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Allografts and Spinal Fusion

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ABSTRACT

Background: Back pain is a common chief complaint within the United States and is caused by a multitude of etiologies. There are many different treatment modalities for back pain, with a frequent option being spinal fusion procedures. The success of spinal fusion greatly depends on instrumentation, construct design, and bone grafts used in surgery. Bone allografts are important for both structural integrity and providing a scaffold for bone fusion to occur.

Method: Searches were performed using terms “allografts” and “bone” as well as product names in peer reviewed literature Pubmed, Google Scholar, FDA-510k approvals, and clinicaltrials.gov.

Results: This study is a review of allografts and focuses on currently available products and their success in both animal and clinical studies.

Conclusion: Bone grafts used in surgery are generally categorized into 3 main types: autogenous (from patient’s own body), allograft (from cadaveric or living donor), and synthetic. This paper focuses on allografts and provides an overview on the different subtypes with an emphasis on recent product development and uses in spinal fusion surgery.

Special Issue

Keywords: spine fusion, allograft, bone graft material, bone grafts

INTRODUCTION

Back pain is a common chief complaint within the United States and is caused by a multitude of etiologies. According to the National Center for Health Statistics, more than 650 000 spinal fusion surgeries are performed annually.¹ The success of arthrodesis in spine surgery depends on multiple factors; however, an important component to success depends on the bone graft and graft substitutes used in surgery. Bone grafts and graft substitutes are materials that are used to rapidly induce or support biologic bone remodeling after surgical procedures to reconstruct bony structures and/or to provide initial structural support.² The graft material used in spinal fusion procedures can be categorized generally into 3 main types of materials: autogenous bone graft (autograft) from the patient’s own body, allograft from human cadavers and/or living donors, and synthetic bone graft or substitutes.^{3,4} Autograft is considered the “gold standard”; however, the authors believe allograft and synthetics are currently replacing separate surgical site–harvested autografts as the standard because of patient donor site morbidity,

advancement in the development of other products, limited quantity available, host limiting bone quality, and lack of training of young surgeons in the technique of autograft harvest.⁴ This paper focuses on allografts and recent advancements in product development and uses in spinal fusion surgery.

BONE GRAFT PROPERTIES

Osteogenesis, or bone formation, occurs via 2 mechanisms: endochondral ossification or intramembranous ossification. Intramembranous ossification involves direct conversion of mesenchymal tissue into bone, does not require cartilage as an intermediate, and does require bone morphogenic proteins and CBFA1 transcription factors.⁵ Endochondral ossification requires cartilage as an intermediate and can be divided into 5 stages. The stages of endochondral ossification are as follows:—mesenchymal cells differentiate to cartilage cells, formation of chondrocytes, proliferation of chondrocytes to form the model for the bone, formation of hypertrophic chondrocytes, and invasion of blood vessels.⁵ Both mechanisms of bone formation

rely on complex intracellular signaling events, and each contributes to bone formation after spinal fusion surgeries.

Critical elements that are required for bone formation and are important in bone graft properties include osteoconduction, osteoinduction, osteogenesis, mechanical stability, and vascularization. Osteoconduction relies on a scaffold that supports cell ingrowth, facilitates vascularization, and provides a network for cells to attach.⁴ Osteoinduction relies on the provision of signals that act on the precursor cells and encourage cell migration, proliferation, and differentiation into bone-forming cells, leading to rapid bone formation.⁴ Osteogenesis relies on the immediate provision of viable cells emanating from the host to the defect site differentiating into bone-forming cells.⁴ Autologous bone is the only bone graft available that intrinsically contains all 3 properties and is therefore considered the “gold standard.” However, with advancements in allograft processing and development, recent products have theoretically been able to acquire all 3 properties of bone development.

ALLOGRAFT

Allograft bone is obtained from either living or deceased donors and then processed for sterility. Common preparation includes freezing or lyophilization (ie, freeze drying), which involves dehydration and vacuum packaging to store at room temperature.⁶ In general, allografts are primarily osteoconductive with minimal osteoinductive potential and are traditionally not osteogenic because the donor cells are eradicated during processing.^{7,8} Surgeons prefer allografts because they are readily accessible, available in various forms delivering handling properties, facilitate bone formation, and do not require donor site morbidity. However, traditionally available allografts consist of nonviable tissue and cannot stimulate bone formation without the addition of bone-stimulating factors and cells.^{9–11} These limitations lead to slower and less complete incorporation with native bone. Additionally, allografts have a potential risk of disease transmission even if the incidence is very low and the risk can be controlled during the procurement and sterilization process.⁷ Allogenic bone is traditionally available in many forms: cortico-cancellous, demineralized bone matrix (DBM), morselized and cancellous chips, and osteochondral and whole bone-segments.¹²

Recently, a new class of allograft has emerged called *viable cellular allografts* or *cellular bone matrices* (CBMs), which are designed to have all 3 properties of bone formation: osteoconduction, osteoinduction, and osteogenesis. CBMs are created using osteoconductive cadaveric bone with the retention or addition of allogeneic stem cells (ie, mesenchymal stem cells) to initiate an osteogenic process.¹³ The efficacy of mesenchymal stem cells has been shown to be as efficacious as rhBMP and allograft.¹² Overley et al¹⁴ retrospectively examined 78 patients (98 fusion levels) and found no difference in radiographic fusion and rate of revision surgery in patients who underwent MS-TLIF with either rhBMP-2 or CBM as fusion adjuncts.

Table 1 provides a description of the different types of allografts and their corresponding characteristics. For a more thorough description of all classes of bone grafts, please refer to the chapter by Yang et al⁴ in the *Handbook of Spine Technology* or the review article by Gruskin et al.³ A comprehensive review of bone graft characteristics can be found in the chapter by Bae et al²³ in *AAOS Comprehensive Orthopaedic Review 2*.

Cortico-Cancellous Allograft

Cortico-cancellous allografts are the most commonly used allograft today. They are strictly osteoconductive without any osteoinductive or osteogenic properties. These grafts can be prepared as whole pieces, such as rings of femoral head/neck used traditionally for interbody fusion, or prepared as chips to aid in void-filling scenarios or posterolateral fusion.²⁴ Cortical allograft is most commonly used as a mechanical strut graft, whereas cancellous allograft functions as a osteoconductive scaffold for bone formation.⁴ In a study by Park et al,²⁵ 46 patients underwent ACDF with either a cortico-cancellous allograft or iliac crest autograft, and there was no significant difference in fusion status between the 2 groups. Another study by Suchomel et al²⁶ evaluated fibular allografts versus autologous iliac crest grafts in 80 patients undergoing ACDF procedures and found in single-level procedures that there was no difference in fusion rates and graft collapse between autograft and allograft. Table 2 provides a list of commercially available cortico-cancellous allografts used for spinal fusions and specifics on each product.

Table 1. Description characteristics of different types of allografts.

Grafting Material	Grafting Material (Typical Abbreviation)	Grafting Material Category and Description	Variability	Osteogenic	Osteoinductive	Osteoconductive	Immunogenicity/ Disease Transmission	Strength (Immediate)	Donor Site Morbidity
Allograft	Fresh ¹⁵	1. Living donor (patient-to-patient transfer) 2. Cadaveric donor (harvested within 12 h and allograft transplantation within 72 h) → Femoral head (as osteochondral form)	Lot-to-lot variability donor's bone condition + sterilization processing techniques	? (No data for osteogenic graft for human)	? (No data for osteogenic graft for human)	? (No data for osteogenic graft for human)	+++ (Generally causes an unacceptable host immune reaction as osteogenic graft) → Not used commercially only animal studies.		–
Allograft	Fresh (osteochondral graft) ¹⁶	1. Living donor (patient-to-patient transfer) 2. Cadaveric donor (harvested within 12 h and allograft transplantation within 24 h) → Femoral head (as osteochondral form) ¹⁷		+/- (Only chondrocyte viability remains)	–	++	+ (Reduced/mild immune reaction by cartilaginous portion of graft) + (Infection risk due to storage media)	++ (Grafted at articular portion for weight support)	–
Allograft	Fresh-frozen ¹⁸	From 1. living donor 2. cadaveric donor		–	–	++ (Less than autogenous bone) ¹⁹	+ (Reported cases)	++ ¹	–
Allograft	Freeze-dried	From 1. living donor 2. cadaveric donor		–	–	++	+/-	+/- (Significantly affected by drying process) ²⁰	–
Allograft	Gamma sterilization			–	–	++	+/-	+ (By radiation effect) ²¹	–
Allograft	Demineralized bone matrix ²²	Mostly cadaveric donors	Demineralization processes + particle sizes	–	+/-	++	+/-	–	–
Selective cell retained allografts	Osteogenic cell		Patient characteristics	+	+/-	–	–	–	–

+++ Characteristic is definitely observed from biologic, clinical, and preclinical studies.

++ Characteristic is somewhat observed from biologic, clinical, and preclinical studies.

+ Suggested by clinical and preclinical studies. There may be some controversy or effect is minimal.

+/- Debate status; for demineralized bone matrix osteoinductive depending on the processing and sterilization techniques (product variability).

– None/no effect.

Table 2. Commercially available allograft mineralized products, structural and/or nonstructural.^{a,<}

Company	Allograft Spinal Graft Products	Formulation, Product Composition	Clinical Evidence; ClinicalTrials.gov/ Ongoing Study	Regulatory Clearance/Approvals; US by FDA-Registered Tissue Bank Establishments; 21CFR1270, CFR 1271 AATB; US Pharmacopoeia USP standard 71
AlloSource, Centennial, Colorado, 1995 Allosource.org	AlloFuse Spinal grafts—freeze-dried	Cortical/cancellous spacers Cancellous cervical spacers Cortical cervical spacers Bicortical blocks Dowel Patella wedge Cervical spacers, parallel spacer/textured lordotic Femoral rings Fibular rings, radial rings, ulna rings Cortical Strut TriCortical ilium wedges, strips	n/a n/a	Regulated human tissue CFR 1270, 1271 Regulated human tissue CFR 1270, 1271
	Spinal grafts—freeze-dried/ frozen		n/a	Regulated under CFR 1270, 1271 as a human tissue http://activize.com/wp-content/uploads/2014/05/Allograft-Catalog.pdf
AlloSource	Allofuse cortical fibers Allofuse cortical chips Cancellous	Cortical/cancellous chips Cancellous chips, crushed, cubed, block, unicortical dowels, tricortical ilium, femoral shafts, AlloTrue terminal sterility gamma irradiation Vacuum-level allograft designed to hydrate	(None in spine) NCT01413061 Subtalar arthrodesis	
ATEC, Carlsbad, California Australian Biotechnologies	AlphaGRAFT Structural Allografts Cervical spacers Femoral ring	PureCleanse, then chemical soak; low-temperature, high-pressure CO ₂	n/a	AATB standards and Good Tissue Practices
Beijing Datsing Bio-Tech Co Ltd, Beijing, China	BioCage	Cortical bone (from donor femur) contoured wedge-shaped, end plates large contact area with dentate protrusions (saw-tooth), sagittal convex angle, center open “window” and side hole	Spinal fusion anterior portion with BioCage 2 y (30/33, 90.9% vs 30/34, 88.2%) PEEK† (360° posterior rods and screws), 1-level lumbar spine ²⁷	Therapeutic Good Administration (TGA), code of Good Manufacturing Practice for Therapeutic Goods—Human Blood and Blood Components, Human Tissues and Human Cellular Therapy Products, 2013 Tissue banks in China products are now approved by the National Medical Products Administration, China. Previously CFDA/State Food and Drug Administration, China
BoneBank Allografts, Texas	SteriSorb*	Osteoconductive sponge allografts (100% cancellous bone) Characteristics of a sponge by absorbing saline, blood, or bone marrow aspirate	n/a	Bone Bank Allografts Registration—FDA BBA Manufacturing Registration—FDA (previously THB) Bone Bank Allografts—Accreditation AATB CTO Registration Certificate—Bone Bank Allografts (International Registration)
	SteriFlex	Wrappable bone allografts (100% cortical bone) Can be bent, contoured, rolled, trimmed, molded, or sewn, making this flexible bone material	n/a	

Table 2. Continued.

Company	Allograft Spinal Graft Products	Formulation, Product Composition	Clinical Evidence: ClinicalTrials.gov/ Ongoing Study	Regulatory Clearance/Approvals: US by FDA-Registered Tissue Bank Establishments; 21CFR1270, CFR 1271 AATB; US Pharmacopoeia USP standard 71
	SteriGraft—cervical ACF SteriGraft—ACF cortical-cancellous spacer SteriGraft—ALIF SteriGraft—PLIF SteriGraft—uncortical dense cancellous block SteriGraft—dense cancellous block	Fully machined, constructed of 100% human cortical bone (femur or tibia) Fully machined, constructed of 100% human cortical bone with an internal cancellous plug (femur or tibia) Fully machined, constructed of 100% human cortical bone (femur) Fully machined, constructed of 100% human cortical bone (femur or tibia) Uncortical dense cancellous block (femoral head, patella, distal tibia, talus, or calcaneus) Dense cancellous block (femoral head, patella, distal tibia, talus or calcaneus) Traditional-type cancellous bone chip or tricortical alloiliac bone	n/a	
	Traditional bone/cancellous bone allografts Traditional bone/cortical-cancellous bone allografts		n/a	
DePuy Synthes Spine	Zero-P Natural Plate System*	Zero-profile plate with allograft spacer (cervical spine)	n/a	21 CFR 888.3060, K152239 (December 2, 2015) FDA 510(k) cleared
Hospital Innovations	Ilium tricortical strips* Bone blocks* Whole shaft and hemishaft* FORGE* FORGE Oblique*	Traditional cortical/cancellous bone graft Available freeze-dried (FD) or frozen (FZ) Sterilized SAL 10 ⁻⁶ Fully machined corticocancellous spacer (cervical spine fusion) Fully machined cortical spacer designed to provide a natural option for transforaminal lumbar fusion Fully machined cortical-cancellous spacer (from femur and tibia) for cervical spine	n/a n/a n/a	K153203 (December 3, 2015) FDA 510(k) cleared AATB FDA Florida, California, and New York Holds a permit to provide tissue in Maryland Processed at an AATB-accredited facility
Life Link Tissue Bank	Cortical cancellous spacer*			
Maintain States Medical → Merged into Zimmer	OsteoStim*	Fully machined cortical spacer (from femur and tibia) for cervical spine		
Medtronic Spinal and Biologics	Allograft structural Cornerstone SR* Cornerstone ASR* Cornerstone-RESERVE* Cornerstone tricortical Cornerstone bicortical Cornerstone uncortical Cornerstone dense cancellous block Cornerstone selective/cortical wedge	Fully machined cortical block (from femur or tibia) with capital D shape Fully machined cortical lateral wall with a cancellous center with capital D shape Fully machined cortical ring with cancellous plug Freeze-dried cortical/cancellous (iliac crest) Freeze-dried cortical/cancellous (iliac crest) Freeze-dried anterior cortical wall with cancellous center Freeze-dried dense cancellous with capital D shape Freeze-dried cortical ring	ClinicalTrials.gov identifier: NCT01491399, no results posted	AATB standards, FDA regulations, and applicable Public Health Service guidelines for donor screening AATB standards, FDA regulations, and applicable Public Health Service guidelines for donor screening AATB standards, FDA regulations, and applicable Public Health Service guidelines for donor screening

Table 2. Continued.

Company	Allograft Spinal Graft Products	Formulation, Product Composition	Clinical Evidence: ClinicalTrials.gov/ Ongoing Study	Regulatory Clearance/Approvals: US by FDA-Registered Tissue Bank Establishments; 21CFR1270, CFR 1271 AATB; US Pharmacopoeia USP standard 71	
Orthofix	AlloQuent-s, Monolithic Cortical* Structural allograft*	Structural allograft (cervical fusion, lumbar fusion) Different sizes and shapes (ALIF, PLIF, TLIF)	NCT00637312, has results posted—cervical disc Trial was stopped; approval not being pursued for device (clinicaltrials.gov)	Unknown	
RTI Surgical	Elemax cortical spacer allograft* Elemax cortical spacer allograft* Elemax PLIF allograft*	Precision-machined cortical spacer for anterior cervical discectomy and fusion procedures Fully machined cortical lateral wall with a cancellous center with capital D shape for anterior cervical discectomy and fusion procedures Fully machined cortical spacer designed to provide a natural option for PLIF	n/a	AATB Accreditation Certificate (Florida) FDA Establishment Registration and Listing for Human Cells, FDA-HCT/Ps Florida Tutogen Medical, GmbH (Germany) International Organization of Standards (ISO) Tutogen Medical, GmbH (Germany) CMDCAS—RTI Surgical (Florida) CE certificates Pioneer Surgical Technology (Michigan) International Facility Registrations Canada—CTO Registration State Tissue Banking Licenses California, Florida, Maryland, New York, Oregon, Illinois, Delaware FDA Establishment Registration and Listing for Human Cells, FDA-HCT/Ps	
	AlloWedge bicortical allograft bone	Options for approaching opening wedge osteotomies in the foot and ankle Preshaped bicortical allografts	n/a	FDA Establishment Registration and Listing for Human Cells, FDA-HCT/Ps	
	Cross-Fuse Advantage lateral allograft	All-cortical bone implant designed for a lateral approach to provide maximum potential for fusion	n/a	FDA Establishment Registration and Listing for Human Cells, FDA-HCT/Ps	
	Bigfoot ALIF allograft	Produced from femoral or tibial tissue All-cortical bone implant designed for use as an intervertebral spacer in ALIF approach Freeze-dried: rehydrate for a minimum of 30 s Frozen: thaw for a minimum of 15 min	n/a	FDA Establishment Registration and Listing for Human Cells, FDA-HCT/Ps	
	Traditional cortical and/or cancellous strut allograft	Femoral head, hemifemoral shaft, humeral head, ilium tricortical block, ilium tricortical strip, proximal and distal femur, proximal and distal humerus, proximal and distal tibia, unicortical block, whole femur, fibula and humerus, and bicortical block	n/a	FDA Establishment Registration and Listing for Human Cells, FDA-HCT/Ps	
SeaSpine, Carlsbad, California	Capistrano System*	Cervical allograft spacer system is precision machined from cortical and cancellous allograft bone	n/a	361-HCT/P US-FDA 21 CFR 1271 Restricted to homologous use for the repair, replacement, or reconstruction of bony defects by a qualified health care professional (eg, physician) AATB US FDA regulations for tissue management. US-FDA 21 CFR 1271	
Stryker	AlloCraft CA, CL, CP, CS*	Machined from femoral/tibial allograft → ACDF Freeze-dried Chamfered edge	n/a		

Table 2. Continued.

Company	Allograft Spinal Graft Products	Formulation, Product Composition	Clinical Evidence: ClinicalTrials.gov/ Ongoing Study	Regulatory Clearance/Approvals: US by FDA-Registered Tissue Bank Establishments; 21CFR1270, CFR 1271 AATB; US Pharmacopoeia USP standard 71
Xiant USA	Ilium tricortical blocks,* unicortical blocks,* fibula segments,* and femoral struts*	Traditional allografts	n/a	Processed by tissue banks that are members of the AATB
X-spine Systems Inc/ Xiant USA	Atrix-C cervical allograft spacer	Precision-milled cortical bone with teeth like keel surfaces	n/a	Processed by tissue banks that are members of the AATB
Zimmer Biomet	OsteoStim cervical allograft system* OsteoStim PLIF* OsteoStim ALIF*	Fully machined cortical spacer bone for cervical and lumbar with teeth like keel surfaces	n/a	Processed by tissue banks that are members of the AATB

Abbreviations: AATB, American Association of Tissue Banks; ALIF, anterior lumbar interbody fusion; FDA, US Food and Drug Administration; n/a, not available on ClinicalTrials.org/no clinical data found or clinical trial registered (December 31, 2020); PLIF, posterior lumbar interbody fusion; THB, xxxx.

*AATB policies.²⁸

*Indicates cancellous chips “crunch” available.

†PEEK cage made from engineered plastic polyetheretherketone.

Demineralized Bone Matrix

DBM is derived from human allografts and prepared by acid extraction of innate minerals to create an osteoconductive organic matrix with differing quantities of proteins that aid in osteoinduction.⁵ DBM is a composite of collagens (mostly type I), noncollagenous proteins and growth factors, residual calcium phosphate mineral (1%–6%), and some cellular debris.³ The use of DBM was developed in 1965 by Urist,²⁹ who observed that soluble signals contained within the organic phase of bone were capable of promoting bone formation. After processing, DBM lacks structural integrity but retains osteoconductive and osteoinductive properties.³ DBM base is available, and when mixed with other substances these DBM-based products come in many forms, including powders, granules, gels, putties, and strips.³⁰ Importantly, the concentration of native BMP in DBM products differs significantly by manufacturer, donor lot, and batch, making it difficult to study the efficacy of DBM in clinical trials.^{30–33} In an athymic rat model, Bae et al³⁴ observed significant lot-to-lot variability of a single DBM-based product, commercially available “off-the-shelf” with regard to BMP concentrations and associated in vivo bone formation for fusion rates.³⁵ Therefore, it is important to note the efficacy of DBM’s osteoconduction and osteoinduction properties in clinical studies is limited by mainly narrative study designs with limited levels of evidence, small sample size, and lack of appropriate controls.²⁶

In current clinical practice, because DBM-based products lack structural integrity, they are exclusively/mostly used in spinal applications as bone graft extenders, typically mixed with surgical site local bone or morselized harvested bone from the iliac crest (ICBG) autografts, and/or exogenous peptide/differentiation factors (rhBMP-2) to promote bone growth.⁴ Kang et al³⁶ completed a 2-year prospective randomized clinical trial comparing outcomes of Grafton DBM with local bone to those of ICBG in a single-level instrumented posterior lumbar fusion. In the study, 46 patients (30 Grafton, 16 ICBG) were evaluated, and primary outcome was solid posterolateral lumbar fusion. Results indicated no significant difference in overall fusion rates between the 2 study groups (86% for Grafton, 92% for ICBG). Lower blood loss was recorded in the patients who received an implant of DBM-base

matrix (Grafton DBM-Matrix), but with equal or slightly greater improvement in Oswestry Disability Index scores for the DBM-base matrix patients.

Cammissa et al³⁷ completed a multicenter, prospective, side-to-side (right versus left) comparison of a DBM-based gel (Grafton DBM gel) combined with iliac crest autograft (2:1 ratio) placed on one side of the fusion construct versus iliac crest autograft alone on the other side in 120 patients who underwent posterolateral spinal fusion (PLF) procedures. At 24 months nearly equivalent fusion rates between the sides implanted with a composite of DBM-based gel (Grafton DBM gel) + one-third iliac autograft were 52% fused (42 of 81 sides) versus contralateral sides at 54% fused (44 of 81 sides) after being implanted with autograft alone. Specifically, radiographically fused rates of 40.7% bilateral (33 of 81 consistently both right and left sides fused) or 24.7% unilateral (only autograft side fused in 14% [11 of 81] versus DBM-based gel + autograft composite fused in 11% [9 of 81]). Although 34.6% (28 of 81) were not radiographically fused, the pseudarthrosis revision surgery rate was <1% (1 of 81). Interestingly, the fusion rate in this study is substantially lower than the accepted solid fusion rate of PLF surgery (90%),³⁸⁻⁴⁰ and the authors ascribe this discrepancy to a difficult patient population, strict radiologic criteria for fusion, and only evaluating bone graft lateral to the instrumentation on anteroposterior film.

These authors conclude that DBM-based allograft products may be used to augment the amount of autograft bone graft needed for successful lumbar fusion. Cammissa et al³⁷ report that one third the quantity of autograft may be used with this DBM-based gel graft extender to achieve consolidated bony fusion, and Kang et al³⁶ used 15 to 20 cm³ of autograft with DBM compared with 25 to 30 cm³ ICBG for successful fusion. The studies by Kang et al and Cammissa et al provide level 1 evidence that Grafton can be used as a bone graft extender for lumbar spinal fusion.³⁷

Interestingly, Grafton is the only bone graft extender to have level 1 evidence and shows different efficacy in the lumbar spine versus the cervical spine. As the above studies showed Grafton to be effective in lumbar spinal fusions, a study by An et al showed level 1 evidence that Grafton DBM is not useful for cervical spinal fusion.^{41,42} In a randomized control trial, An et al⁴² compared 77

ACDF patients with either Grafton DBM + tricortical bone versus tricortical bone alone. Nonunion developed in 46% of patients in the Grafton group compared with 26% of patients in the standalone tricortical bone group.

Table 3 provides a list of commercially available DBM-based products used for spinal fusion and specifics on each product.

Viable Cellular Allografts (Cellular Bone Matrices)

The advancement in the field of stem cell procurement has generated the development of allogenic bone grafts containing live mesenchymal stem cells (MSCs), also known as cellular bone matrices.⁶³ Mesenchymal stem cells were identified in 1966 by Fridenstein et al in bone marrow and have been shown to differentiate into chondroblasts and osteoblasts.^{63,64} These commercially available bone allografts are composed of osteoconductive partially demineralized cadaveric bone as matrix carriers with components of cryopreserved allogeneic cells (MSCs) that promote osteogenesis and osteoinduction.^{6,65} MSCs can be isolated from bone marrow, placenta, umbilical cord blood, connective tissue, skin, synovial fluid, fat, and teeth.^{63,66} MSCs are capable of evading the immune system because they uniquely do not express human leukocyte antigen class II molecules, which are essential for activation of the cellular immune response.^{63,67-69}

In the United States, the process to manufacture these materials involves the American Association of Tissue Banks (AATB) approval processes for cadaveric human bone recovering (contract with independent US Food and Drug Administration [FDA]-registered tissue recovery groups), processing, storing, and preserving cellular components of the bone, or addition of cells, and removal of noncellular proteins. Marketed under FDA-HCT wherein the regulation of product directive is safety, safety is exercised by restricted donor screening. Unlike other DBM-based allografts approved via 510(k) or premarket approval pathways, CBMs are not required to be terminally sterilized, relying on the donor screening and aseptic processing to ensure safety. The exact procedures vary by manufacturer. The HCT/P classification does not require lot-to-lot cell composition or validation of growth factor production. (Per FDA guidance documents on HCT/P products, to “rely on the metabolic activity of living

cells for their primary function” would render a product as a biologic drug [section 360], which would require a biologic license application and clinical trials.)

CBMs are commercially provided as frozen products and must be stored at -80°C , and they require thawing prior to surgical implantation. Neither the reproducibility of cell recovery, after thaw, nor the viability of the cells following implantation has been established for commercially available products or production lots of them. The average number of cells across products is claimed to range from 66 000 to 3 million. Attempting to preserve the viable cells, these products are not terminally sterilized, like 510(k) DBMs or premarket approval products, but rely on aseptic processing to ensure safety. Table 4 provides a list of commercially available CBMs used for spinal fusion and specifics on each product.

The efficacy of viable cellular allografts in spinal fusion is difficult to determine. Given the properties of mesenchymal stem cells, their ability to promote osteogenesis, and their ability to evade the immune system, it is reasonable to think they would be advantageous for bone fusion. Several *in vivo* studies have demonstrated theoretical benefits of using CBMs. Cui et al⁹⁰ compared cloned osteoprogenitor cells to mixed marrow cells and found that cloned cells produced a greater amount of mature osseous tissue at an earlier time point during spine fusion in an athymic rat model. Gupta et al⁹¹ used an ovine posterolateral lumbar fusion model and found similar fusion rates with osteoprogenitor-enriched graft compared with autograft.

To date, there have been very few non-industry-sponsored clinical trials. McAnany et al⁹² evaluated 57 patients who underwent a 1- or 2-level ACDF using interbody allograft with Osteocel (NuVasive, San Diego, California). The patients were matched to a control group of 57 patients where only interbody allograft was used. At the 1-year follow-up, 87% in the Osteocel cohort had solid fusion compared with 94.7% in the control group.⁸¹

There are many factors that can influence the efficacy of CBMs and therefore result in limitations to these products. Hernigou et al⁹³ showed that bone marrow aspirates containing fewer than 1500 MSC/cc were ineffective for the treatment of tibial nonunion, suggesting that this is the minimal MSC concentration for bony healing.⁶³ Preparation of

MSCs is not standardized, and variation in donor age, donor site, and viability of stem cells after thawing the allograft can all influence the effectiveness of CBM.

Although human clinical data are lacking, the athymic rat model allows for direct testing of CBM bone graft products. In a well-established rat model, fusion is assessed by manual palpation of a bony mass 6 to 8 weeks after implantation of DBM-based or CBM-based graft placed between the transverse processes during a posterolateral fusion procedure.^{33,34,76} Using this model, Bhamb et al³³ reported at 8 weeks a 0 of 16 fusion rate in rats implanted with CBM Osteocel Plus Pro (NuVasive) compared with 88% to 100% fusion rate after noncellular human DBM-based products were implanted (Acell Evo3, DBX Mix, DBX Strip, Grafton Crunch, Grafton Flex, and Grafton Matrix), and 13% (2 of 16) were manually fused when implanted with syngeneic bone graft. Lin et al⁷⁶ at 6 weeks detected manual palpation fusion in 73% (11 of 15) of Cellentra (Zimmer Biomet, Warsaw, Indiana), 53% (8 of 15) of Trinity Elite (OrthoFix, Lewisville, Texas), 13% (2 of 15) of Vivi-Gen (Dupey Synthes, Raynham, Massachusetts) and 0 of 15 for each of Osteocel Plus Pro, Bio4 (BIO, Stryker, Kalamazoo, Michigan), and Map3 (RTI Surgical, Marquette, Michigan) implanted rats; 33% (5 of 15) were manually fused for syngeneic bone graft-implanted rats. Johnstone et al⁸⁰ recently evaluated manual palpation results after posterolateral fusion performed with several commercially available human CBM grafts; the highest manual palpation fusion rates were 71% (10 of 14) for Trinity Evolution and 77% (10 of 13) for Trinity Elite compared with 7% (1 of 14) for Osteocel Plus Pro and 40% (6 of 15) for syngeneic bone-implanted rats.

The findings of these studies highlight the variability among CBM commercial products and potentially among production lots.³² Yet, interestingly, there are common observations across these studies: Syngeneic bone graft, a proxy for ICBG in this model, containing some live cells yielded low fused rates (13%, 33%, and 40%) across the studies, whereas the Osteocel Plus preparations consistently yielded almost no sites fused (0%, 0%, and 7%). Trinity Elite (53% and 77%) and Trinity Evolution (71%) formulations, along with Cellentra (73%), seem to yield somewhat comparable results. Preparations, sterilization, formulation, manufacturing

Table 3. Commercially available demineralized bone matrix (DBM)-based products.^a

Company	DBM-Based Product (Human)	Formulation	Product Composition	Peer-Reviewed Clinical Evidence/Ongoing Study ClinicalTrials.gov Identifier	Regulatory Clearance/Approval FDA 510(k), CFR 1270, CFR 1271
AlloSource Inc Centennial, Colorado, 1995 Allosource.org	AlloFuse Gel AlloFuse Putty (identical to Stimublast Putty and Gel manufactured for Arthrex)	Injectable gel and putty	DBM, RPM carrier Carrier composed of polyethylene oxide polypropylene oxide block copolymer dissolved in water exhibiting reverse-phase characteristics (ie, an increase in viscosity as temperature increases) DBM, RPM, cancellous chips Cancellous bone allograft, DBM, strip form, no carriers added	n/a	K071849, December 2008
Amend Surgical Inc	Allofuse Plus Alloflex NanoFUSE Bioactive Matrix NanoFUSE DBM	Paste, putty Strips, blocks, fillers Putty Putty 2-10 cc	DBM + 45S5 bioactive glass Bond void filler 45S5 bioactive glass + porcine gelatin + DBM 45S5 bioactive glass: osteoconductive scaffold, DBM: osteoinductive potential	Kirk et al, ⁴³ 2013 In vivo mouse muscle Kirk et al, ⁴³ 2013 In vivo mouse muscle	K103036, January 2011 Marketed as human tissue K161996, February 2017 Regulated under CFR 1270, 1271 as a human tissue K110976, May 2011 www.accessdata.fda.gov/cdrh_docs/pdf11/K110976.pdf www.accessdata.fda.gov/cdrh_docs/pdf16/K161996.pdf 510(k) DCI regulatory classification LIT-84817A, LIT-84806A Linked to K150621, August 2015 (Bacterin International Inc)
ATEC, Carlsbad, California/Alphatec Spine Inc	ALPHAGRAFT DBM	Putty or gel	DBM of 100% demineralized fiber, an RPM DBM with superior handling characteristics and ready-to-use application. RPM: Thickens at body temperature	n/a	
Australian Biotechnologies, Sydney, Australia	Alloavance Fibre Mat	Demineralized bone fibers	Demineralized bone long fibers cut (low-energy technique) preserving bone collagen alignment and microstructure 74% DBM dry weight	Rajadurai et al, ⁴⁴ 2019 Case report ALIF	Australian Therapeutic Goods Administration (TGA), Code of Good Manufacturing Practice for ~2017 K091321, September 2009 K130498, May 2013
Bacterin International Inc → Changed to Xiant Medical	OsetoSelect DBM OsetoSelect Plus DBM OsteoSponge OsteoSponge SC OsteoWrap	Putty Putty The malleable sponge The malleable sponge Flexible handling characteristics with a scalpel or scissors Various shape (fiber, boat shape, strip)	74% DBM dry weight + demineralized cortical chips (1-4 mm) DBM (100% human demineralized cancellous bone) Demineralized cancellous bone intended to treat the pathology of damaged subchondral bone of the articulating joints 100% Human demineralized cortical bone 100% Human demineralized cortical bone fiber Contain BMPs and other growth factors 3Demin allografts are also available as loose cortical fibers in 3 volume options 100% DBM putty and crush-mix	Yao et al, ⁴⁵ 2020 MI-TLIF, lumbar spine Yao et al, ⁴⁶ 2019 MI vs open TLIF n/a Shehadi and Elzein, ⁴⁷ 2017 Galli et al, ⁴⁸ 2015, 717-722, <i>Journal of Foot & Ankle Surgery</i>	K150621, August 2015 HCT/P (FEI 3005168462) HCT/P (FEI 3005168462), November 2017 HCT/P (FEI 3005168462), November 2017 HCT/P (FEI 3005168462), November 2017 Compliance with FDA guidelines regarding human cells, tissues, and cellular tissue-based products HCT/P 361 regulated viable allogeneic bone scaffold AATB guidelines
Berkeley Advanced Biomaterials, California	H-GENIN	Putty Matrix sponge Powder	100% DBM putty and crush-mix	Shehadi and Elzein, ⁴⁷ 2017	510(k) cleared (as B-GENIN, R-GENIN) K092046, March 2010 510(k) cleared K082793, April 2009 K031399, February 2005
Biomet Osteobiologics → Merged into Zimmer Biomet	InterGro DBM	Putty (40% DBM) Paste (35% DBM)	DBM, lethicin carrier (resorbable, biocompatible, semiviscous lipid)	Prospective case series	

Table 3. Continued.

Company	DBM-Based Product (Human)	Formulation	Product Composition	Peer-Reviewed Clinical Evidence/Ongoing Study ClinicalTrials.gov Identifier	Regulatory Clearance/Approval FDA 510(k), CFR 1270, CFR 1271
Bioventus surgical	Exponent	Putty form	Demineralized bone matrix is composed of human demineralized bone (DBM) mixed with resorbable carrier, carboxymethylcellulose	n/a	AATB US FDA 21 CFR 1271. (HCT/P)
	PUREBONE	Sponge shape (available in block or strip format)	100% Demineralized cancellous bone (osteoconductive matrix with osteoinductive potential that provides a natural scaffold for cellular ingrowth and revascularization)	n/a	FDA 510(k) Cleared AATB US FDA 21 CFR 1271. (HCT/P)
BoneBank Allografts 2017/ Texas Human Biologics	SteriFuse DBM Putty	Flowable, formable putty	Sterilized by gamma irradiation 100% DBM from human bone	n/a	Regulated under 21 CFR Part 1271 (h) FDA requirements for HCT/P
	SteriFuse Crunch	Flowable, formable crunch	SteriFuse DBM putty with cortical cancellous bone chips (composition?) DBM + sodium hyaluronate	n/a	Regulated under 21 CFR Part 1271 (h) FDA requirements for HCT/P
DePuy Synthes	DBX	Putty type Paste Mix		NCT02005081: DBX and Autograft vs. Actifuse in ACC Cervical spine (translational PLF: Russell et al. ⁴⁹ 2020; Bhamb et al. ³³ 2019) NCT04635865	K103795, April 2011 K080399, October 2008
	SYNTHESES Dento	Powder type Granule type Putty type Paste	Powder type: demineralized cortical powder, mineralized cancellous powder, mineralized cortical powder Granule type: demineralized cortical (80%)/cancellous granules, mineralized cortical (80%)/cancellous granules DBM putty type: 93% DBM Synthetic calcium phosphate, an inert carrier, carboxymethyl cellulose, and DBM		
ETEX/Zimmer Biomet	CaP Plus	CaP Plus		n/a	K063050, November 2007 K080329, April 2008
Exactech	Optecure	Injectable paste	DBM (81% by dry weight), hydrogel carrier	NCT00254852 (terminated)	K121989, November 2012 K061668, September 2006 K050806 February 2006 K061668, September 2006 K121989, November 2012
	Optecure + CCC	Injectable paste	Polymer powder, DBM, cortical cancellous chips (1-3 mm)	NCT02127112 Optecure + CCC vs allograft Adams BD 2016 Wrist Arthrodesis ⁵⁰ n/a (translational Wang et al. ³² 2007; Togawa et al. ⁵¹ 2003)	K043420, February 2005
	OSTEOFIL DBM Paste, OSTEOFIL RT DBM Paste	DBM paste or Dry powder—hydrated to become injectable paste	DBM in gelatin carrier		
	Opteform	Putty or dry powder—hydrated to become paste	Gelatin, DBM, and cortical-cancellous bone chips	n/a	K043421, February 2005

Table 3. Continued.

Company	DBM-Based Product (Human)	Formulation	Product Composition	Peer-Reviewed Clinical Evidence/Ongoing Study ClinicalTrials.gov Identifier	Regulatory Clearance/Approval FDA 510(k), CFR 1270, CFR 1271
Integra Orthobiologics (IsoTis OrthoBiologic) Inc, Irvine, California, SeaSpine 2018	Accell Connexus	Injectable putty	DBM (70% by weight), RPM	Retrospective comparative Schizas et al. ⁵² 2007	K060306, March 2006
	Accell Evo3TM	Injectable putty	DBM (Accell Bone Matrix), RPM	NCT02018445 Instrumented Lumbar PLF DBM (Accell Evo3) + LB	K061880, August 2007
				NCT01714804 Instrumented Lumbar PLF (Accell Evo3) Orndorff DG 2019, NASS 2019 ⁵³	K103742, March 2011
				NCT01430299 Prospective cohort, PLF DBM (Accell Evo3) vs rhBMP-2 (Infuse) Klineberg et al. ⁵⁴ 2020 AOSpine	
				n/a	K081817, September 2008
Lifenet Health	Accell TBM	Preformed matrix (strip, square, round)	100% DBM (Accell Bone Matrix)	n/a	K040419, March 2005
	Dynagraft II	Injectable gel, putty	DBM (Accell Bone Matrix), RPM, cancellous bone chips	n/a	K050642, December 2005
	Orthoblast II	Injectable paste, putty	DBM (Accell Bone Matrix), RPM, cancellous bone chips from same donor	Lee et al. ⁵⁵ 2019 ADCF plate fixation + DBM (Orthoblast II) vs tricortical iliac autograft	Regulated under CFR 1270, 1271 as a human tissue
	IC Graft Chamber	Freeze-dried in injectable delivery chamber, can be mixed with whole blood, PRP, or BMA	DBM, cancellous chips	n/a	
	Optium DBM Putty Optium DBM Gel Collect DBM	Putty Gel Provided in a specialized cartridge	DBM, glycerol carrier Particulate DBM and glycerol DBM fibers + cancellous chips	n/a n/a Lee et al. ⁵⁶ 2009—case reports treat secondary osteonecrosis	K053098, November 2005 K053098, November 2005 Regulated under CFR 1270 and 1271
Medtronic Spinal and Biologics	Osteofil DBM	Injectable paste, moldable strips	DBM (24% by weight) in porcine gelatin	Prospective case series Epstein et al. ⁵⁷ 2007	K043420, February 2005
	Progenix TM Plus	Putty with demineralized cortical chips	DBM in type I bovine collagen and sodium alginate	n/a	K081950, July 2008
	Progenix Putty	Injectable putty	DBM in type I bovine collagen and sodium alginate	Muzević et al. ⁵⁸ 2018 ACDF Blinded observations/assessment of study in rabbit (Smucker et al. ⁵⁹ 2008)	K080462, May 2008
	Magnifuse Family 1. Magnifuse Bone Graft substitute/bone void filler 2. Magnifuse II Bone Graft		DBM mixed with autograft in 1:1 ratio packed into polyglycolic acid resorbable mesh bag 1. DBM + surface-demineralized chips 2. Combination of surface demineralized cortical chips and allograft fibers that have been processed, removing the mineral component and leaving only the organic portion	NCT02684045: PLF 1- to 2-level retrospective review cases Spine	K123691, January 2013 K082615, October 2008

Table 3. Continued.

Company	DBM-Based Product (Human)	Formulation	Product Composition	Peer-Reviewed Clinical Evidence/Ongoing Study ClinicalTrials.gov Identifier	Regulatory Clearance/Approval FDA 510(k), CFR 1270, CFR 1271
MTF/Synthes	DBX	Paste, putty mix, strip	DBM (32% by weight), sodium hyaluronate carrier (mix varies for paste, putty, mix), processed human cortical bone	NCT02005081: DBX and Autograft vs Actifuse SHAPE (Baxter) in ACC cervical spine	K040262, March 2005 (putty, paste, matrix mix) K040501, 2005—(putty, paste, matrix mix) April 2005 K053218, December 2006 (putty, paste, matrix mix) K063676, March 2007 (putty, paste, matrix mix) K080399, October 2008 (paste) K091217, October 2009 (putty) K091218, September 2009 (putty) K103795, April 2011 (putty) K103784, April 2011 (putty) K042829, January 2006 (strip) DBX approved in more than 50 countries
Nanotherapeutics Inc NanoFuse Biologics LLC, Malden, Massachusetts	Origen DBM with Biosotive Glass (NanoFUSE DBM)	A malleable, puttylike, bone-void filler	Human DBM and synthetic calcium phosphor-silicate particulate material particles (45s5 bioactive glass), both coated with gelatin derived from porcine skin	NCT03751943 PLF with autograft NCT03762811 (NanoFUSE with autograft in voids fusion)	K120279, April 2012 K110976, May 2011
NuTech Medical Inc	Matrix: Osteoconductive Matrix Plus Matrix: FiberOS	Putty type Putty type	Allograft cancellous and demineralized cortical mixture Freeze-dried for convenient ambient temperature storage Demineralized cortical fibers, mineralized cortical powder, and demineralized cortical powder Gamma-sterilized for patient safety Freeze-dried for convenient ambient temperature storage	(See: Table 4 NCT02023372)	
Osteotech/Medtronic	GRAFTON A-Flex GRAFTON Crunch GRAFTON Flex GRAFTON Gel GRAFTON Matrix PLF GRAFTON Matrix Scoliosis Strips GRAFTON Orthoblend Large Defect GRAFTON Orthoblend Small Defect GRAFTON PLUS DBM Paste Grafton Putty 22076647	Round, flexible sheet Packable graft Flexible sheets, varying sizes Injectable syringe Troughs Strips, various sizes Packable graft Packable, moldable graft Paste Packable, moldable graft	DBM DBM, demineralized cortical cubes DBM DBM DBM DBM, crushed cancellous chips DBM, crushed cancellous chips Human bone allograft DBM + inert starch-based carrier has been added DBM (17% by weight), glycerol	n/a n/a Retrospective comparative study RCT, prospective case series RCT Retrospective case series n/a n/a n/a Kang et al, ³⁶ 2012 PLF RCT Grafton and local bone vs ICBG Park 2013 ³⁵ ACD, prospective case series PEEK cage packed with Grafton Cammisa et al, ³⁷ 2004 PLF Prospective comparative study, side-by-side in same patient: Grafton DBM gel vs ICBG An et al, ⁴² 1995, cervical ACD Prospective comparative study DFDBA tricortical graft filled with Grafton vs ICBG	K051188, January 2006 K051188, January 2006 K051195, December 2005 K051195, December 2005 K051195, December 2005 (Recalled October 18, 2012) 510(k) cleared 510(k) cleared K043048, November 2005 (Osteotech)—traditional K042707, November 2005 (Osteotech) K051195, December 2005

Table 3. Continued.

Company	DBM-Based Product (Human)	Formulation	Product Composition	Peer-Reviewed Clinical Evidence/Ongoing Study ClinicalTrials.gov Identifier	Regulatory Clearance/Approval FDA 510(k), CFR 1270, CFR 1271
Pioneer Surgical Technology and Regeneration Technologies → All companies merged into RTI Surgical	BioSet	Injectable paste, putty, strips, and blocks with cortical cancellous chips	DBM, gelatin carrier	n/a	510(k) cleared Regulated under 21 CFR Part 1271 (h FDA requirements for HCT/P) December 7, 2016 (validated by FDA)
	BioAdapt DBM	Powder form	Dried powder form (70% DBM by weight) donated from 100% donated human musculoskeletal tissue	n/a	Regulated under 21 CFR Part 1271 (h FDA requirements for HCT/P) December 7, 2016 (validated by FDA)
	BioReady DBM Putty and Putty with Chips	Putty/putty with bone chip	<ul style="list-style-type: none"> Putty: 56% DBM by weight Putty with chips: 42% DBM by weight + small or large mineralized cortical cancellous chip → 100% allograft DBM	n/a	Regulated under 21 CFR Part 1271 (h FDA requirements for HCT/P) December 7, 2016 (validated by FDA)
	OsteoBallast Demineralized Bone Matrix OsteoSurge 300 Demineralized Bone Matrix	DBM in resorbable mesh	100% DBM	n/a	FDA 510(k) cleared
SeaSpine, Carlsbad, California	OsteoSurge 300c Demineralized Bone Matrix	The moldable putty form including cancellous chips	DBM + Accell bone matrix (it is an open-structured, dispersed form of DBM) + cancellous bone	NCT01430299 (Same Accell Evo3)	AccellEvo3, same material
	OsteoSurge 300c Demineralized Bone Matrix	The moldable putty, including cancellous chips	DBM + Accell bone matrix (it is an open-structured, dispersed form of DBM) + cancellous bone + bioresorbable, RPM carrier	NCT01430299 (Same Accell Evo3)	AccellEvo3, same material (SeaSpine, new sponsor)
	OsteoSpaxx Demineralized Bone Matrix OsteoSpaxx C Demineralized Bone Matrix Accell Total Bone Matrix	Gel or puttylike consistency Gel or puttylike consistency	DBM + RPM carrier + cancellous bone	NCT01430299 (Same Accell Evo3)	AccellEvo3, same material (SeaSpine, new sponsor) It is the same material as Accell Evo3
	Accell Evo3c	Preformed shape (round or rectangular) Putty	DBM + Accell bone matrix → 100% DBM open-structured, dispersed form of DBM) + cancellous bone + bioresorbable, RPM carrier	NCT01430299	It is the same material as Accell Evo3
Accell Evo3		Putty	DBM + Accell bone matrix (it is an open-structured, dispersed form of DBM) + cancellous bone + bioresorbable, RPM carrier	n/a	K103742, March 2011
				NCT02018445	K103742, March 2011
				Case study PLIF (December 2013 ~ June 2017) DBM (Accell Evo3) + LB	
				NCT01714804 Prospective PLF vs retrospective PLF rhBMP-2 (December 2017 ~ January 2018)	
SeaSpine Orthopaedics Corp, Irvine, California (IsoTis Orthobiologics)	Capistrano OsteoStrand Plus OsteoStrand	DBM + allobone Bone matrix	DBM + machined cortical and cancellous allograft bone 100% demineralized bone fibers with (Powered by Accell Bone Matrix)	NCT01430299 RCT on PLF DBM (Accell Evo3) (93.5% fused) vs rhBMP-2(100% fused).	FDA 510(k) cleared
				Eleswarapu et al., ⁶⁰ 2020	361 HCT/P
				n/a	
				NCT04629807, ALIF DBM vs DBM NCT04629794 PLF deformity correction: DBM (OsteoStrand [Fibers]) vs rhBMP-2	

Table 3. Continued.

Company	DBM-Based Product (Human)	Formulation	Product Composition	Peer-Reviewed Clinical Evidence/Ongoing Study ClinicalTrials.gov Identifier	Regulatory Clearance/Approval FDA 510(k), CFR 1270, CFR 1271
SeaSpine Inc	All Products SeaSpine			NCT04364295 (Global Registry Study) Effectiveness of SeaSpine products n = 500	
Smith & Nephew	VIAGRAF	Putty, paste, gel, crunch, and flex	DBM, glycerol	n/a	K043209, December 2005
Spinal Elements	Hero DBM	Putty, paste, gel	DBM, RPM	n/a	Regulated under CFR 1270, 1271 as human tissue
	Hero DBM Powder	Powder	DBM	n/a	Regulated under CFR 1270, 1271 as human tissue
SpineFrontier, Malden, Massachusetts		Included DBM	Interbody fusion device		K 193106 (likely a combination product, June 2020)
Wright Medical Technology	ALLOMATRIX	Various volumes, consistency varies depending on proportion of cancellous chips used	DBM (86% by volume) with or without CBM in surgical-grade calcium sulfate powder	Fu et al. ⁶¹ 2016, TLIF/PLIF with DBM (Allomatrix) + LB HA/β-TCP vs AIBG + LB + HA/β-TCP; retrospective comparative study	K041663, September 2004
	ALLOMATRIX RCS	Formable putty	DBM, synthetic RCS, calcium sulfate, and hydroxypropylmethylcellulose	n/a	K041663, September 2004
	ALLOMATRIX C	Putty	ALLOMATRIX + small cancellous chips	n/a	510(k) cleared K040980 (July 14, 2004)
	ALLOMATRIX CUSTOM	Putty	ALLOMATRIX + large cancellous chips	n/a	K040980 September 2004
	ALLOMATRIX	Injectable	DBM (86% by volume) + OSTEOSET (surgical-grade calcium sulfate)	NCT00274378 Injectable DBM (Allomatrix) putty in distal radius fracture	510(k) cleared K020895
	ALLOMATRIX DR	Putty	Calcium sulfate, DBM, and small cancellous chips	n/a	K040980, July 2004
	PRO-STIM	Procedure kits, various volumes of injectable paste/formable putty	50% Calcium sulfate, 10% calcium phosphate, and 40% DBM by weight	n/a	FDA 510(k) cleared

Table 3. Continued.

Company	DBM-Based Product (Human)	Formulation	Product Composition	Peer-Reviewed Clinical Evidence/Ongoing Study ClinicalTrials.gov Identifier	Regulatory Clearance/Approval FDA 510(k), CFR 1270, CFR 1271
Zimmer → it merged into Zimmer Biomet company	IGNITE	Percutaneous graft for fracture malunion/nonunion	DBM in surgical-grade calcium sulfate powder to be mixed with BMA	n/a	510(k) cleared K052913, November 2005
	Osteoset DBM Pellets	Packable pellets	3.0- or 4.8-mm pellets Surgical-grade calcium sulfate, DBM (53% by volume), stearic acid	Xie et al, ⁶² 2014 Cervical fusion (ACDF) PEEK with either Osteoset vs ICBG	510(k) cleared K022828, April 2004 K053642, January 2006
	PRO-STIM Injectable Inductive Graft	Injectable paste/formable putty	DBM (40% by weight), calcium sulfate (50% by weight), calcium phosphate (10% by weight)	n/a	510(k) cleared K190283, February 2019
	Puros DBM with RPM Gel and Paste	Gel, paste	DBM, RPM, ground cancellous bone (<500 microns)	NCT03112772 (Socket Preservation)	Regulated under CFR 1270, 1271 as human tissue
	Puros DBM with RPM Putty & Putty with chips	Putty	DBM, RPM, with or without cortical bone chips (850 microns to 4 mm)	n/a	Regulated under CFR 1270, 1271 as human tissue
	Puros DBM Block and Strip	Blocks, strips in varying sizes	DMB (100%)	n/a	Regulated under CFR 1270, 1271 as human tissue
	Bonus CC Matrix	Putty type (molded, packed)	50% Demineralized cortical bone (DBM) + 50% mineralized cancellous chips	n/a	FDA registration number: FEI 1000160576 (until June 30, 2020) AATB and HTC/P
	SiaGraft DBM Putty and Plus	Putty/granules (molded, packed)	DBM + natural lecithin carrier + resorbable coralline hydroxyapatite/calcium carbonate granules. Available as a 40% DBM Putty or 35% DBM PLUS	n/a	FDA registration number: FEI 1000160576 (until June 30, 2020)
	SiaGraft Cancellous DBM Sponge and Strips	Sponge strips from a single piece cancellous bone	Cancellous DBM sponge and strips are machined from a single piece of cancellous bone. Osteoinductive bone, trabecular structure, spongelike handling	n/a	FDA registration number: FEI 1000160576 (until June 30, 2020)
	FiberStack Demineralized Bone Matrix	Molded, packed	Manufactured entirely from cortical bone, which has been demonstrated to maintain higher osteoinductivity than cancellous bone after demineralization 100% DBM (without carrier)	n/a	FDA registration number: FEI 1000160576 (until June 30, 2020)

Abbreviations: AATB, American Association of Tissue Banks guidelines; ACC, anterior cervical corpectomy with fusion; ACDF, anterior cervical discectomy fusion; AIBG, autologous bone chips; ALB, autologous Local bone chips; ALIF, anterior lumbar interbody fusion; BMA, bone marrow aspirate; BRC, bone repair cells; CBM, cellular bone matrix, cellular bone allograft; FDA, US Food and Drug Administration; HA/β-TCP, hydroxyapatite β-tricalcium phosphate; ICBG, iliac crest bone graft; LB, local bone; LIF, lumbar interbody fusion; OLIF, oblique lateral lumbar interbody fusion; PEEK, a polyetheretherketone material used for cage devices employed as instrumentation in anterior interbody spinal fusion procedures; PLIF, posterolateral lumbar fusion; RCT, randomized control trial; RbBMP-2, recombinant human morphogenic protein-2, infuse; RPM, reverse-phase medium; TLIF, transforaminal lumbar interbody fusion; VBM, viable bone matrix; VCBM, viable cell bone matrix; XLIF, extreme lateral interbody fusion.

"510(k) is a premarket submission made to the FDA to demonstrate that the device to be marketed is at least as safe and effective as, that is, substantially equivalent to, a legally marketed device that is not subject to premarket approval. 501(k) documentation for individual products is available via the FDA online database (<http://www.accessdata.fda.gov>). CFR Code of Federal Regulations 1270 (human tissue intended for transplantation) and 1271 (human cells, tissues, and tissue-based products) are federal regulations relating to the procurement and processing of human-derived tissues. Human Tissue Banks: https://images.magnetmail.net/images/clients/AATB/attach/Bulletin_Links/18_2/AATB_Accreditation_Policies_February_08_2018.pdf (last update February 2018). TBI: Tissue Banks International National Processing Center (an AATB-accredited tissue bank). US human tissue bank license states: California, Florida, Maryland, and New York.

Table 4. Commercially available combination grafting products, naturally occurring peptides, growth differentiating factors, cellularized grafts, and cellular bone matrices (CBMs).

Company	Combination Product	Formulation	Product Composition	Peer-Reviewed Clinical Evidence/Ongoing Study ClinicalTrials.gov Identifier: NCT	Regulatory Clearance/Approval FDA 510(k), FDA 361, 21 CFR Part 1271 CFR 1270, CFR 1271 21 CFR 3.2(e) HCT/P 361, Human Allografts (No Clinical Studies) Biologic Drugs and Devices 351 (Clinical Trials)
Advanced Biologics, Carlsbad, California, 2009 (marketed OsteoAMP in the USA since 2009/ Bioventus)	OsteoAMP	Granules or sponge	OsteoAMP, an allogeneic growth factor implant, exploits the angiogenic, mitogenic, and osteoinductive growth factors that are within marrow cells	Field et al, ⁷⁰ 2014 Cervical Spine-Fusion NCT02225444	Bioventus manages orders and sales of HCT/Ps (not a distributor, FDA)
OsteoAMP in the USA since 2009/ Bioventus			Growth factor-rich naturally occurring growth factors, including BMP-2, BMP-7, aFGF, and TGF- β 1 bone graft substitute: intended for homologous use repair, replacement, or reconstruction of musculoskeletal defects	Lumbar Spine-PLF (TLIF, LLIF) Roh et al, ⁷¹ 2013 Yeung et al, ⁷² 2014, evaluation of donor bone, processing aseptically terminal sterilization in cervical/ lumbar	Regulated under CFR 1270, 1271 as a human tissue, registration held by Tissue Bank Permit: Millstone Medical Outsourcing LLC, Olive Branch, Mississippi (Bone, Demineralized Bone Matrix, Ligament, Musculoskeletal Tissues, Tendons) Maryland, New York State
Bioventus Surgical, Durham, North Carolina (original developer)					Tissue Bank Permit: Advanced Biologics LLC (Bone Demineralized Bone Matrix) Regulated under CFR 1270, 1271 as a human tissue
AlloSource, Centennial, Colorado, 1995 Allosource.org	Allostem Cellular Bone Autograft (ACBM) AlloWrap	Strips, blocks, cubes, morselized Amniotic membrane	Partially demineralized allograft bone combined with adipose-derived MSCs Amniotic membrane dual-sided epithelial layer	NCT01413061 ACBM (69.2%) vs tibia/ICBG (45.6%). Nonunion rate after Subtalar Arthrodesis Myerson et al, ⁷³ 2019 NCT04684901 (Cervical Spine, 2-level, ACDF)	
Aziyo Biologics Inc Richmond, California	FiberCel (Medtronics) OsteoGro V OsteoGro V ViBone	Putty	OsteoGro V Fiber Cancellous bone particles with preserved cells combined with demineralized cortical particles Viable Bone Matrix (ViBone, Aziyo gentle VBM processes) OsteoGro Allograft Bone Matrix sterile bone matrix composed of cancellous particles and demineralized cortical fibers TCP + natural cocktail of bone proteins (growth factors)	Reduction of Soft Tissue Swelling NCT03896347 (3-level OLIF) NCT03425682 Lumbar (PLIF, TLIF) or Cervical (ACDF) Fusion using ViBone	Regulated under CFR 1270, 1271 as a human tissue
BBS-Bioactive Bone Substitutes Oyi, Finland	ARTEBONE			NCT02480868: case series study for ankle fusion	FDA 510(k) cleared
Bioventus Surgical Durham, North Carolina Hoofddorp, Netherlands	OSTEOAMP	Granule, putty, and sponge form	Cervical and lumbar spine fusion procedures Allograft with growth factors (such as BMP-2, BMP-7, TGF- β 1, aFGF, VEGF, and ANG1, within bone marrow cells)	PLF with OsteoAMP NCT02225444 (Roh et al, ⁷¹ 2013) Comparative study with rhBMP-2 with OsteoAMP (Roh et al, ⁷¹ 2013)	FDA 510(k) cleared AATB US FDA 21 CFR 1271. HCT/P

Table 4. Continued.

Company	Combination Product	Formulation	Product Composition	Peer-Reviewed Clinical Evidence/Ongoing Study		Regulatory Clearance/Approval
				ClinicalTrials.gov Identifier: NCT	(No Clinical Studies)	
Bone Biologics Corp, Victoria, Australia BONESUPPORT AB: Lund, Sweden		Putty (NBI bone graft)	Demineralized bone, sodium hyaluronate (DBX) + rhNell-1 (osteogenic factor)	NCT03810573 (TLIF)		Regulated Australia Regulation
	CERAMENT G With MSCs + cytokines	Injectable type	Injectable antibiotic-eluting bone graft substitute that provides local sustained	NBI rhNELL-1/DBX) low vs high dose NCT02820363 (RCT) for open tibial fracture (recruiting status)		CE Mark approval
			CERAMENT (40% hydroxyapatite + 60% calcium sulfate) + 17.5 mg gentamicin/mL paste.	NCT02128256: case series study (reinfection prophylaxis)		FDA Combination Products (CDRH's Division of General Restorative and Neurological Devices)
	CERAMENT V With MSCs + cytokines	Injectable type	Injectable antibiotic-eluting bone graft substitute that provides local sustained CERAMENT (40% hydroxyapatite + 60% calcium sulfate) + iohexol (as a radio-opacity enhancer) + 66 mg vancomycin/mL paste	NCT0424942 (Registry Study) Cell study Alfotawi et al, ⁷⁴ 2013 Cell study Alfotawi et al, ⁷⁴ 2013		CE Mark approval FDA Approvals Separate for Cerement/Bone Void Filler K090871 September 2009 K073316, June 2008 Iohexol, initial approval 1985
DePuy/Synthes	ViviGen Cellular Bone Matrix Vertigraft	Cryo Cortical cortical cancellous bone matrix and demineralized bone	ViviGen Cellular Bone Matrix is composed of cryopreserved viable cortical cancellous bone matrix and demineralized bone. ViviGen Cellular Bone Matrix is an HCT/P. ViviGen Cellular Bone Matrix is processed from donated human tissue, resulting from the generous gift of an individual or his or her family	NCT02814825 (ACDF cervical) HCT/P Divi SN 2017 Divi SN 2017 ⁷⁵ NCT03733626 (Lumbar) NCT04007094 (PLF lumbar) Translational PLF CBMs (Lin et al, ⁷⁶ 2020) NCT03527966 (n = 3, V-CBA (ViviGen) vs rhBMP-2, Lumbar Fusion) Retrospective study 1- to 2-level study V-CBA vs rhBMP-2, Lumbar Fusion (Wetzell et al, ⁷⁷ 2020)		(HCT/P) as defined by the FDA in 21 CFR 1271.3(d). 21CFR 1271
	CONFORM CUBE	Cube shape	Demineralized Cancellous Bone, organic matrix (osteoinductive, promotes cellular ingrowth and vascularization) General bone-void filler and use with lumens of allograft spinal spacers			(HCT/P) as defined by the FDA in 21 CFR 1271.3(d). 21CFR 1271
	CONFORM SHEET	Sheet shape	Demineralized cancellous bone, organic matrix (osteoinductive, promotes cellular ingrowth and vascularization) For PLF (posterolateral gutters of the spine)	n/a		(HCT/P) as defined by the FDA in 21 CFR 1271.3(d). 21CFR 1271

Table 4. Continued.

			Regulatory Clearance/Approval	
			FDA 510(k), FDA 361, 21 CFR Part 1271 CFR 1270, CFR 1271 21 CFR 3.2(e)	
			HCT/P 361, Human Allografts (No Clinical Studies)	
			Biologic Drugs and Devices 351 (Clinical Trials)	
Company	Combination Product	Formulation	Product Composition	Peer-Reviewed Clinical Evidence/Ongoing Study ClinicalTrials.gov Identifier: NCT
Mesoblast Ltd, Australia Angioblast Systems Inc, USA	NeoFuse	Cells + granules	Allogenic mesenchymal precursor cells combined with MasterGraft in PEEK cage	NCT00549913 (3 Doses NeoFuse, Lumbar PLF)
	NeoFuse	Cells + granules	Allogenic mesenchymal precursor cells combined with MasterGraft in ACDF	NCT00996073 (LIF) NCT01106417 (ACDF, cervical) NCT01097486
	Trinity Evolution	Moldable allograft fibers, varying sizes	Anterior cervical plate fixation Allogenic DBM, OPC, MSC (minimum of 500 000 cells/cc, 100 000 of which are MSC and/or OPC)	(ACDF) NCT00951938 Anterior Cervical Vanichkachorn et al. ⁷⁸ 2016 Peppers, 2017 JOSR Lumbar Observational Musante et al. ⁷⁹ 2016 JOSR NCT00965380 (PLIF/TLIF) Observational (completed)
MTF Orthofix	Trinity Elite	Moldable allograft fibers, varying sizes	DBM, OPC, MSC (minimum of 500 000 cells/cc, 100 000 of which are MSC and/or OPC) Trinity Elite and/or local bone with supplemental pedicle screw fixation Allogenic cancellous bone matrix containing viable OPCs, MSCs, and a demineralized cortical bone	Regulated under CFR 1270, 1271 as a human tissue

Table 4. Continued.

Company	Combination Product	Formulation	Product Composition	Peer-Reviewed Clinical Evidence/Ongoing Study ClinicalTrials.gov Identifier: NCT	Regulatory Clearance/Approval FDA 510(k), FDA 361, 21 CFR Part 1271 CFR 1270, CFR 1271 21 CFR 3.2(e) HCT/P 361, Human Allografts (No Clinical Studies) Biologic Drugs and Devices 351 (Clinical Trials)
NuVasive	Osteoecel	Moldable bone matrix	DBM, OPC, MSC (<50 000 cells/cc, >70% viability)	Retrospective case series	Regulated under CFR 1270, 1271 as a human tissue
	Osteoecel Plus	Moldable bone matrix	DBM, OPC, MSC (<50 000 cells/cc, >70% viability)	McAnany et al, ⁸¹ 2016, retrospective comparative study; NCT00948532 (Osteoecel Plus in eXtreme Lateral Interbody Fusion [XLIF]; Kerr et al, ⁸² 2011; Tohmeh et al, ⁶⁵ 2012 Extreme lateral interbody fusion [XLIF])	Prospective case series Retrospective case series, clinical trial: ClinicalTrials.gov identifier: Evaluation of Radiographic and Patient Outcomes Regulated under CFR 1270, 1271 as a human tissue
				Osteoecel Plus in a polyetheretherketone cage and anterior plating at 1 or 2 consecutive levels)	
				Lumbar spine: NCT00948831 (ALIF, observational) NCT00941980 (PLIF, observational) NCT00947583 (TLIF, observational) Ammerman et al, ⁸³ 2013 NCT03649490 (XLIF 1 or 2 levels, comparative: interbody implant [PEEK] with cancellous allograft + BMA vs with cellular allograft [Osteoecel])	
				Attenello et al 2018 LLIF XLIF (open vs percutaneous) IBF with PEEK + DBM (Osteoecel Plus cellular bone matrix)	
				Cervical spine: NCT00942045 (ACDF) Eastlack et al, ⁸⁴ 2014 *Johnstone et al, ⁸⁰ 2020 (translational PLF, Osteoecel Plus)	
				NCT02023372: LIF NuCel and Autograft	
				NCT02808234: Prospective, DDD Lumbar spine LIF Efficacy NuCel NCT02070484 (RCT) for PLF NuCel vs DBX	
				Other: Nunley et al, ⁸⁵ 2016 (ALIF, LLIF, TLIF) retrospective	
NuTech Medical Inc	NuCel	Putty type	Cryopreserved, bioactive amniotic suspension allograft Cellular, growth factor, and extracellular matrix components	NCT02023372: LIF NuCel and Autograft	AATB and FDA guidelines for banked human tissues (is a minimally manipulated allograft tissue)
				NCT02808234: Prospective, DDD Lumbar spine LIF Efficacy NuCel NCT02070484 (RCT) for PLF NuCel vs DBX	

Table 4. Continued.

Company	Combination Product	Formulation	Product Composition	Peer-Reviewed Clinical Evidence/Ongoing Study ClinicalTrials.gov Identifier: NCT	Regulatory Clearance/Approval	
					FDA 510(k), FDA 361, 21 CFR Part 1271 CFR 1270, CFR 1271 21 CFR 3.2(e)	HCT/P 361, Human Allografts (No Clinical Studies) Biologic Drugs and Devices 351 (Clinical Trials)
Osteotech Merged into Medtronic	Plexur P Plexur M	Moldable type (puttylike)	Human cortical bone allograft fibers + resorbable polymer Processed human bone particles that are mixed with resorbable/biodegradable nontissue components.	NCT00837473 (Pilot Study, iliac crest backfill) Note MAUDE Adverse Event Report	FDA 510(k) cleared K073405 (March 3, 2008)	
RTI Surgical Inc Alachua, Florida	map3 Cellular Allogeneic Bone Graft	Putty type Strip type	Cortical cancellous bone chips (or strip shape bone) + DBM + cryogenically preserved, viable multipotent adult progenitor-class cells	NCT02161016: case series study in foot and ankle. Results posted Dekker et al. ⁸⁶ 2016 Dekker et al. ⁸⁷ 2017 (revisions nonunions) NCT02628210: A Prospective, Multi-Center, Non-Randomized Study for lumbar interbody fusion (active status) Other: Lee, ⁸⁸ 2017	Unknown Status Cell Components, 2018 (FDA biologics license needed [201(g)FDA 21USC 321(g)351(i) of PHS Act 42 USC262] based product [HCT/P]. Also bone chip DBMs regulated under 361 PHS Act 42 USC 264 and reg. tissues part 21 CFR 1271.3 + 21/CFR 1271.10)	
Stryker Spine, Allendale, New Jersey Manufactured by Osiris Therapeutics Inc	BIO ⁴	Putty type (1, 2.5, 5, and 10 cc)	Allograft bone (cortical and cancellous) + periosteum A viable bone matrix containing endogenous bone-forming cells (including MSCs, OPCs, and osteoblasts) as well as osteoinductive and angiogenic growth factors	NCT03077204: Clinical case series study (ACDF, cervical spine), completed	AATB US FDA regulations for tissue management. US FDA 21 CFR 1271 (Osiris Therapeutics—data on file)	
Vivex Biomedical, Marietta, Georgia Miami, Florida	Via Graft ^M Via Form ^M Via Form ^M	“Wet Sand” (matrix + gel) Putty type (matrix + gel)	Allograft bone microparticulate scaffold (cortical and cancellous) + cell mixture (cell population derived from vertebral body that includes MIAAMI cells [Vivex]) M = added bone gel component	Tally et al. ⁸⁹ 2018, MIS-TLIF case review (level of evidence IV, n = 75) Inserted expandable cage prefilled with ViaGraft sponge-soaked BMA (from pedicles) was placed interbody with posterior pedicle screws and packed Beta TCP + BMA ⁸⁹	US FDA regulations for tissue management. US FDA 21 CFR 1271	
Xiant/distribution agreement with Vivex, Marietta, Georgia (formerly Bacterin International Holdings Inc)	OsteoVive	Putty type	A cell population derived from vertebral body that includes MIAAMI cells (Vivex) Blend of microparticulate cortical, cancellous, and demineralized cortical allograft bone (particle size range of 100-300 microns) DMSO-free cryoprotectant (to protect MIAAMI cells)	Application: Spine, Extremity, Foot & Ankle	FDA 510(k) cleared, compliance with FDA guidelines regarding human cells, Tissues, and cellular tissue-based products, HCT/P 361 regulated viable allogeneic bone scaffold AATB guidelines	

Table 4. Continued.

Company	Combination Product	Formulation	Product Composition	Peer-Reviewed Clinical Evidence/Ongoing Study ClinicalTrials.gov Identifier: NCT	Regulatory Clearance/Approval FDA 510(k), FDA 361, 21 CFR Part 1271 CFR 1270, CFR 1271 21 CFR 3.2(e) HCT/P 361, Human Allografts (No Clinical Studies) Biologic Drugs and Devices 351 (Clinical Trials)
Zimmer Biomet	Cellentra Viable Cell Bone Matrix		Naturally occurring cells in fresh frozen, cryopreserved allograft comprising cancellous bone mix with cortical bone	NCT02182843, prospective ACDF interventional, results 2018 clinicaltrials.org Lin et al, ⁷⁶ 2020 (translational)	AATB US FDA regulations for tissue management. US FDA 21 CFR 1271

Abbreviations: AATB, American Association of Tissue Banks guidelines; ACDF, anterior cervical discectomy fusion; ALIF, anterior lumbar interbody fusion; BLA, biologics license application; BMA, bone marrow aspirate; BRC, bone repair cell; DBM, demineralized bone matrix; FDA, US Food and Drug Administration; IBF, XXXX; LB, local bone (from surgical site dissection); LIF, lumbar interbody fusion; MIAMI, marrow-isolated adult multilineage-inducible; MSC, mesenchymal stem cell; OLIF, oblique lateral lumbar interbody fusion; OSC, osteoprogenitor cell; PEEK, a polyetheretherketone material used for cage devices employed as instrumentation in anterior interbody spinal fusion procedures; PLF, posterolateral lumbar fusion; PLIF, posterior lumbar interbody fusion; RCT, randomized control trial; TCP, tricalcium phosphate; TLIF, transforaminal lumbar interbody fusion; VBM, viable bone matrix; VCBM, viable cell bone matrix; XLIF, extreme lateral interbody fusion.

^aCFR Code of Federal Regulations (CFR) 1270 (Human tissue intended for transplantation), and 1271 (Human cells, tissues and tissue-based products) are federal regulations relating to the procurement and processing of human-derived tissues. Claims: grafting with component to provide the required osteoconduction, osteogenesis, and osteoinduction necessary for successful bone grafting FDA510(k) cleared. 510(k) is a premarket submission made to FDA to demonstrate that the device to be marketed is at least as safe and effective, that is, substantially equivalent, to a legally marketed device that is not subject to premarket approval. 501(k) documentation for individual products is available via FDA online database (<http://www.accessdata.fda.gov>). FDA premarket approval, typically investigational; HDE, humanitarian device exemption, FDA-approved under an HDE; IND, investigational new drug application.

processes, and the donor bone itself contribute to differences among the products. Unlike for clinical use, for purposes of testing in rats, the products are not mixed with autograft bone. Clinically these allografts are not used in isolation; bone from the surgical dissection is morselized and mixed with allograft bone graft extenders of DBM-based or CBM products. Autograft potentially compensates for allograft products' debility.

In conclusion, there is no definitive clinical evidence that viable cellular allografts promote increased fusion compared with regular allograft DBM-based products. The claimed advantage of osteoinductive and osteogenic properties remains theoretical. The CBM allografts are available at an increased cost compared with other allografts, and more research is needed to justify each product's use instead of standard allografts.

CONCLUSION

Use of bone grafting techniques performed in surgical procedures for spinal fusion have been reported since the beginning of the 20th century.⁹⁴ Novel instrumentation and surgical techniques are designed and inspired by advances in grafting technologies. The history of allografts dates back many decades and has greatly evolved since Urist's first observation on how bone demineralization impacts the incorporation at the graft-host interface. The advancements in allograft products have purposely been designed to facilitate surgical procedures for fracture healing and spinal fusion. Allografts vary in size, shape, consistency, strength, viable cellular components, and many other properties. For the past decades, with a clinical history of use of allografts and DBM bases, diverse materials and composites have been continually combined with various materials and allograft forms to improve material properties, and further developed as novel grafting options.⁴ Once bone allografts in various forms are approved or cleared by the responsible agency of the intended market country, they are rapidly adopted into specific surgical application. However, graft-contributing complications may still occur, and sometimes systematically with the use of a particular form or product. The target allograft then moves from bedside to "bench" for reevaluation. In the application process for approval, grafts' safety is evaluated, yet the osteoinductive and conductive

effectiveness burden may not have been investigated, which likely has unintended consequences.

As discussed in this paper, there is a great unmet need for improvement in allografts. The ideal bone graft provides a biocompatible scaffold that promotes osteoconduction, osteoinduction, and osteogenesis. Allografts predominantly contain osteoconductive and some osteoinductive potential. However, with the advancement of viable cellular allografts, there is the theoretical addition of osteogenesis. Allografts with blood-derived augmentation (either with BMAC or PRP) were not directly discussed in this paper because this subject is the primary focus of another article in submission. With time and technologic advantages in stem cells and differentiation factors, more products will be developed to enrich the bone graft-to-fusion process and increase the rapidity and success rate of bone healing after spinal fusion procedures.

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Corrections

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In this article, the author's name Andrew J. Tronits was misspelled and should have appeared as Andrew J. Trontis.
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