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Clinical outcomes of posterior lumbar interbody fusion in chronic renal failure patients on hemodialysis

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ABSTRACT

Chronic kidney disease (CKD) and its treatment with hemodialysis (HD) pose unique challenges for spinal surgery due to complications such as destructive spondyloarthropathy (DSA). This study retrospectively compared the surgical outcomes of posterior lumbar interbody fusion (PLIF) between 48 HD patients and 57 non-HD controls. Patients with tumors, infections, prior spinal surgery, or severe osteoporosis were excluded. HD patients had a mean dialysis duration of 16.2 years, while controls were treated for degenerative lumbar conditions. HD patients exhibited significantly higher intraoperative blood loss (415.8 ± 231.7 mL vs 293.4 ± 57.3 mL, $P < 0.001$) and lower 2-year bony fusion rates (72.9% vs 94.7%, $P = 0.008$). Pseudoarthrosis and adjacent segment disease (ASD) were more common in the HD group, necessitating reoperation in five cases versus one in controls. Neurological recovery at 2 years was worse in the HD group, with a mean Japanese Orthopaedic Association score of 19.6 ± 4.3 compared to 26.5 ± 2.2 in controls ($P < 0.01$). Despite facilitating initial neurological recovery, PLIF outcomes in HD patients were compromised by greater complication rates, including pseudoarthrosis and ASD. Thus, PLIF facilitates early neurological improvement in HD patients, but long-term functional outcomes are compromised due to higher rates of pseudoarthrosis and ASD, necessitating careful long-term management. Strategies minimizing mechanical stress and maintaining spinal alignment could further support long-term patient recovery.

Keywords: adjacent segment disease, bone fragility, chronic renal failure, destructive spondyloarthropathy, hemodialysis

Abbreviations:
HD: hemodialysis
PLIF: posterior lumbar interbody fusion
ASD: adjacent segment disease
JOA: Japanese Orthopaedic Association
CKD: chronic kidney disease
DSA: destructive spondyloarthropathy

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INTRODUCTION

Chronic kidney disease (CKD) has emerged as a critical global health concern, with its prevalence steadily increasing because of population aging and prevalence of diabetes mellitus. In the past decade, CKD cases have increased by 15%, highlighting the urgent need for effective, long-term management strategies.[1,2] Hemodialysis (HD) remains a life-sustaining treatment modality for CKD, significantly extending their lifespan. However, chronic maintenance HD is associated with a myriad of complications, including dialysis-related amyloidosis and osteoarthritis, which severely affect patients' quality-of-life and mobility.[1,2]

Destructive spondyloarthropathy (DSA) is one of the most severe complications arising from long-term HD; it was first described by Kuntz et al[3] in 1984. DSA is characterized by intervertebral disc space narrowing, vertebral erosion, and irregular endplate destruction, typically without significant osteophyte formation.[3] The estimated incidence of DSA in patients undergoing HD is approximately 20%, particularly affecting the cervical spine.[4-6] Sudo et al highlighted the vulnerability of the cervical spine due to the accumulation of β2-microglobulin amyloid deposits, which contribute to structural instability and neurological impairment.[7]

Although surgical interventions such as pedicle screw fixation and circumferential spinal fusion have demonstrated promise in the management of cervical DSA, significant challenges remain, particularly due to the progressiveness of the disease and associated comorbidities. Cervical DSA has received much attention in the literature; however, the lumbar spine is similarly at risk of destructive processes in patients undergoing HD. Posterior lumbar interbody fusion (PLIF) is a well-established surgical technique for managing spondylosis and spinal instability, offering enhanced fusion rates, deformity correction, and stabilization. However, performing PLIF in patients undergoing HD presents unique challenges because of the combination of severe bone fragility, amyloid deposition, and metabolic disturbances resulting from CKD.[4,5] These factors not only increase the risk of perioperative complications but also contribute to poorer postoperative outcomes, including pseudoarthrosis and revision surgery.[8-11]

Although PLIF is an important approach for managing spinal instability in patients undergoing HD, large-scale studies are lacking, and few studies have directly compared outcomes with those of nonHD populations. Thus, this study aimed to address this gap by comparing the surgical outcomes of PLIF between patients undergoing HD and nonHD controls, thereby offering insights that could inform more effective management strategies for this vulnerable patient group.

MATERIALS AND METHODS

This study retrospectively enrolled 67 patients undergoing HD for CKD who underwent single-level PLIF. This study was conducted at a single institution. The study's inclusion criteria were as follows: adult patients (aged ≥20 years) who had undergone single-level PLIF and had at least 2 years of follow-up available after surgery. The exclusion criteria were as follows: presence of tumors, infections, previous spinal surgery, severe osteoporosis, severe psychiatric or neurological disorders, or any spinal surgery involving more than one level or minimally invasive PLIF. Patients with systemic diseases, such as malignancies or autoimmune disorders (eg, rheumatoid arthritis) that could affect surgical outcomes were also excluded.

This study was conducted in accordance with the ethical standards of Nagoya University Graduate School of Medicine and the 1964 Declaration of Helsinki and its later amendments. This retrospective study was conducted in accordance with the guidelines of the institutional review board, and informed consent was obtained in the form of opt-out, whereby participants were provided the opportunity to decline the use of their data.

Four patients who could not be followed for >2 years after surgery were excluded, resulting in 48 final participants (31 males and 17 females; mean age, 61.2 ± 13.2 years). The mean HD duration was 16.2 (range, 7–33) years. The fusion levels L1/2 (n = 1), L2/3 (n = 1), L3/4 (n = 15), L4/5 (n = 26), and L5/S (n = 5; Table 1).

Table 1 Baseline data

	HD group (n = 48)	Control group (n = 57)	*P*
Age (years)	61.2 ± 13.2	62.0 ± 16.1	NS
Sex (male:female)	31/17	36/21	NS
DM	19	14	0.14
Disease			
DSA	48	–	
Canal stenosis	–	31	
Degenerative spondylolisthesis	–	16	
Disc hernia	–	4	
Spondylolisthesis	–	4	
Degenerative scoliosis	–	2	
Level			0.02
L1/2 (n)	1	–	
L2/3 (n)	1	5	
L3/4 (n)	15	3	
L4/5 (n)	26	48	
L5/S (n)	5	1	
Graft bone			
Iliac (n)	31	43	NS

DM: diabetes mellitus
DSA: destructive spondyloarthropathy
HD: hemodialysis
NS: not significant

For the control group, 98 patients not undergoing HD who underwent single-level PLIF were retrospectively enrolled. After excluding patients with infections, tumors, previous spinal surgery, rheumatoid arthritis, or severe osteoporosis or those who underwent minimally invasive PLIF, 57 participants remained. Diagnoses in the control group included lumbar spinal canal stenosis (n = 31), degenerative lumbar spondylolisthesis (n = 16), lumbar disc herniation (n = 4), lumbar spondylolisthesis (n = 4), and lumbar degenerative scoliosis (n = 2). Fusion levels in the control group were L2/3 (n = 5), L3/4 (n = 3), L4/5 (n = 48), and L5/S (n = 1; Table 1).

Surgical method

PLIF was performed using a standardized technique by three surgeons at the same institution, ensuring uniformity in the procedure. All procedures were performed under general anesthesia, with the patient in the prone position. A midline incision was made over the affected spinal level, and the spine was accessed using a posterior approach. To minimize instability while preserving ligament integrity, two-thirds of the facet joint at the fusion level was excised.

Titanium pedicle screws and rods were used for fixation, and the disc and cartilaginous endplates were meticulously removed to prepare the graft bed. The iliac bone or locally milled bone chips were implanted anteriorly and laterally in the interbody space, and two titanium cages filled with graft material were then insertion. The iliac bone was used in 64.6% patients in the HD group and 75.4% in the control group (Table 1). All patients received standardized perioperative care, including the administration of prophylactic antibiotics and thromboprophylaxis according to institutional protocols.

Postoperative care and follow-up

Postoperatively, patients were mobilized within 48 h, and physical therapy was initiated during hospitalization. All patients were followed regularly in the outpatient clinic at 3, 6, and 12 months and then annually thereafter. To assess bony fusion and implant stability, radiographs were obtained at each follow-up. Computed tomography (CT) scans were obtained if pseudoarthrosis was suspected. At each follow-up visit, neurological function was evaluated using the Japanese Orthopaedic Association (JOA) score for lumbar spinal stenosis.

Fusion was defined as the presence of continuous bone bridging across the graft site without evidence of implant loosening or motion on flexion–extension radiographs, with less than 3° of motion, and confirmed by CT showing bone continuity at the fusion site. Pseudoarthrosis was identified as the absence of bone bridging and the presence of hardware failure or motion at the fusion level. Adjacent segment disease (ASD) was defined as new-onset neurological symptoms caused by degenerative changes at the levels adjacent to the fused segment.

Statistical analysis

Continuous variables were expressed as means ± standard deviations and compared between groups by Student's t-test for normally distributed data. Categorical variables were analyzed using the chi-square test. The significance level was set at $P < 0.05$. Kaplan–Meier survival analysis was performed to evaluate the time to reoperation because of ASD, and the log-rank test was employed to compare survival curves between the groups. All statistical analyses were conducted using IBM SPSS Statistics version 29.0 (IBM Corp, Armonk, NY, USA).

RESULTS

Baseline characteristics, including age, and sex distribution were not significantly different between the HD and control groups. The HD group had DSA, whereas the control group had various diagnoses, including canal stenosis and degenerative spondylolisthesis. A significant difference in fusion levels was observed between the two groups ($P = 0.02$), with L4/5 as the most common level in both groups. Graft bone usage (iliac or local) was not significantly different between the groups.

Blood loss and operation time

Operation times were not significantly different between the HD (120.3 ± 34.2 min) and control (122.4 ± 26.1 min) groups ($P > 0.05$). However, the mean intraoperative blood loss was significantly greater in the HD group (415.8 ± 231.7 mL) than in the control group (293.4 ±

57.3 mL) ($P < 0.001$).

Neurological recovery

Figure 1 illustrates the neurological assessment results, depicted using the JOA score for lumbar spinal stenosis. Preoperative scores were comparable between the HD group (14.3 ± 4.0) and the control group (15.6 ± 3.9). One year after surgery, scores remained comparable (HD group, 25.2 ± 3.4; control group, 26.3 ± 2.5). However, at 2 years after surgery, the HD group exhibited significantly worse JOA scores (19.6 ± 4.3) than the control group (26.5 ± 2.2) ($P < 0.01$), indicating a significant decline in neurological recovery over time in the HD group.

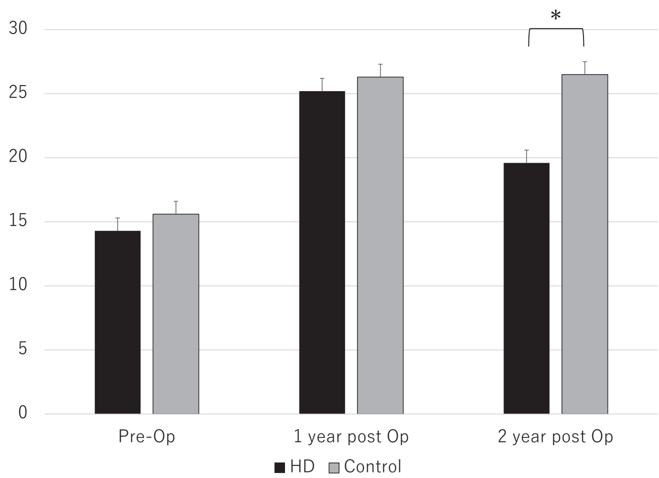

Fig. 1 Comparison of clinical outcomes (JOA score) between the hemodialysis (HD) and control groups over time

The graph shows the mean values with standard deviations at preoperation (Pre-Op), 1 year postoperation (1 year post Op), and 2 years postoperation (2 year post Op) in the HD and control groups. Significant differences between the HD and control groups are indicated by brackets ($P < 0.05$).

JOA: Japanese Orthopaedic Association

Perioperative and postoperative complications

The overall frequency of perioperative complications was not significantly different between the groups. However, the HD group experienced one case of deep wound infection, which proved challenging to manage, and one case of gastrointestinal bleeding, necessitating intensive care unit admission because of unstable vital signs.

Within 2 years after surgery, bony fusion was achieved in 35 (72.9%) patients in the HD group and 54 (94.7%) in the control group. The incidence of pseudoarthrosis was significantly higher in the HD group ($P = 0.008$). ASD occurred in 10 (20.8%) patients in the HD group and 5 (8.7%) in the control group. Although postoperative improvement in ASD symptoms was initially observed, it gradually deteriorated, resulting in radicular pain and/or sensory and motor disturbances because of adjacent segment degeneration.

Reoperation for ASD was necessary in five patients in the HD group and one in the control group. Table 2 details the clinical courses of these patients, revealing a significantly shorter interval between the first and second operations in the HD group (19 months) than in the control group (41 months), highlighting the rapid progression of ASD in the HD group.

Table 2 Detail data for patients who underwent reoperation

Case	Age (yr)/ Sex	Group (Diagnosis)	Duration of HD (yrs)	JOA Score (Preop.)	JOA Score (Max)	JOA Score (Pre-2nd Op)	Time to 2nd Operation (mo)	1st Operation	2nd Operation
1	66/M	HD	15	6	26	8	16	L4/5 PLIF	L5/S PLIF
2	75/M	HD	6	15	24	4	20	L4/5 PLIF	L2/3/4 PLIF
3	57/M	HD	24	9	25	12	26	L4/5 PLIF	L3/4 PLIF
4	68/F	HD	14	11	27	9	15	L4/5 PLIF	L2/3/4 PLIF
5	53/M	HD	20	17	24	11	18	L4/5 PLIF	L3/4 PLIF
6	74/F	Control (degenerative scoliosis)	–	14	26	13	41	L4/5 PLIF	L5/S PLIF

F: female
HD: hemodialysis
JOA: Japanese Orthopaedic Association
M: male
PLIF: posterior lumbar interbody fusion
Preop.: preoperative

Representative case

A 54-year-old male veterinarian with a history of CKD, who was undergoing dialysis for 5 years, and diabetes mellitus presented with acute onset of pain in the lower back, bilateral buttocks, and left lower limb, which significantly impaired his ability to stand and walk (Figure 2). He also reported pain while lying supine. He was referred to our clinic from a nearby hospital for surgical intervention. The JOA score was eight points. Radiographic images confirmed lumbar spinal stenosis and degenerative spondylolisthesis at L4–5. The patient underwent a PLIF. At the 2-year follow-up, the patient remained symptom-free, with no recurrence of lower limb pain; however, bony fusion was not achieved.

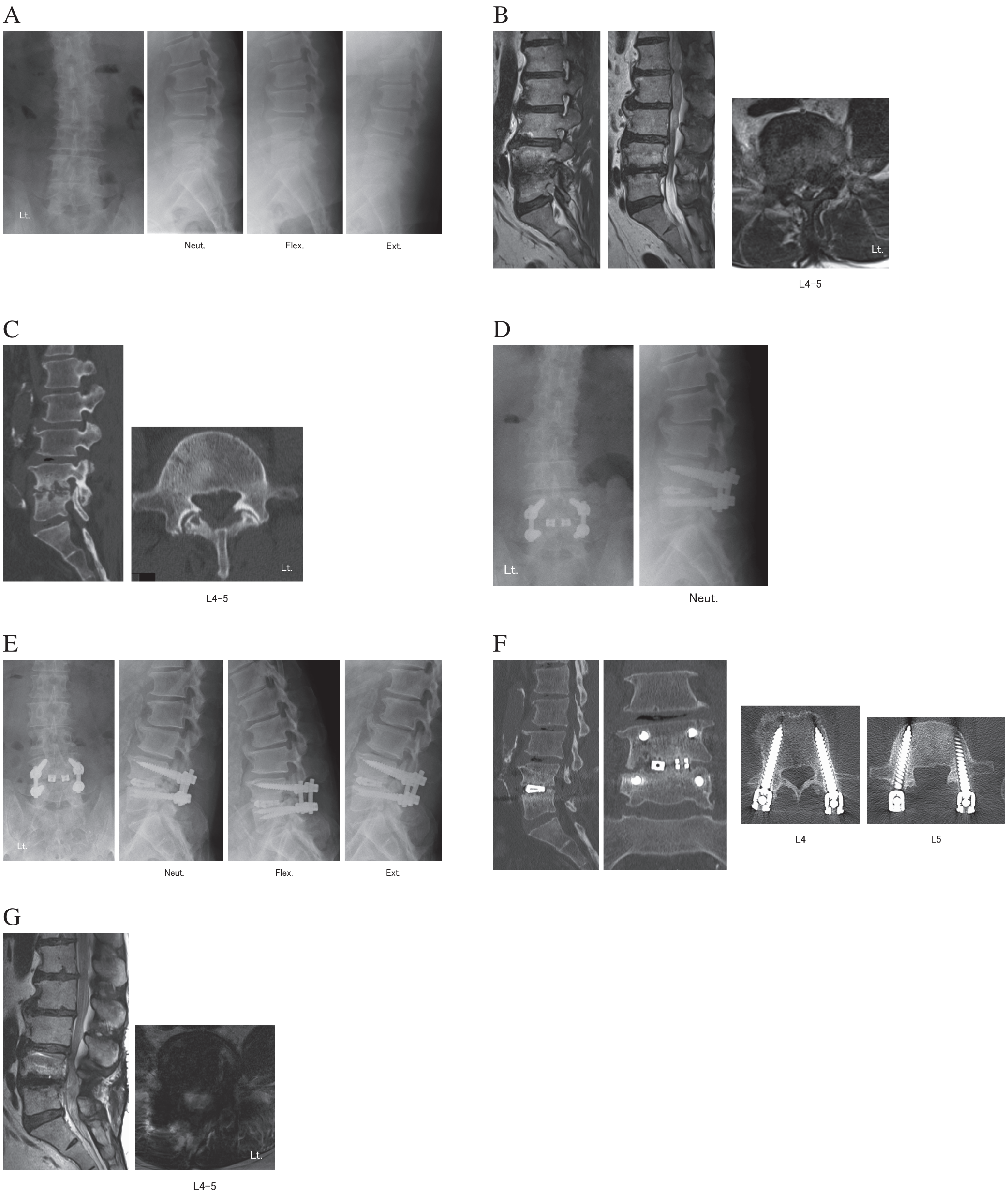

Fig. 2 A representative case of a 54-year-old male undergoing dialysis

Preoperative X-ray (A), computed tomography (CT) (B), and magnetic resonance imaging (MRI) (C) showed irregularities in the vertebral endplates and spinal canal stenosis at the L4–5 level. Although kyphosis was observed, L4–5 posterior lumbar interbody fusion (PLIF) was performed (immediate postoperative X-ray imaging, D). Two years postoperatively, symptoms improved with no instability seen on X-ray images (E). However, CT indicated the lack of bony continuity at the surgical site and screw loosening (F). MRI (G) revealed adequate decompression at the surgical level with no significant adjacent segment disease.

Lt.: left

Neut.: neutral

Flex.: flexion

Ext.: extension

DISCUSSION

This study provides a detailed analysis of the surgical outcomes of PLIF in patients with DSA undergoing HD. Our findings emphasize the complexities inherent to spinal surgery in patients undergoing HD, revealing several important differences in outcomes between the HD and nonHD populations. The HD group experienced significantly greater intraoperative blood loss and lower bony fusion than the control group, corroborating previous studies reporting that compromised bone quality—largely a consequence of CKD and prolonged dialysis—creates significant surgical challenges.[1,12]

These differences in surgical outcomes can largely be attributed to variations in the underlying pathology between the two groups. DSA in HD patients results in a more aggressive disease course due to amyloid deposition, progressive vertebral endplate destruction, and metabolic bone disease. These factors contribute to greater structural instability, increasing the complexity of surgical management and fusion success rates. In contrast, degenerative spondylolisthesis and canal stenosis in non-HD patients typically progress in a more gradual manner, with less severe osseous resorption and comparatively preserved biomechanical stability. Given these differences, HD patients exhibit significantly lower fusion rates, likely due to CKD-associated bone fragility and impaired healing potential. The increased incidence of pseudoarthrosis in HD patients further underscores the need for tailored perioperative management, including preoperative bone health optimization and careful intraoperative handling to enhance fusion success. Additionally, HD patients face a higher risk of ASD, which may be attributable to dialysis-related metabolic disturbances that accelerate degenerative changes in adjacent segments. The combination of increased mechanical stress, altered calcium and phosphate homeostasis, and persistent inflammation contributes to early ASD progression in this population. These findings highlight the need for vigilant postoperative monitoring and early intervention strategies to mitigate the risk of reoperation.

Neurological recovery, as assessed by the JOA score, was notably worse in the HD group at the 2-year follow-up. This decline underscores the progressive nature of DSA in patients undergoing HD, exacerbated by ongoing metabolic disturbances caused by CKD.[7] Patients on long-term HD often experience destructive changes in adjacent spinal segments after surgery, necessitating additional interventions. These changes are likely due to increased mechanical stress and amyloid deposition, contributing to ASD development.[7,11,13] The results of this study further underscore the need for continuous, vigilant monitoring of patients undergoing HD to prevent further functional decline and intervene promptly when neurological symptoms reappear.

Clinically, these findings have significant implications. The higher intraoperative blood loss in the HD group highlights the need for meticulous preoperative planning and intraoperative management. Surgeons should be prepared to manage the increased HD-related risks by employing strategies such as intraoperative cell salvage, use of antifibrinolytics, and adoption of advanced surgical techniques that minimize tissue trauma. In addition, the lower bony fusion rates in the HD group indicate the need for enhanced perioperative care protocols. Preoperative optimization of bone health,[14] including the management of CKD-related mineral and bone disorders and the use of bone anabolic agents, may improve fusion outcomes and reduce pseudoarthrosis development.[13,15]

Long-term follow-up is essential for patients on HD undergoing PLIF, given their increased risk of ASD development and the potential need for reoperation. These patients require continuous monitoring for signs of neurological decline or symptom recurrence. Known risk factors for ASD include advanced age, high body mass index, preexisting disc degeneration, longer fusion constructs, and poor sagittal alignment.[16-18] In addition, the role of HD as a potential accelerant of

ASD progression should not be overlooked. To clarify this relationship, more studies with long-term follow-up comparing the HD group with the nonHD group are warranted. Early intervention, potentially employing less invasive techniques, may help mitigate the need for extensive revision surgeries and improve long-term outcomes in this high-risk population. Beyond long-term follow-up, additional perioperative management strategies should be considered to improve outcomes in HD patients. Given their compromised bone quality and metabolic disturbances, prolonged corset wear (typically for at least six months) may provide additional mechanical support and reduce early instability at the fusion site. Additionally, structured rehabilitation protocols, incorporating progressive mobilization and supervised exercise regimens, may facilitate neurological recovery while minimizing disuse-related muscle atrophy. Activity modification, including a more gradual return to weight-bearing activities, could further reduce the risk of pseudoarthrosis and adjacent segment degeneration. Furthermore, postoperative hospitalization duration tends to be longer in HD patients due to the need for intensive perioperative monitoring, dialysis coordination, and careful wound management. On average, HD patients require a significantly longer hospital stay (mean duration: 21.3 ± 5.7 days vs 14.2 ± 3.8 days in non-HD patients). Extended inpatient care may allow for better optimization of postoperative rehabilitation and nutritional support, both of which are critical for enhancing bone healing and overall recovery.

However, this study has several limitations. Its retrospective nature and relatively small sample size may introduce selection bias, limiting the generalizability of the findings. In addition, the single-center design and exclusion of patients with complex comorbidities may restrict the applicability of the results to broader populations. Finally, the 2-year follow-up period may not fully capture long-term complications, and the lack of quality-of-life assessments limits the comprehensive evaluation of surgical outcomes. Future studies should aim to include larger multicenter populations with extended follow-up periods and incorporate quality-of-life measures to provide a more thorough understanding of the long-term effect of PLIF in patients undergoing HD.

In conclusions, PLIF facilitates early neurological improvement in HD patients, but long-term functional outcomes are compromised due to higher rates of pseudoarthrosis and ASD, necessitating careful long-term management.

CONFLICT OF INTEREST

There are no conflicts of interest, and we have not received any funding for this work.

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REFERENCES

1 Adogwa O, Elsamadicy AA, Sergesketter A, et al. The Impact of Chronic Kidney Disease on Postoperative Outcomes in Patients Undergoing Lumbar Decompression and Fusion. *World Neurosurg*. 2018;110:e266–e270. doi:10.1016/j.wneu.2017.10.147
2 Aguilar A, Gifre L, Ureña-Torres P, et al. Pathophysiology of bone disease in chronic kidney disease: from basics to renal osteodystrophy and osteoporosis. *Front Physiol*. 2023;14:1177829. doi:10.3389/fphys.2023.1177829
3 Kuntz D, Naveau B, Bardin T, Drueke T, Treves R, Dryll A. Destructive spondylarthropathy in hemodialyzed patients. A new syndrome. *Arthritis Rheum*. 1984;27(4):369–375. doi:10.1002/art.1780270402

4 Yamada T, Yoshii T, Hirai T, et al. Clinical Outcomes of Spinal Surgery for Patients Undergoing Hemodialysis. *Orthopedics*. 2016;39(5):e863–e868. doi:10.3928/01477447-20160509-06

5 Maruo K, Tachibana T, Arizumi F, Kusuyama K, Kishima K, Yoshiya S. Clinical outcomes after posterior cervical decompression and fusion surgery for destructive spondyloarthropathy in patients undergoing long-term hemodialysis: A matched case-control study. *J Orthop Sci*. 2019;24(3):404–408. doi:10.1016/j.jos.2018.10.019

6 Fukutake T, Takagi K, Kuwabara S, et al. Destructive spondyloarthropathy of the cervical spine in hemodialyzed patients. Article in Japanese. *Brain Nerve*. 1997;49(8):713–722. doi:10.11477/mf.1406902092

7 Sudo H, Ito M, Abumi K, et al. Long-term follow up of surgical outcomes in patients with cervical disorders undergoing hemodialysis. *J Neurosurg Spine*. 2006;5(4):313–319. doi:10.3171/spi.2006.5.4.313

8 Furuya M, Nagamoto Y, Okuda S, et al. Long-term outcomes of spine surgery in dialysis patients, focusing on activities of daily living, life expectancy, and the risk factors for postoperative mortality. *J Orthop Sci*. 2024;29(2):508–513. doi:10.1016/j.jos.2023.02.016

9 Wada K, Tamaki R, Inoue T, Hagiwara K, Okazaki K. Postoperative Complications and Survival Rate in Hemodialysis-Dependent Patients Undergoing Cervical Spine Surgery. *Spine Surg Relat Res*. 2022;6(3):233–239. doi:10.22603/ssrr.2021-0173

10 Ottesen TD, McLynn RP, Zogg CK, et al. Dialysis is an independent risk factor for perioperative adverse events, readmission, reoperation, and mortality for patients undergoing elective spine surgery. *Spine J*. 2018;18(11):2033–2042. doi:10.1016/j.spinee.2018.04.007

11 Chikawa T, Sakai T, Bhatia NN, et al. Clinical outcomes of spinal surgery in patients treated with hemodialysis. *J Spinal Disord Tech*. 2013;26(6):321–324. doi:10.1097/BSD.0b013e318246af73

12 Scarpioni R, Ricardi M, Albertazzi V, De Amicis S, Rastelli F, Zerbini L. Dialysis-related amyloidosis: challenges and solutions. *Int J Nephrol Renovasc Dis*. 2016;9:319–328. doi:10.2147/ijnrd.S84784

13 Hori Y, Takahashi S, Terai H, et al. Impact of Hemodialysis on Surgical Outcomes and Mortality Rate after Lumbar Spine Surgery: A Matched Cohort Study. *Spine Surg Relat Res*. 2019;3(2):151–156. doi:10.22603/ssrr.2018-0025

14 Anderson PA, Binkley NC, Bernatz JT. Bone Health Optimization (BHO) in Spine Surgery. *Spine (Phila Pa 1976)*. 2023;48(11):782–790. doi:10.1097/brs.0000000000004618

15 Saito T, Mizobuchi M, Kato T, et al. One-Year Romosozumab Treatment Followed by One-Year Denosumab Treatment for Osteoporosis in Patients on Hemodialysis: An Observational Study. *Calcif Tissue Int*. 2023;112(1):34–44. doi:10.1007/s00223-022-01031-6

16 Kim KH, Lee SH, Shim CS, et al. Adjacent Segment Disease After Interbody Fusion and Pedicle Screw Fixations for Isolated L4-L5 Spondylolisthesis: A Minimum Five-Year Follow-up. *Spine (Phila Pa 1976)*. 2010;35(6):625–634. doi:10.1097/BRS.0b013e3181bb8168

17 Nakashima H, Kawakami N, Tsuji T, et al. Adjacent Segment Disease After Posterior Lumbar Interbody Fusion: Based on Cases With a Minimum of 10 Years of Follow-up. *Spine (Phila Pa 1976)*. 2015;40(14):E831–E841. doi:10.1097/brs.0000000000000917

18 Matsumoto T, Okuda S, Maeno T, et al. Spinopelvic sagittal imbalance as a risk factor for adjacent-segment disease after single-segment posterior lumbar interbody fusion. *J Neurosurg Spine*. 2017;26(4):435–440. doi:10.3171/2016.9.spine16232