic filler is mixed with the cancellous bone graft, the graft is more radio-opaque and remodeling or resorption must be interpreted to assess the progress of bone fusion. Plain X-ray films are dependent on obtaining a true lateral and a true Ferguson parallel view of the interbody end plates. Suboptimal films when seen should be repeated.

A helical CT scan with sagittal and coronal reconstructions has become the preferred imaging to assess both posterolateral and interbody fusion [12,14,26,27]. CT coronal reconstructions are particularly helpful in evaluation of the continuity of the posterolateral fusion. With the fine detail of bone trabeculations within the interspace, a helical CT scan would seem to be the ideal adjunct imaging for evaluation of suspected pseudarthrosis. However, a helical CT scan may overestimate the significance of lucencies in the interbody space and may not correctly predict fusion at exploration. Comparison of true positives and true negatives for X-ray films (Table 4) found no significant difference between the imaging modalities (chi-square test= 1.172, p=.2789). The accuracy of plain x-ray films and helical thin-cut CT scans methods was not statistically different when compared with the results of surgical exploration.

One point of concern with this study is that surgical exploration of a lumbar fusion is not commonly indicated today. Indications for late re-exploration of a lumbar fusion (more than 1 year after initial fusion) are commonly radiographic pseudarthrosis, persistent pain or recurrent symptoms, instrumentation failure, or progressive degeneration at another spine level [6,8–10,28–31]. Martin et al. [31] found the rate of late reoperation was 21.5% after lumbar fusion. The indications for late reoperation more than year after fusion are not significantly different than the Brantigan FDA-IDE series in 2000 and 10-year follow-up in 2004 [1,2]. A statistical problem of this study is the small incidence of pseudarthrosis. A larger sample size would clarify our results [32]. Another concern is that this study may have been better if all patients had both CT and plain radiographic studies. However, statistical comparison of patients with and without CT studies showed no significant differences in fusion grades. In practical clinical use for our study group, admittedly without statistical support of efficacy, helical CT scans were more often performed in patients in whom the plain films showed indeterminate evidence of fusion. With these results, the additional cost and increased radiation exposure with helical CT scanning may not be justified. Our results indicate that when the plain films show strong evidence either of fusion or pseudarthrosis, the helical CT is unlikely to provide useful new information.

Conclusion

In a study of surgical exploration after PLIF and posterolateral fusion using a radiolucent interbody fusion device, X-ray and CT methods performed very similarly in evaluating lumbar fusion success with no significant differences in accuracy between the two methods. Both x-ray and helical CT scans predicted pseudarthrosis with 100% sensitivity and interbody and posterolateral fusion success with a 100% negative predictive value. Our results indicate that when plain films show strong evidence of fusion or pseudarthrosis the helical CT is unlikely to provide useful new information.

Fig. 2. A patient with true-positive pseudarthrosis of L1–2 fusion. Plain X-ray films graded "1D," CT scan graded "1D," and L1–2 pseudarthrosis was found at exploration. (A) An anteroposterior view of L1–2; no posterolateral fusion mass is visible (Lenke "D") and lucencies around the interbody cages (BSF-1) are seen. (B) A lateral view showing subsidence of the cages with lucencies between the end plate and the cages (BSF-1). (C) A CT coronal with poor posterolateral fusion mass on only one side (Lenke "C"). (D) A CT coronal through interspace showing lucencies around the cages (BSF-1). (E) A CT sagittal view with subsidence and lucencies around an interbody cage (BSF-1).

References

[1] Brantigan JW, Neidre A, Toohey JS. The lumbar I/F cage for posterior lumbar interbody fusion with the variable screw placement system: 10-year results of a Food and Drug Administration clinical trial. Spine J 2004;4:681–8.

[2] Brantigan JW, Steffee AD, Lewis ML, Quinn LM, Persenaire JM. Lumbar interbody fusion using the Brantigan I/F cage for posterior lumbar interbody fusion and the variable pedicle screw placement system: two-year results from a Food and Drug Administration investigational device exemption clinical trial. Spine 2000;25: 1437–46.

[3] Kim KS, Yang TK, Lee JC. Radiological changes in the bone fusion site after posterior lumbar interbody fusion using carbon cages impacted with laminar bone chips: follow-up study over more than 4 years. Spine 2005;30:655–60.

[4] Miura Y, Imagama S, Yoda M, Mitsuguchi H, Kachi H. Is local bone viable as a source of bone graft in posterior lumbar interbody fusion? Spine 2003;28:2386–9.

[5] Stromberg L, Toohey JS, Neidre A, Ramsey M, Brantigan JW. Complications and surgical considerations in posterior lumbar interbody fusion with carbon fiber interbody cages and Steffee pedicle screws and plates. Orthopedics 2003;26:1039–43.

[6] Brodsky AE, Kovalsky ES, Khalil MA. Correlation of radiologic assessment of lumbar spine fusions with surgical exploration. Spine 1991;16(6 suppl):S261–5.

[7] Cleveland M, Bosworth D, Thompson F. Pseudarthrosis in the lumbosacral spine. J Bone Joint Surg Am 1948;30:302–12.

[8] Hilibrand AS, Dina TS. The use of diagnostic imaging to assess spinal arthrodesis. Orthop Clin North Am 1998;29:591–601.

[9] Blumenthal SL, Gill K. Can lumbar spine radiographs accurately determine fusion in postoperative patients? Correlation of routine radiographs with a second surgical look at lumbar fusions. Spine 1993;18:1186–9.

[10] Kant AP, Daum WJ, Dean SM, Uchida T. Evaluation of lumbar spine fusion. Plain radiographs versus direct surgical exploration and observation. Spine 1995;20:2313–7.

[11] Lang P, Genant HK, Chafetz N, Steiger P, Morris JM. Three-dimensional computed tomography and multiplanar reformations in the assessment of pseudarthrosis in posterior lumbar fusion patients. Spine 1988;13:69–75.

[12] Burkus JK, Transfeldt EE, Kitchel SH, Watkins RG, Balderston RA. Clinical and radiographic outcomes of anterior lumbar interbody fusion using recombinant human bone morphogenetic protein-2. Spine 2002;27:2396–408.

[13] Chafetz N, Cann CE, Morris JM, Steinbach LS, Goldberg HI, Ax L. Pseudarthrosis following lumbar fusion: detection by direct coronal CT scanning. Radiology 1987;162:803–5.

[14] Santos ER, Goss DG, Morcom RK, Fraser RD. Radiologic assessment of interbody fusion using carbon fiber cages. Spine 2003;28: 997–1001.

[15] Siambanes D, Mather S. Comparison of plain radiographs and CT scans in instrumented posterior lumbar interbody fusion. Orthopedics 1998;21:165–7.

[16] Shah RR, Mohammed S, Saifuddin A, Taylor BA. Comparison of plain radiographs with CT scan to evaluate interbody fusion following the use of titanium interbody cages and transpedicular instrumentation. Eur Spine J 2003;12:378–85.

[17] Brantigan JW, Steffee AD. A carbon fiber implant to aid interbody lumbar fusion. Two-year clinical results in the first 26 patients. Spine 1993;18:2106–7.

[18] Lenke LG, Bridwell KH, Bullis D, Betz RR, Baldus C, Schoenecker PL. Results of in situ fusion for isthmic spondylolisthesis. J Spinal Disord 1992;5:433–42.

[19] Zdeblick TA. A prospective, randomized study of lumbar fusion. Preliminary results. Spine 1993;18:983–91.

[20] Frymoyer JW, Hanley EN Jr, Howe J, Kuhlmann D, Matteri RE. A comparison of radiographic findings in fusion and nonfusion patients ten or more years following lumbar disc surgery. Spine 1979;4: 435–40.

[21] Lehmann TR, Spratt KF, Tozzi JE, et al. Long-term follow-up of lower lumbar fusion patients. Spine 1987;12:97–104.

[22] Kuslich SD, Danielson G, Dowdle JD, et al. Four-year follow-up results of lumbar spine arthrodesis using the Bagby and Kuslich lumbar fusion cage. Spine 2000;25:2656–62.

[23] Pearcy MJ, Whittle MW. Movements of the lumbar spine measured by three-dimensional X-ray analysis. J Biomed Eng 1982;4:107–12.

[24] Luk KD, Chow DH, Evans JH, Leong JC. Lumbar spinal mobility after short anterior interbody fusion. Spine 1995;20:813–8.

[25] Lee CK, Langrana NA. Lumbosacral spinal fusion. A biomechanical study. Spine 1984;9:574–81.

[26] Cook SD, Patron LP, Christakis PM, Bailey KJ, Banta C, Glazer PA. Comparison of methods for determining the presence and extent of anterior lumbar interbody fusion. Spine 2004;29:1118–23.

[27] Williams AL, Gornet MF, Burkus JK. CT evaluation of lumbar interbody fusion: current concepts. AJNR Am J Neuroradiol 2005;26: 2057–66.

[28] McAfee PC, Cunningham BW, Lee GA, et al. Revision strategies for salvaging or improving failed cylindrical cages. Spine 1999;24: 2147–53.

[29] Wild A, Pinto MR, Butler L, Bressan C, Wroblewski JM. Removal of lumbar instrumentation for the treatment of recurrent low back pain in the absence of pseudarthrosis. Arch Orthop Trauma Surg 2003; 123:414–8.

[30] Nottingham P, Ball H. Hardware removal surgery in patients with persistent low back pain. Presented at the North American Spine Society Meeting. 2005. Philadelphia, PA.

[31] Martin BI, Mirza SK, Comstock BA, Gray DT, Kreuter W, Deyo RA. Reoperation rates following lumbar spine surgery and the influence of spinal fusion procedures. Spine 2007;32:382–7.

[32] Smith JE, Winkler RL, Fryback DG. The first positive: computing positive predictive value at the extremes. Ann Intern Med 2000;132:804–9.