Bioactive glass grants equivalent fusion compared to autologous iliac crest bone for ALIF: a within-patient comparative study

Marc Szadkowski1, Sami Bahroun1, Ivan Aleksić1, Michiel Vande Kerckhove1, Sonia Ramos-Pascual2*, Mo Saffarini2, Vincent Fièvre1 and Henri d’Astorg1

Abstract

Purpose: To determine within-patient fusion rates of chambers filled with bioactive glass versus autologous iliac crest bone on computed tomography (CT) following anterior lumbar interbody fusion (ALIF).

Methods: A consecutive series of 40 patients (58 levels) that underwent single-level (L5-S1 only) or two-level (L5-S1 and L4-L5) ALIF were assessed. Indications for fusion were one or more of the following: degenerative disc disease with or without Modic changes, spondylolisthesis, and stenosis. Each intervertebral cage had a middle beam delimiting two chambers, one of which was filled with bioactive glass and the other with autologous iliac crest bone. CT scans were graded using the Bridwell classification (grade I, best; grade IV, worst). Patients were evaluated using the Oswestry Disability Index (ODI), and by rating pain in the lower back and legs on a Visual Analog Scale (pVAS); complications and reoperations were noted.

Results: At 15 ± 5 months follow-up, there were no significant differences in fusion across chambers filled with bioactive glass versus chambers filled with autologous bone (p = 0.416). Two patients with Bridwell grade III at both chambers of the L4-L5 cages required reoperation using posterior instrumentation. Clinical assessment of the 38 remaining patients (54 levels) at 25 ± 2 months, revealed ODI of 15 ± 12, lower back pVAS of 1.4 ± 1.5 and legs pVAS of 1.9 ± 1.6.

Conclusions: For ALIF at L5-S1 or L4-L5, within-patient fusion rates were equivalent for bioactive glass compared to autologous iliac crest bone; thus, bioactive glass can substitute autologous bone, avoiding increased operative time and blood loss, as well as donor site morbidity.

Keywords: Bioactive glass, ALIF, Bridwell grade, Fusion, Complications

Introduction

Spinal fusion is a common surgical procedure, with over 400,000 surgeries performed in the United States every year [23]. Fusion is used increasingly for the treatment of spondylolisthesis, scoliosis, disc degeneration, herniation and stenosis [12, 18]. Its main goal is to fuse two or more vertebrae by inducing bone growth between segments, though fusion is not always successful, with pseudarthrosis reported in up to 50% of cases [8]. In 2016, a meta-analysis reported that patients with successful fusion had better improvements in clinical outcomes compared to patients with pseudarthrosis [21].

Autologous iliac crest bone is the gold standard graft material used during spinal fusion [24]. Harvesting autologous iliac crest bone has been associated with increased operative time and blood loss, donor site pain and morbidity, as well as increased complication rates [14, 22, 25]. Therefore, synthetic alternatives to autologous iliac crest...
bone graft continue to be developed and evaluated [24], of which various formulations of bioactive glass have shown promising results, when used alone or in combination with autologous bone [8].

For the last five years, the authors have been performing anterior lumbar interbody fusion (ALIF) for a variety of indications, using intervertebral cages with one chamber filled with bioactive glass and the other chamber filled with autologous iliac crest bone, within the same patient. The aim of this study was to determine the fusion rates of chambers filled with bioactive glass versus autologous iliac crest bone, within the same patient, on computed tomography (CT) following ALIF. The hypothesis was that there would be no differences in fusion rates of chambers filled with bioactive glass compared to those filled with autologous iliac crest bone.

Materials and methods
The authors retrospectively assessed a consecutive series of 40 patients that underwent ALIF at L5-S1 between November 2017 and April 2019, operated on by 2 surgeons (BLINDED). Twenty-two patients had single-level ALIF (L5-S1 only), whereas 18 patients had two-level ALIF (L5-S1 and L4-L5). Each of the 58 intervertebral cages (L5-S1 and L4-L5) had a middle beam delimiting two chambers, one of which was filled with bioactive glass, and the other was filled with autologous iliac crest bone. Indications for ALIF surgery were one or more of the following: degenerative disc disease with or without Modic changes, spondylolisthesis, and stenosis. Posterior fixation was used in 24 patients (60%) that either had spondylolisthesis or required posterior spinal decompression (these patients required posterior incisions, so screws were added to increase stability). None of the patients had prior spine surgery, other than foraminotomy or lumbar discectomy, nor did any patients require fusion at other levels.

Standing lateral radiographs were performed to measure disc height and magnetic resonance images (MRI) were acquired to assess disc degeneration, considering modified Pfirrmann grade $\geq 4$ and/or Modic changes to indicate degenerative disc disease (DDD). Patients were managed conservatively for at least 1 year, and if pain persisted, surgical intervention was discussed with a physiatrist. All patients provided written informed consent to use their data and images for research and publication purposes. The study was approved in advance by

| Table 1 | Patient demographics and surgical data |
|---------|--------------------------------------|
|         | Initial cohort (n = 40) | No posterior instrumentation (n = 16) | Posterior instrumentation (n = 24) |
|         | mean ± SD (range) | mean ± SD (range) | mean ± SD (range) |
| n (%)   |                      | n (%)               | n (%)               |
| Age (years) | 48.7 ± 9.8 (29 – 65) | 47.3 ± 8.9 (34 – 65) | 49.7 ± 10.4 (29 – 65) |
| BMI (kg/m²) | 25.8 ± 3.5 (18 – 39) | 26.0 ± 4.6 (20 – 39) | 25.6 ± 2.7 (18 – 30) |
| Female | 26 (65%) | 11 (69%) | 15 (63%) |
| Smokers | 15 (38%) | 6 (38%) | 9 (38%) |
| Diabetes | 1 (3%) | 0 (0%) | 1 (4%) |
| Indications at L5-S1* | | | |
| DDD | 26 (65%) | 15 (94%) | 11 (46%) |
| Modic changes | 7 (18%) | 4 (25%) | 3 (13%) |
| Spondylolisthesis | 11 (28%) | 0 (0%) | 11 (46%) |
| Stenosis | 23 (58%) | 11 (69%) | 12 (50%) |
| Levels fused | | | |
| L5-S1 | 22 (55%) | 11 (69%) | 11 (46%) |
| Both | 18 (45%) | 5 (31%) | 13 (54%) |
| Type of cage at L4-L5 | | | |
| Roi A (Zimmer Biomet) | 12 (30%) | 0 (0%) | 12 (50%) |
| Synfix (DePuy Synthes) | 6 (15%) | 5 (31%) | 1 (4%) |
| None | 22 (55%) | 11 (69%) | 11 (46%) |
| Type of cage at L5-S1 | | | |
| Roi A (Zimmer Biomet) | 7 (18%) | 1 (6%) | 6 (25%) |
| Idys ALIF (Clariance) | 33 (83%) | 15 (94%) | 18 (75%) |

*Abbreviations: BMI Body Mass Index, DDD Degenerative Disc Disease, SD Standard Deviation, n number of patients

* Subgroups are not mutually exclusive
Surgical technique
The same pre-operative protocol was used by both surgeons. Surgery was performed under general anesthesia with the patient in supine position, using a left retroperitoneal approach and implanting an ALIF intervertebral cage. Each ALIF cage had a middle beam delimiting two chambers. Grafting was performed as follows, systematically by the two surgeons: one chamber was filled with bioactive glass putty only (Glassbone®, Noraker, Lyon, France), and the other chamber was filled with autologous bone only (obtained from the patient’s iliac crest). The bioactive glass putty had a composition of 45% SiO₂, 24.5% Na₂O, 24.5% CaO, and 6% P₂O₅. The implants used at L5-S1 included both Roi A cages (n = 7; Zimmer Biomet, Warsaw, IN, USA) and Idys ALIF cages (n = 33; Clariance, Beaurains, France), while at L4-L5 they included both Roi A cages (n = 12; Zimmer Biomet, Warsaw, IN, USA) and Synfix cages (n = 6; DePuy Synthes, Raynham, MA, USA).

Clinical and radiographic assessment
CT scans were routinely performed at 12 months, and two experienced readers (MS, SB) assessed fusion using the Bridwell classification (grades I-IV): grade I indicated fusion with remodeling and trabeculae present; grade II indicated an intact graft, not fully remodeled and incorporated, but without lucency present; grade III indicated an intact graft, with potential lucency present at the top and bottom of the graft; and grade IV indicated absence of fusion with collapse/resorption of the graft [6]. Only patients with persistent back pain after surgery or worsening clinical scores had further radiographic follow-up, to not re-expose all patients unnecessarily to additional radiation. Clinical assessment was performed preoperatively and at 3, 6, 12, and 24 months using the Oswestry.
Disability Index (ODI; 0–100%) and Short Form 12 (SF-12) questionnaires, and rating pain in the lower back and legs on a Visual Analog Scale (pVAS; 0–10). Only the latest follow-up of 24 months is shown in the present study. All complications, reoperations and revisions were noted.

**Statistical analysis**

Descriptive statistics were used to summarize the data. Comparisons of fusion rates between autologous bone and bioactive glass were performed using Chi-squared tests. Agreement on fusion rates between the two readers were calculated using Gwet’s AC [9], and were found to be good to excellent (Gwet’s AC > 0.691; \( p < 0.001 \)) [7]. Patients were stratified to determine whether the addition of posterior instrumentation affected clinical outcomes. Statistical analyses were conducted using R version 3.6.1 (R Foundation for Statistical Computing). \( P \)-values < 0.05 were considered statistically significant.

**Results**

The initial cohort comprised 40 patients, 26 females and 14 males, with an age at index surgery of 49 ± 10 years and a BMI of 26 ± 3 kg/m² (Table 1). Fifteen patients (38%) were smokers, all of whom confirmed to have stopped smoking at least 8 weeks before surgery. There were two early postoperative complications (5%); one
hematoma and one radiculopathy, neither of which required reoperation.

At a mean follow-up of 15 ± 5 months (range, 10–24), CT scans of the 40 patients (58 levels) indicated no significant differences in fusion across chambers filled with bioactive glass versus chambers filled with autologous bone (p = 0.416), with Bridwell grade I at 30 levels (52%) in chambers with bioactive glass versus 23 levels (40%) in chambers with autologous bone, Bridwell grade II at 26 levels (45%) in chambers with bioactive glass versus 33 levels (57%) in chambers with autologous bone, and Bridwell grade III at 2 levels (3%) in chambers with bioactive glass versus 2 levels (3%) in chambers with autologous bone (Table 2, Figs. 1 and 2). The 4 chambers that had fusion of Bridwell grade III (graft intact, but a definite lucency at the top or bottom of the graft) were observed in the L4-L5 cages of 2 patients that had undergone two-level stand-alone ALIF. The first was a 38-year-old woman, non-smoker, that had Bridwell grade I fusion at the L5-S1 chamber filled with bioactive glass, but grade II fusion at the L5-S1 chamber filled with autologous bone; she was reoperated 10 months after the index ALIF procedure, using posterior instrumentation filled with autologous local bone and allograft. The second was a 44-year-old woman, also non-smoker, that had Bridwell grade II fusion at both L5-S1 chambers; she was reoperated 23 months after the index ALIF procedure, also using posterior instrumentation filled with autologous local bone and allograft. Both patients that required reoperations were excluded from clinical assessment. There were no cases of cage subsidence, cage displacement, metal-plate migration, metal-plate fracture or bony fracture. For chambers filled with bioactive glass, there were no statistically significant differences in fusion rates among patients with posterior instrumentation versus those without at either L5-S1 (p = 0.755) or L4-L5 (p = 0.120). For chambers filled with autologous bone, there were no statistically significant differences in fusion rates among patients with posterior instrumentation versus those without at L5-S1 (p = 0.399), but fusion at L4-L5 was significantly better for patients with posterior instrumentation (p = 0.007).

At a mean follow-up of 25 ± 2 months (range, 23–34), clinical assessment of the 38 remaining patients (54

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| Table 3 Pre- and post-operative clinical assessment |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Final cohort (n = 38) | No posterior instrumentation (n = 14) | Posterior instrumentation (n = 14) | p-value* |
| Follow-up (months) | mean ± SD | (range) | mean ± SD | (range) | mean ± SD | (range) | 0.143 |
| Lower back pVAS | | | | | | | |
| Preoperative | 4.9 ± 1.4 | (2 – 8) | 5.0 ± 1.2 | (3 – 7) | 4.9 ± 1.5 | (2 – 8) | 0.755 |
| Postoperative | 1.4 ± 1.5 | (0 – 6) | 1.6 ± 1.8 | (0 – 6) | 1.3 ± 1.2 | (0 – 4) | 0.742 |
| Net change | -3.5 ± 1.9 | (-7 – 0) | -3.4 ± 2.0 | (-7 – 0) | -3.6 ± 1.9 | (-7 – 0) | 0.735 |
| Leg pVAS | | | | | | | |
| Preoperative | 3.7 ± 2.0 | (0 – 8) | 3.5 ± 2.2 | (0 – 7) | 3.8 ± 2.0 | (0 – 8) | 0.137 |
| Postoperative | 1.9 ± 1.6 | (0 – 6) | 2.4 ± 1.5 | (1 – 6) | 1.6 ± 1.6 | (0 – 5) | 0.207 |
| Net change | -1.8 ± 2.8 | (-8 – 5) | -1.1 ± 2.9 | (-6 – 5) | -2.3 ± 2.7 | (-8 – 2) | 0.910 |
| ODI | | | | | | | |
| Preoperative | 47.9 ± 11.4 | (32 – 72) | 49.6 ± 12.1 | (35 – 72) | 46.9 ± 11.1 | (32 – 72) | 0.647 |
| Postoperative | 14.8 ± 12.4 | (0 – 54) | 16.1 ± 14.0 | (0 – 54) | 14.0 ± 11.6 | (0 – 42) | 0.340 |
| Net change | -33.1 ± 15.7 | (-64 – 6) | -33.5 ± 16.7 | (-64 – 6) | -32.9 ± 15.4 | (-62 – 6) | 0.214 |
| SF-12 physical | | | | | | | |
| Preoperative | 27.5 ± 6.4 | (16 – 44) | 27.2 ± 7.0 | (16 – 43) | 27.7 ± 6.2 | (17 – 44) | 0.910 |
| Postoperative | 45.4 ± 9.1 | (20 – 59) | 43.6 ± 9.7 | (20 – 55) | 46.5 ± 8.8 | (24 – 59) | 0.705 |
| Net change | 17.9 ± 9.4 | (-9 – 36) | 16.4 ± 9.0 | (-1 – 32) | 18.8 ± 9.7 | (-9 – 36) | 0.137 |
| SF-12 mental | | | | | | | |
| Preoperative | 35.8 ± 8.0 | (22 – 53) | 33.7 ± 8.0 | (25 – 53) | 37.0 ± 7.9 | (22 – 50) | 0.755 |
| Postoperative | 46.4 ± 9.3 | (21 – 59) | 46.3 ± 11.2 | (21 – 58) | 46.5 ± 8.2 | (27 – 59) | 0.207 |
| Net change | 10.6 ± 13.2 | (-32 – 37) | 12.5 ± 15.9 | (-32 – 28) | 9.5 ± 11.6 | (-8 – 37) | 0.207 |

Abbreviations: SD Standard Deviation, pVAS pain on Visual Analogue Scale, ODI Oswestry Disability Index, SF-12 Short-form 12

* Comparison of patients with and without posterior instrumentation
Table 4: Previous clinical studies reporting on the use of bioactive glass during spinal surgery

| First author | Year | Type of surgery | Indication | Name of bioactive glass | Combined w/ bone | Comparator | Levels | n    | Follow-up | Fusion rate of bioglass | Fusion rate of comparator | Recommend Bioglass |
|--------------|------|-----------------|------------|-------------------------|------------------|------------|--------|------|-----------|------------------------|-----------------------|-------------------|
| Westerlund [27] | 2020 | ACDF Neurocompresive disorders | Bioactive glass bone graft (Bio-Sphere Putty) | Yes, cancellous allograft | 1–4 (cervical) | 115 | > 1 year | 100% |
| TLIF Neurocompresive disorders | Bioactive glass bone graft (Bio-Sphere Putty) | Yes, cancellous allograft | 1–3 (lumbar) | 30 | > 1 year | 100% |
| ALIF Neurocompresive disorders | Bioactive glass bone graft (Bio-Sphere Putty) | Yes, autologous bone | 1–3 (lumbar) | 103 | > 1 year | 100% |
| Barrey [4] | 2019 Posterior fusion Degenerative diseases, trauma or spinal deformities | 45S5 bioactive glass (GlassBoneTM, Noraker) | Yes (S0S0) | 2–10 (lumbar) | 27 | > 1 year | 82% |
| Rantakokko [22] | 2012 Posterior fusion Burst fractures | BAG-S54P4 | Yes Autologous iliac crest bone | 1–2 (lumbar) | 16 | 10 years | 50% 100% |
| Frantzen [11] | 2011 PLF Degenerative spondylolisthesis | BAG-S53P4 | No Autologous bone | 2–3 (lumbar) | 17 | 11 years | 71% 100% |
| Ameri [3] | 2009 Posterior fusion Adolescent idiopathic scoliosis Metal-derived bioactive glass (Novabone) | Yes, local bone Autologous iliac crest bone and local bone | Average 10 thoracolumbar | 40 | > 2 years | 90% 85% |
| Acharya [2] | 2008 PLF Spondylolisthesis or stenosis Hydroxyapatite-bioactive glass ceramic composite (Chitra-HABg) | Yes, bone marrow Autologous bone | 1–3 (lumbar) | 24 | > 1 year | 0% 73% |
| Hashimoto [13] | 2002 PLF Lumbar degenerative pathologies with instability | 2:1 of bone:AWGC | Yes, autologous bone | 2 (lumbar) | 35 | > 2 years | 83% |
| Stenosis | 1:1 of bone:AWGC | Yes, autologous bone | 2 (lumbar) | 35 | > 2 years | 83% |
| Stenosis | 1:2 of bone:AWGC | Yes, autologous bone | 2 (lumbar) | 35 | > 2 years | 82% |
| Kasai [16] | 2003 PLF Stenosis | Bioactive ceramic granules (AWGC) | Yes, autologous bone | 1 (lumbar) | 25 | > 2 years | 100% |

Note: AWGC = Alumina-Wollastonite-Glass-Ceramic
Table 4 (continued)

| First author | Year | Type of surgery | Indication | Name of bioactive glass | Combined w/ bone | Comparator | Levels | n | Follow-up | Fusion rate of bioglass | Fusion rate of comparator | Recommend Bioglass |
|---------------|------|-----------------|------------|-------------------------|-----------------|------------|--------|---|-----------|------------------------|----------------------|------------------|
| Ido [15]      | 2000 | PLIF            | Spondylolisthesis | AWGC        | Yes, autologous bone | L4-L5      | 5      |   | 1.5 years | 20%                    | 50%                  | Yes               |
|               |      | PLF             | Spondylolisthesis or vertebral fracture | AWGC        | Yes, autologous bone | Multi (lumbar) | 6      |   | 1.5 years | 17%                    | 50%                  |                  |

Abbreviations: AFBP, Autogenous Fine Particulate Bone Powder; BMSC, Bone Marrow mesenchymal Stem Cells; ACDF, Anterior Cervical Decompression and Fusion; TLIF, Transforaminal Lumbar Interbody Fusion; ALIF, Anterior Lumbar Interbody Fusion; PLF, Postero-Lateral Fusion; RCT, Randomised Controlled Trial; PLIF, Posterior Lumbar Interbody Fusion; ICBG, Iliac Crest Bone Graft; BMA, Bone Marrow Aspirate; TCP, Tri-calcium Phosphate; AWGC, Apatite-Wollastonite Glass-Ceramics; n, number of patients.
levels) revealed that ODI improved from 48 ± 11 preoperatively to 15 ± 12 postoperatively (Table 3). Furthermore, lower back pVAS improved from 4.9 ± 1.4 to 1.4 ± 1.5 and legs pVAS improved from 3.7 ± 2.0 to 1.9 ± 1.6. Finally, the SF-12 physical component improved from 28 ± 6 to 45 ± 9 and the SF-12 mental component improved from 36 ± 8 to 46 ± 9. There were no statistically significant differences in postoperative clinical outcomes nor in the net change in clinical outcomes among the 24 patients with posterior instrumentation versus the 14 patients without.

Discussion

The most important finding of this study is that, for ALIF at L5-S1 or L4-L5, fusion rates were equivalent for bioactive glass compared to autologous iliac crest bone, within the same patient. As reported for other ALIF implants [17, 19, 26], the present study found significant improvements of clinical outcomes at a follow-up ≥ 2 years, including ODI, lower back pain and leg pain. Therefore, the findings of this study suggest that for patients undergoing ALIF, bioactive glass can be used as a substitute to autologous iliac crest bone; thus, avoiding increased operative time and blood loss, as well as donor site morbidity [14, 22, 25]. While the follow-up of two years may not be sufficient to ascertain long-term clinical outcomes, the fusion rates of chambers filled with bioactive glass were already equivalent or better than the fusion rates of chambers filled with autologous bone graft, which led the authors to hesitate regarding the acquisition of further CT scans at longer follow-up, due to both ethical (exposure to radiation) and logistical (travel to radiology centers during the pandemic) considerations.

Comparing Bridwell grades observed in the present study suggests that fusion was better in chambers filled with bioactive glass (grade I in 52%) than in those filled with autologous bone (grade I in 40%), though the difference was not statistically significant (p = 0.416). There are two possible explanations for this trend: the first is that bioactive glass may induce better or faster bone growth; the second is that bioactive glass may appear more consolidated because it has greater radiopacity (Fig. 2). Considering Bridwell grades I and II to be satisfactory, the present study suggests fusion rates of 97%, both for bioactive glass and for autologous bone. These findings are similar to the only other published study that assessed ALIF using bioactive glass (combined with autologous bone), which reported a fusion rate of 100% at 1 year follow-up, in patients with neuro-compressive disorders at one to three lumbar levels [27]. Previous published studies on posterior fusion have reported fusion rates of 0–100% for bioactive glass (with or without autologous bone) [2–4, 11, 13, 15, 16, 22, 27], with only one of nine studies not recommending the use of bioactive glass [2] (Table 4). Furthermore, our fusion rate of 97% and complication rate of 5% are consistent with those reported for other studies investigating ALIF [5, 20, 26]. Of the 40 patients included in the present study, there were 2 patients that had to be reoperated because of inadequate fusion at L4-L5. It is important to note that both patients had undergone two-level stand-alone ALIF, and neither had posterior instrumentation. These findings suggest that when performing ALIF at two levels, posterior fixation may be necessary to stabilize the spine.

The present study has several limitations. First, comparisons between bioactive glass and autologous bone have been made within the same patient, and thus fusion or lack thereof in one chamber may have affected fusion in the other chamber; additionally, it is not possible to measure the effect of each material on postoperative clinical scores. Second, patients were operated on for a variety of indications, which may result in some variability in outcomes; although, this can also be regarded as a strength of the study since similar fusion rates were found for both materials across a range of indications. Third, ALIF cages of different sizes were used depending on the intervertebral height of each patient, which could mean that different cage sizes were filled with different amounts of material; however, this effect was diminished because we investigated within-patient fusion rates, and the amount of filler material was equal for both chambers of each patient. Finally, the follow-up of the present study may not be sufficient to ascertain long-term clinical outcomes, although it is sufficient to evaluate fusion rates. Previous studies on other types of spinal surgery have demonstrated that early outcomes, such as ODI and Core Outcome Measures Index, improve or remain stable after 12 months and up to 8 years [1, 10].

Conclusions

For ALIF at L5-S1 or L4-L5, within-patient fusion rates were equivalent for bioactive glass compared to autologous iliac crest bone. The findings of this study suggest that for patients undergoing ALIF, bioactive glass can be used as a substitute to autologous iliac crest bone; thus, avoiding increased operative time and blood loss, as well as donor site morbidity.

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Authors’ contributions

MSz study design, data collection, manuscript editing. SB study design, data collection and analysis, manuscript editing. IA study design, data collection, manuscript editing. MVK literature review, data analysis and interpretation, manuscript writing. MSa literature review, data analysis and interpretation, manuscript writing. VF study design, data collection, manuscript editing. HA study design, data collection, manuscript editing. The author(s) read and approved the final manuscript.
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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations
Ethics approval and consent to participate
All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee (‘GCS Ramsay Santé pour l’Enseignement et la Recherche’), IRB# COSS-RCGS-2021–05-004-SZADKOWSKI-M) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. All patients provided written informed consent to use their data and images for research and publication purposes.

Consent for publication
Not applicable.

Competing interests
MSz consultancy fees and royalties from Clariance, and consultancy fees from Zimmer.
SB no conflicts of interest.
IA no conflicts of interest.
MVK no conflicts of interest.
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Author details
1 Ramsay Santé, Hôpital Privé Jean Mermoz, Lyon, France. 2 ReSurg SA, Rue Saint-Jean 22, 1260 Nyon, Switzerland.

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References
1. Abdu WA, Sacks OA, Tosteson ANA, Zhao W, Tosteson TD, Morgan TS, Pearson A, Weinstein JN, Lurie JD (2018) Long-term results of surgery compared with nonoperative treatment for lumbar degenerative spondylolisthesis in the Spine Patient Outcomes Research Trial (SPORT). Spine (Phila Pa 1976) 43(8):1623–1630
2. Achariya NK, Kumar R, Varma HK, Menon VK (2008) Hydroxyapatite-bioactive glass ceramic composite as stand-alone graft substitute for posterolateral fusion of lumbar spine: a prospective, matched, and controlled study. J Spinal Disord Tech 21(2):106–111
3. Ameri E, Behshar H, Molbini B, Omid-Kashani F, Nojomi M (2009) Bioactive glass versus autogenous iliac crest bone graft in adolescent idiopathic scoliosis surgery. Acta Med Iran 47(1):41–45
4. Barrey C, Broussolle T (2019) Clinical and radiographic evaluation of bioactive glass in posterior cervical and lumbar spinal fusion. Eur J Orthop Surg Traumatol 29(8):1623–1629
5. Behrbalk E, Uri O, Parks RM, Musson R, Sch RC, Boszczyk BM (2013) Fusion and subsidence rate of stand alone anterior lumbar interbody fusion using PEEK cage with recombinant human bone morphogenetic protein-2. Eur Spine J 22(12):2869–2875
6. Bridwell KH, Lenke LG, McEneny KW, Baldus C, Blanke K (1995) Anterior fresh frozen structural allografts in the thoracic and lumbar spine. Do they work if combined with posterior fusion and instrumentation in adult patients with kyphosis or anterior column defects? Spine (Phila Pa 1976) 20(12):1410–1418
7. Cicchetti DV, Showalter D, Rosenheck R (1997) A new method for assessing interexaminer agreement when multiple ratings are made on a single subject: applications to the assessment of neuropsychiatric symptomatology. Psychiatry Res 72(1):51–63
8. Cottrill E, Pennington Z, Lankapalle N, Ehresman J, Valenza C, Schilling A, Foghali J, Perdomo-Pantoja A, Theodore N, Scibbia DM, Witham T (2020) The effect of bioactive glasses on spinal fusion: a cross-disciplinary systematic review and meta-analysis of the preclinical and clinical data. J Clin Neurosci 78:34–46
9. de Vet HC, Mokkink LB, Terwee CB, Hoekstra OS, Knol DL (2013) Clinicians are right not to like Cohen’s kappa. BMJ 346:f2125
10. Fekete TF, Loibl M, Jeszenszky D, Haschtmann D, Banczerowski P, Klein-stuck FS, Becker HJ, Porchet F, Mannion AF (2018) How does patient-rated outcome change over time following the surgical treatment of degenerative disorders of the thoracolumbar spine? Eur Spine J 27(3):700–708
11. Frantzen J, Rantakokko J, Aro HT, Heinanen J, Kajander S, Gullichsen E, Kotilainen E, Lindfors NC (2011) Instrumented spondylolisthesis in degenerative spondylothesis with bioactive glass and autologous bone: a prospective 11-year follow-up. J Spinal Disord Tech 24(7):455–461
12. Grotle M, Mjøstuen MC, Fjeld O, Gravle L, Helgeoland J, Storheim K, Solberg TK, Zwart JA (2019) Lumbar spine surgery across 15 years: trends, complications and reoperations in a longitudinal observational study from Norway. BMJ Open 9(8):e028743
13. Hashimoto T, Shigenobu K, Kanayama M, Harada M, Oha F, Okhoshi Y, Tada H, Yamamoto K, Yamane S (2002) Clinical results of single-level posterior lumbar interbody fusion using the Brantigan I/F carbon cage filled with a mixture of local morselized bone and bioactive ceramic granules. Spine (Phila Pa 1976) 27(3):258–262
14. Huang YC, Chen CY, Lin KC, Rnt JH, Tsung YW, Hsu CJ, Chang WN, Yang SW (2018) Comparing morbidity of bone graft harvesting from the anterior iliac crest and proximal tibia: a retrospective study. J Orthop Surg Res 13(1):115
15. Ido K, Asada Y, Sakamoto T, Hayashi R, Kuriyama S (2000) Radiographic evaluation of bioactive glass-ceramic grafts in posterolateral lumbar fusion. Spine 25(5):315–318
16. Kasai Y, Takegami K, Uchida A (2003) Mixture ratios of local bone to artificial bone in lumbar posterolateral fusion. J Spinal Disord Tech 16(1):31–37
17. Lee CW, Yoon KJ, Ha SS (2017) Which approach is advantageous to preventing development of adjacent segment disease? Comparative analysis of 3 different lumbar interbody fusion techniques (ALIF, LLIF, and PLIF) in L4–5 spondylolisthesis. World Neurosurg 105:612–622
18. Martin BI, Mirza SK, Spina N, Spiker WR, Lawrence B, Brodie DS (2019) Trends in lumbar fusion procedure rates and associated hospital costs for degenerative spinal diseases in the United States, 2004 to 2015. Spine (Phila Pa 1976) 44(5):369–376
19. Mobbs RJ, Phan K, Assen Y, Pelletier M, Walsh WR (2016) Combination TUPEEK ALIF cage for anterior lumbar interbody fusion: early clinical and radiological results. J Clin Neurosci 34:94–99
20. Norotte G, Barrios C (2018) Clinical and radiological outcomes after stand-alone ALIF for single L5–S1 degenerative discopathy using a PEEK cage filled with hydroxyapatite nanoparticles without bone graft. Clin Neurosurg Neurosurg 168:24–29
21. Noschentko A, Lindley EM, Burger EL, Cain CM, Patel WV (2016) What is the clinical relevance of radiographic nonunion after single-level lumbar interbody arthrodesis in degenerative disc disease? A meta-analysis of the YODA project database. Spine (Phila Pa 1976) 41(1):9–17
22. Rantakokko J, Frantzen JF, Heinanen J, Kajander S, Kotilainen E, Gullichsen E, Lindfors NC (2012) Posterolateral spondylolisthesis using bioactive glass SS3P4 and autogenous bone in instrumented unstable lumbar spine burst fractures. A prospective 10-year follow-up study. Scand J Surg 101(1):66–71
23. Reisener MJ, Pumberger M, Shue J, Girardi FP, Hughes AP (2020) Trends in lumbar spinal fusion—a literature review. J Spine Surg 6(4):752–761
24. Salamanna F, Tschon M, Borsari V, Pagani S, Martini L, Fini M (2020) Spinal fusion procedures in the adult and young population: a systematic review on alllogenic bone and synthetic grafts when compared to autologous bone. J Mater Sci Mater Med 31(6):51
25. Schaaf H, Lendeckel S, Howaldt HP, Streckbein P (2010) Donor site morbidity after bone harvesting from the anterior iliac crest. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 109(1):52–58

26. Siepe CJ, Stosch-Wiechert K, Heider F, Amnajtrakul P, Krenauer A, Hitzl W, Szemies U, Stabler A, Mayer HM (2015) Anterior stand-alone fusion revisited: a prospective clinical, X-ray and CT investigation. Eur Spine J 24(4):838–851

27. Westerlund LE, Borden M (2020) Clinical experience with the use of a spherical bioactive glass putty for cervical and lumbar interbody fusion. J Spine Surg 6(1):49–61

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