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Bone substitutes in vertebroplasty

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Abstract Vertebroplasty – percutaneous cement augmentation of vertebral bodies – is an efficient procedure for the treatment of painful vertebral fractures in osteoporosis. At the present time, polymethylmethacrylate (PMMA) is the only available cement with reports of clinical application and experience. The material is easy to handle, the radiopacity can be adapted by adding contrast dye, and it is mechanically efficient. Composite cements (acrylic cements in conjunction with ceramics) are bioactive, highly radiopaque, and feature excellent mechanical properties. One such cement, Cortoss, is currently undergoing clinical trials

for vertebroplasty and has so far been shown to be a potentially valuable alternative to PMMA. Several in vitro studies with injectable calcium phosphate (CaP) cements show their feasibility and mechanical effectiveness. Animal studies confirm their biocompatibility and osteoconductivity. However, handling problems and the limited radiopacity of these cements currently preclude their clinical use.

Keywords Vertebroplasty · Polymethylmethacrylate · Osteoporosis · Bone cement · Calcium phosphate · Bone substitutes

Introduction

Galibert and Deramond first introduced the technique of percutaneous vertebroplasty with polymethylmethacrylate (PMMA) as a reinforcement procedure for the treatment of vertebral angiodysplasias in 1987 [26]. Following encouraging early clinical results, particularly with respect to pain relief, indications for PMMA augmentation were extended. At present, osteoporotic compression fractures of the spine represent the most important indication for vertebroplasty, followed by metastatic bone diseases. Clinical series of vertebroplasty almost exclusively report the use of PMMA; however, several disadvantages have been recognized and described [16, 18, 25, 31, 32, 36, 53]. PMMA cures with a strongly exothermic reaction, potentially damaging adjacent soft tissue structures, particularly in the event of cement extrusion. In addition, with maximal PMMA filling, adjacent vertebral overload has been

reported, possibly provoking fractures [6] (Fig. 1a,b). For the purpose of vertebral augmentation, PMMA seems to be a successful, but not an optimal material. Researchers and clinicians therefore have to consider and evaluate alternative substances for use in vertebroplasty.

Bone substitutes have always been an important issue in orthopedics, especially in spine surgery. The use of (solid) autogenous bone grafts (iliac crest, ribs, fibulae) is associated with considerable morbidity and mechanical limitations [3, 14, 23] (Fig. 2a–c). PMMA was and still is the material of choice for defect reconstruction, especially in palliative treatment of spinal metastasis [33]. Allografts have a long history as a bone substitute, but their value remains controversial [11, 13, 56]. Bone growth factors show an enormous potential with encouraging experimental and initial clinical results [8, 9, 10, 49].

Fig. 1 **a** Osteoporotic collapse of T12 and endplate fracture of L1 (arrows) in a 66-year-old man due to long-term steroid medication. **b** After reduction of T12 with correction of kyphosis by 18° (kyphoplasty) and vertebroplasty at L1, the first standing X-ray shows immediate impression of the endplate adjacent to the augmentation (asterisk)

Fig. 2 **a** L3 compression fracture, AO type A 1.2.1 in a 45-year-old woman. **b** Percutaneous anatomical reduction of the endplate using a bone tamp technique (kyphoplasty) and filling of the defect with autologous bone (arrows). **c** Loss of reduction to preoperative status after mobilization

or replace any tissue, organ, or function of the body [54]) can be divided into three different classes:

1. Metals
 - a) Titanium
 - b) Stainless steel
 - c) Tantalum (e.g., Hedrocel)
2. Polymers (large group of materials of heterogenous origin)
 - a) Polymethyl methacrylate
 - b) Polyhydroxyethyl methacrylate
 - c) Polyethylene
 - d) Polyglycolide, polylactide
 - e) Polyether-ether-ketone (PEEK)

Contemporary bone substitutes

Several bone substitutes are in clinical use, mainly as bone graft expanders for spinal fusion [8, 22, 28, 29, 34, 43, 45, 46, 57]. Biomaterials (materials intended to interface with biological systems to evaluate, treat, augment,

Table 1 Calcium phosphates (CaP) and calcium salts used in CaP cements

Name	Abbreviation	Formula
Dicalcium phosphate dihydrate	DCPD	$\text{CaHPO}_4 \bullet 2\text{H}_2\text{O}$
Dicalcium phosphate, anhydrous	DCPA	CaHPO_4
Tetracalcium phosphate	TTCP	$\text{Ca}_4(\text{PO}_4)_2\text{O}$
Dicalcium phosphate	DCP	CaHPO_4
α -Tricalcium phosphate	α TCP	$\text{Ca}_3(\text{PO}_4)_2$
β -Tricalcium phosphate	β TCP	$\text{Ca}_3(\text{PO}_4)_2$
Calcium-deficient hydroxyapatite	CDHA	$\text{Ca}_9\text{H}(\text{PO}_4)_5\text{OH}$
Monocalcium phosphate monohydrate	MCPM	$\text{Ca}(\text{H}_2\text{PO}_4)_2 \bullet \text{H}_2\text{O}$
Calcium pyrophosphate	CPP	$\text{Ca}_2\text{P}_2\text{O}_7$
Hydroxyapatite	HA	$\text{Ca}_5(\text{PO}_4)_3\text{OH}$
Hydroxyapatite, precipitated	PHA	$\text{Ca}_{10-x}(\text{HPO}_4)_x(\text{PO}_4)_{6-x}(\text{OH})_{2-x}$
Calciumsulfate, dihydrated	CSD	$\text{CaSO}_4 \bullet 2\text{H}_2\text{O}$
Calcium sulfate, hemihydrated	CSH	$\text{CaSO}_4 \bullet 0.5\text{H}_2\text{O}$

3. Ceramics (crystalline metallic oxides, carbides, nitrides, and borides fused by sintering)
- Bioactive glasses (e.g., Bioglass): high resorption rate
 - Calcium ceramics
 - Calcium sulfate: not osteoconductive, fast degradation
 - Calcium phosphate: tricalcium phosphate, hydroxyapatite (osteoconductive)
 - Calcium carbonate: fast degradation (osteoconductive)

For the clinician, it is extremely difficult to approach this topic and survey the numerous products on the market. We have therefore tried to list the most common bone substitutes available in Europe and United States and focused on injectable bone cements (Tables 1, 2). The information on the products were obtained from the literature and from the Internet. However, we cannot guarantee that it is comprehensive. The same cement material is sometimes marketed by different distributors under different brand names (i.e., α -BSM is produced by Etex and sold in Europe by Merck as Biobon and in the United States by Lorenz Surgical as embarc). Furthermore, basic knowledge about bone cements is required in order to understand important details of different substances. Several articles concerning this issue help to close an existing gap in this field.

Bone substitutes for vertebroplasty

Requirements for an ideal augmentation material

A bone substitute for vertebroplasty needs to have the following properties:

- Injectability
- Ease of handling
- High radiopacity
- Adapted viscosity (not too low)
- Lasting, constant viscosity (5–10 min)

- Long setting time (≈ 15 min)
- Low curing temperature
- Adapted, lasting mechanical properties
- Biocompatibility
- Bioactivity
- Low price
- Slow biodegradation

An optimal bone substitute for vertebroplasty must be easy to apply, i.e., the components are easy to handle, the mixing procedure is simple, and the material can be applied percutaneously through cannulas into the vertebral body. This requires a low initial viscosity of the material, which has to be balanced against potential extravasation if the material is too liquid. Sufficient radiopacity is of utmost importance in order to be able to follow the cement flow. The setting time should be about 10 min, and viscosity of the cement should remain constant during this period to allow controlled application. The curing temperature must be as low as possible.

The optimal mechanical properties (i.e., compressive strength/stiffness) have not yet been defined. Following the operative procedure, the material should provide immediate reinforcement of the vertebral body and allow early ambulation of the patients. Stiffness and yield strength should resemble values of natural bone. Excessively high stress differences in comparison to nonaugmented areas should be avoided. Finally, reinforcement should not deteriorate over time.

The material must not cause adverse reactions in the surrounding tissue. A bioactive cement seems to be advantageous; however, whether or not a biodegradable cement is important is an open question.

Finally, the material should be reasonably priced in order to allow wide-spread application from the point of view of cost-effectiveness and economic restraints.

At present, different compositions of injectable bone substitutes are available (Table 3); several of these are still under laboratory development and not yet ready for clinical application.

Table 2 Overview of bone substitutes

Name	Substance	Producer
Calcium phosphates		
Calciresorb	β TCP	Ceraver Osteal
chronOS	β TCP	Mathys
Vitoss	β TCP	Orthovita
Biosorb	β TCP	SBM France
Bio Base	α TCP	Bio Vision
Vitoss	β TCP	Orthovita
Biologic HA		
Interpore Pro Osteon 500/200 HA/CC®	Coral calcium carbonate $\rightarrow$ HA	Interpore International
Endobon	Bovine HA	Merck KGaA
Pyrost	Bovine HA	Osteo/Stryker Howmedica
Synthetic HA		
Synatite	HA	SBM France
Cerapatite	HA	Ceraver Osteal
permaOS	HA	Mathys
Biphasic ceramics		
Triosite	60% HA, 40% TCP	Zimmer
BCP	60% HA, 40% TCP	Bioland biomateriaux/Sofamor Danek
Ceraform	65% HA, 35% TCP	Teknimed
Biocer-Biogel 2 (Phocalcite, Biogreffé)	75% HA, 25% TCP	Bioland biomateriaux/DePuy
Calciresorb 35–Cerapatite 65	35% β -TCP, 65% HA	Ceraver Osteal
Calcium phosphate cements		
Bone Source	TTCP, DCP	Orthofix/Howmedica
Norian SRS	α -TCP, CaCO_3 , MCPM	Norian
α BSM = Biobon = embarc	ACP, DCPD	Etex/Merck/Biomet/ Lorenz Surgical
Mimix	TCP, TTCP, citric acid	Lorenz Surgical
Biocement D	α -TCP, DCP, CaCO_3 , PHA	Merck/Biomet
Cementek	α -TCP, TTCP, Ca(OH)_2 , H_3PO_4	Teknimed
Fracture Grout	TTCP, CaCO_3 , H_3PO_4	Norian
Biopex	α -TCP, TTCP, DCPD	Mitsubishi
Allografts		
Tutoplast	Collagen, HA	Tuogen
Xenografts		
Surgibone	Bovine HA-like, 20–29% collagen	Unilab Surgibone
Bio Oss/Orthoss	Bovine HA-like	Geistlich
Collagraft	Hydroxyapatite, bovine collagen	Zimmer
Healos	Bovine HA, collagen	Orquest/Sulzer
Others		
Osteoset	Calcium sulfate	Wright Medical Technologies
Stimulan	Calcium sulfate	Encore Orthopaedics
Biocoral	Coralline calcium carbonate	Inoteb
Bioglass	Silicate hydroxyapatite	US Biomaterials
Collapat	HA collagen	Osteo
Grafton	Demineralized bone matrix (allograft)	Osteotech
Dynagraft	Demineralized allograft	GenSci/DePuy

DCP, dicalcium phosphate; DCPD, dicalcium phosphate dihydrate; HA, hydroxyapatite; PHA, precipitated hydroxyapatite; TCP, tricalcium phosphate; TTCP, tetracalcium phosphate.

Polymethylmethacrylate

At present, PMMA is the only material that can be used for vertebroplasty with which there is extensive in vitro

and in vivo experience. PMMA cements most commonly used are Simplex P, Cranioplastic, and Palacos LV 40 [20, 32, 36, 53] Due to the insufficient radiopacity of the material, contrast dye needs to be added. This seems to work

Table 3 Overview of bone substitutes for vertebroplasty

Substance	Chemistry	Applicability	Biomechanics	Biology	Remarks
PMMA, e.g., Simplex, Palacos LV40 ^a	<i>Monomer:</i> methylmethacrylate/ dimethyl- <i>p</i> -toluidin (liquid); <i>polymer:</i> methylmethacrylate/ methylacrylate; benzoylperoxide (solid)	Low viscos- ity, easy to handle, easy to inject, setting time 6–8 min, high curing temperature	In vitro tests on ver- tebroplasty model very efficient [1, 4,31], toxic mono- mers may get into circulation [18], in vitro compressive strength 70–100 MPa, PMMA = gold standard	No testing on in vivo vertebro- plasty model, vast clinically experience, long-term ex- perience for bone defects in tumors and total joint replace- ment [7,47]	Cheap, radiopacity needs to be enhanced by con- trast dye [32], curing temperature probably not important for vertebro- plasty [31], a special, experimental formula of Simplex with increased radiopacity shows good mechanical setting time 5 min properties [1]
Composite cements					
Cortoss (Orthovita)	<i>bis</i> -GMA/ <i>bis</i> -EMA/ TEGDMA	Low-viscosity paste, setting time 5–8 min, curing tem- perature 63°C, long phase of applicability, easy to handle	In vitro tests on ver- tebroplasty model in axial compres- sion very efficient, in vitro compres- sive strength 211 MPa [1, 4,40]	Rabbit femur model shows bone apposition at the surface, sheep femur no interference with bone healing [19]	Bioactive glass ceramic reinforced composite, designed as bone void filler, high radiopacity, some osteoconductive potential – chemical bone bonding to the surface, currently being clinically tested for vertebroplasty
Hydroxyapatite composite resin (CAP) (Kuraray)	Hydroxyapatite acrylic monomer: (<i>bis</i> -phenol-A glycidyl methacrylate 2,2- <i>bis</i> -(4-methacryloyl- ethoxyphenyl) propane/ TEGDMA)	Paste, inject- able in vitro, limited pene- tration into cancellous bone, setting time 4.9 min, curing tem- perature 46°C	In vitro tests on re- inforcement of ped- icle screw fixation, no tests regarding vertebroplasty, in vitro testing of cement: compres- sive strength 259 MPa [52]	Rabbit femur model, histo- logical invest- igation up to 36 weeks: bone ingrowth at the surface [48]	No references/infor- mation on clinical use
CaP cements					
Bone Source (Howmedica)	Tetracalcium phosphate + dicalcium dihydrate hydroxyapatite, setting time 7 s (in sodium monophosphate), 25 s in water	Designed for repair of cran- ial defects, injectable in vitro by 12-G needle, com- pressive strength 50 MPa	In vitro tests in axial compression vertebroplasty model showed no significant increase of yield strength compared to the intact verte-bral body [5,44]		
Norian	Carbonated apatite cement, calcium carbonate, α -tricalcium phosphate and calcium phosphate monohydrate	Injectable in vitro with an irrigation/suct ion technique in a vertebro- plasty model [51], not cur- rently applic- able in vivo	In vitro tests on axial compression model, no change in stiffness, energy ab- sorption higher in reinforced vertebrae only after collapse of more than 25% of vertebral height, in vitro compres- sive strength 50 MPa [51]	Rabbit femoral defect model, canine meta- physeal defect model [15], not assessed on vertebroplasty	Clinical use as bone void filler in metaphyseal defects [15]
Biopex (Mitsubishi)	75% α -TCP, 18% TTCP, 5% DCPD, 2% HA, setting time 7 min	Easy to handle and inject, two formulas depending on the water to powder ratio	No tests on verte- broplasty model, augmentation of screw fixation in femoral neck frac- tures [50], compres- sive strength deter- mined in body fluid shows slow increase to maximum strength (80 MPa) within 7 days [41]	Rabbit mandib- ula model shows slow remodel- ing of Biopex [41]	No information/ex- perience on vertebro- plasty

Table 3 (continued)

Substance	Chemistry	Applicability	Biomechanics	Biology	Remarks
Biobon = α -BSM (Etex/Biomet Merck)	Apatitic CaP	Injectable with a 11-G needle, setting time 20 s	Vertebroplasty model with significant increase of stability like PMMA [2]	Sheep tibia fracture model, rabbit tibia defect model [39], no data on in vivo vertebroplasty model	Used in dentistry, fast resorption
Cementek	α -TCP, TTCP, $\text{Ca}(\text{OH})_2$, H_3PO_4	Compressive strength 20 MPa	No information on vertebroplasty	Rabbit mandibula defect model [27, 42]	
HAC (Howmedica)	No information	Injectable in vitro	In vitro test of a T11 fracture in a cadaver spine model, cementing with HAC and PMMA restores stability after destabilization due to a fracture [21]	No in vivo vertebroplasty model	Probably a variation of Bone Source
Mimix	TCP, TTCP, citric acid	No information	Designed and approved for craniofacial indications		
EBS (experimental brushite cement)	β -TCP, MCPM	Injectable formula, compressive strength 20–60 MPa, setting time 5 min	Axial compression model shows significant increase of yield strength and stiffness, less pronounced than PMMA [31]	Metaphyseal rabbit defect model osteoconductive [35]	Experimental formula, not suitable for clinical use
Collagraft (Zimmer)	65% HA, 35% TCP + type I bovine collagen	Paste	No information on mechanical properties available	Multiple animal and clinical studies show its efficiency regarding osteoconductivity (long bones, spinal fusion) [10, 12, 57]	Not designed for vertebroplasty, no experimental data regarding vertebroplasty
Biocement D	α -TCP, DCP, CaCO_3 , PHA		No information on vertebroplasty [37,38]		

PMMA, polymethylmethacrylate; GMA, phenol glycidyl dimethacrylate; EMA, phenol ethoxydimethacrylate; TEGDMA, triethylenglycol dimethacrylate; CaP, calcium phosphate; TCP, tricalcium phosphate; TTCP, tetracalcium phosphate; DCPD, dicalcium

phosphate dibasic; HA, hydroxyapatite, MCPM, monocalcium phosphate monohydrate; PHA, hydroxyapatite, precipitated.

^aMinimal requirements: compressive strength, 70 N/mm²; maximum curing temperature, 90°C (ISO 5833).

reliably, but there are no data available regarding the mechanical and biological effects of adding dye to the cement. Furthermore, PMMA is not bioactive and generates high polymerization temperatures. Belkoff reported about a modified PMMA with increased BaSO_4 content (Simplex). In vitro tests have confirmed its feasibility and mechanical effect. Clinical experience, however, has not been reported [5].

Composite cements

Composite cements (acrylic cements in conjunction with ceramics) are bioactive but behave basically like PMMA. Orthovita is promoting a PMMA-like material (Cortoss)

which is bioactive and easy to handle. In vitro studies and animal studies have confirmed its efficacy and biocompatibility [1, 4, 19, 24, 55]. This material seems to be advantageous compared with PMMA as it features an optimal and constant viscosity (the components are mixed in the extrusion cannula) and a high radiopacity. Furthermore, the curing temperature is lower than that of regular PMMA. These properties, together with a good penetration into the cancellous bone, reduce the risk if extravasation. Clinical trials on vertebroplasty with this cement are currently being performed.

The remaining materials presented in this article are not ready for clinical use for vertebroplasty at this time. Most of these cements were designed for dentistry and

craniofacial surgery and have proven to be biologically suitable. The need for appropriate bone substitutes in spine surgery, especially in vertebroplasty, has led to these products being evaluated and adapted for these new applications. All the information on injectable bone cements has been summarized here, with a special focus on materials that have been tested *in vitro* for vertebroplasty or screw fixation in the spine.

Kuraray is producing a composite cement of hydroxyapatite (HA) and an acrylic monomer (CAP) that seems to be easy to handle. It shows some bioactivity and a high mechanical performance [48]. *In vitro* tests on pedicle screw fixation have been performed, but not on vertebroplasty [52].

Calcium phosphate cements

Bone Source is an injectable cement primarily designed to repair cranial defects. Lim et al. tested PMMA and Bone Source in vertebral bodies in an axial compression model and achieved a significant increase of yield strength for intact reinforced vertebrae in comparison to the native state. This was more pronounced for PMMA, whereas the increase of a fractured vertebrae was only significant with PMMA but not with calcium phosphate (CaP) [44]. Belkoff compared the use of Bone Source and PMMA in isolated vertebral bodies in an axial compression model and again found a significant increase of the peak load for PMMA; however, CaP cement did not improve the mechanical properties [5].

Schildhauer published a report on the use of Norian for reinforcement of vertebral bodies. Filling could only be achieved by using an irrigation/suction/injection technique. The amount of cement injected is not reported. An increase in energy absorption was able to be achieved, but only the vertebral body height had been reduced by 50%. The change in yield strength and stiffness is not reported [51]. Heini used Norian for *in vitro* reinforcement of vertebral bodies; however, its material properties precluded application through a cannula, as it separated under pressure to the liquid and solid phase [30]. However, its usefulness as a bone substitute in other applications was able to be demonstrated [15].

Biopex is a bone cement with remarkable mechanical properties. Experimental data are available on its use for screw fixation in femoral neck fractures [50]. No further tests have been performed. Personal *in vitro* handling tests show that the cement can be injected very easily over a long period. Its biological behavior was assessed in a rabbit mandibula model [41].

Biobon (or α -BSM or embarc) is a CaP cement that was originally designed for dentistry and craniofacial surgery. Its mechanical efficacy in a vertebroplasty model was assessed and compared with PMMA and shows a significant effect [2, 39]. Whether its radiopacity and handling will allow clinical application is not clear.

Mimix is a cement designed and approved for craniofacial surgery. No test results or information is available for vertebroplasty.

Cementek is a cement paste with suitable mechanical properties. No experience in clinical use has been reported for any application. Its biological behavior was assessed in a rabbit mandibula defect model [27, 42].

EBS (end product: experimental brushite cement) shows good mechanical properties and biological behavior. A biomechanical study on a vertebroplasty model showed a significant increase in the yield strength and stiffness [31, 35]. There are no clinical data available yet.

Collagraft is a paste consisting of CaP cement and bovine collagen. This bone substitute has already been in clinical use for a long time and has proved to be useful for long bone defects and spinal fusion [10, 12, 57]. No information on its mechanical properties or experimental data on vertebroplasty is available.

Biocement D is a calcium-deficient HA cement containing dicalcium phosphate (DCP) and collagen in order to improve the injectability [37, 38]. No further information is available regarding mechanical or biological properties.

Drake et al. compared the stability of a thoracic spine specimen (T7–L1) in a T11 fracture model intact or reinforced with PMMA or HA cement (Howmedica). The three-dimensional load displacement behavior showed significant restoration of stability for both materials following destabilization. There are no further specifications regarding the cement [21].

Conclusion

An optimized cement formula is definitely required for vertebroplasty. The disadvantages of PMMA are its high curing temperature and the potential adverse biological effects. Vertebroplasty has become an important treatment option and has a great potential. There are some promising cements under development, and several of these products will likely soon be available.

Optimal viscosity and sufficient radiopacity are the most important parameters to be addressed. The optimal mechanical properties and filling patterns required for optimal reinforcement need to be evaluated further. It seems that PMMA augmentation leads to a significant increase in vertebral body stiffness, thereby increasing the risk of fractures at adjacent vertebral bodies [6]. On the other hand, it does not seem reasonable to reinforce vertebrae in such manner that their mechanical properties only improve after a considerable collapse has already occurred [51]. Biodegradation is an open question: When treating osteoporotic vertebral fractures by cement augmentation, fast cement resorption without new bone formation will have a contrary effect, as the induced resorption may weaken the vertebral body and promote further collapse. It would be useful to assess the biological behavior and

dynamics of biodegradation in a standardized animal model (i.e., osteoporotic sheep).

The material most appropriate for our patients will eventually be a bioactive/slowly resorbable cement with

mechanical properties comparable to a healthy vertebral body (not equal to cancellous bone) with an adapted viscosity and high radiopacity, available at a reasonable price.

References

- Ahrens J, Fuller M, Burton D, Regan J (2001) In vitro comparison of two different filler materials for vertebroplasty. Transactions of the 47th annual meeting of the Orthopaedic Research Society, San Francisco, 25–28 February 2001
- Bai B, Jazrawi LM, Kummer FJ, Spivak JM (1999) The use of an injectable, biodegradable Calcium Phosphate Bone Substitute for the prophylactic augmentation of osteoporotic vertebrae and the management of vertebral compression fractures. *Spine* 25(15):1521–1526
- Bauwart C, Asher M, Hassanein R (1995) Iliac crest bone graft harvest donor site morbidity: a statistical evaluation. *Spine* 13:566–569
- Belkoff SM, Mathis JM, Erbe EM, Fenton DC (2000) Biomechanical evaluation of a new bone cement for use in vertebroplasty. *Spine* 25(9):1061–1064
- Belkoff S, Mathis J, Deramond H, Jasper L (2001) An ex vivo biomechanical evaluation of a hydroxyapatite cement for use in vertebroplasty. Transactions of the 47th annual meeting of the Orthopaedic Research Society, San Francisco, 25–28 February 2001
- Berlemann U, Ferguson SJ, Nolte LP, Heini PF (2000) Adjacent vertebral failure following vertebroplasty: a biomechanical evaluation. *J Bone Joint Surg [Br]* (accepted for publication)
- Bini SA, Gill K, Johnston JO (1995) Giant cell tumor of bone. Curettage and cement reconstruction. *Clin Orthop* 321:245–250
- Boden S, Martin G, Morone M, Ugbo J, Moskovitz P (1999) Posterolateral lumbar intertransverse process spine arthrodesis with recombinant human bone morphogenetic protein-2/hydroxyapatite-tricalcium phosphate after laminectomy in the nonhuman primate. *Spine* 24:1179–1185
- Boden S, Zdeblick T, Sandhu H, Heim S (2000) The use of rhBMP-2 in interbody fusion cages: definitive evidence of osteoinduction in humans: a preliminary report. *Spine* 25:376–380
- Boden SD, Schimandle JH (1995) Biologic enhancement of spinal fusion. *Spine* 20(24S):113S–123S
- Brown M, Malinin T, Davis P (1976) A roentgenographic evaluation of frozen allografts versus autografts in anterior cervical spine fusion. *Clin Orthop* 119:231–236
- Chapman MW, Bucholz R, Cornell C (1997) Treatment of acute fractures with a collagen-calcium phosphate graft material. A randomized clinical trial. *J Bone Joint Surg [Am]* 79(4):495–502
- Cloward R (1980) Gas-sterilized cadaver bone grafts for spinal fusion operations. A simplified bone bank. *Spine* 5(1):4–10
- Cockin J (1971) Autologous bone grafting complications at the donor-site. *J Bone Joint Surg Br* 53:253
- Constantz BR, Ison IC, Fulmer MT, Poser RD, Smith ST, VanWagoner M, Ross J, Goldstein SA, Jupiter JB, Rosenthal DI (1995) Skeletal repair by in situ formation of the mineral phase of bone. *Science* 267(5205):1796–1799
- Cotten A, Boutry N, Cortet B, Assaker R, Demondin X, Leblond D, Chastanet P, Duquesnoy B, Deramond H (1998) Percutaneous vertebroplasty: state of the art. *Radiographics* 18:311–320
- Daculsi G, LeGeros R, Nery E, Lynch K, Kerebel B (1989) Transformation of biphasic calcium phosphate ceramics in vivo: ultrastructural and physicochemical characterization. *J Biomed Mater Res* 23:883–894
- Dahl OE, Garvik LJ, Lyberg T (1994) Toxic effects of methylmethacrylate monomer on leukocytes and endothelial cells in vitro. *Acta Orthop Scand* 65(2):147–153
- Dallap B, Gadaleta SJ, Prabhu V et al (1998) Histological, radiological and mechanical comparison of polymethylmethacrylate (PMMA) and a novel cement in an ovine model. Transactions of the 45th annual meeting of the Orthopaedic Research Society, New Orleans, 16–19 March 1998
- Deramond H, Depriester C, Galibert P, Le Gras D (1998) Percutaneous vertebroplasty with polymethylmetacrylate. Technique, indications, and results. *Radiol Clin North Am* 36:533–546
- Drake J, Rogge T, Taggard D, Goel V, Hitchon P (2001) Stability assessment of two vertebroplasty materials. Transactions of the 47th annual meeting of the Orthopaedic Research Society, San Francisco, 25–28 February 2001
- Emery S, Fuller D, Stevenson S (1996) Ceramic anterior spinal fusion: biologic and biomechanical comparison in a canine model. *Spine* 21:2713–2719
- Fernyhough J, Schimandle J, Weigel M, Edwards C, Levine A (1992) Chronic donor-site pain complicating bone graft harvesting from the posterior iliac crest for spinal fusion. *Spine* 17:1474–1480
- Fujita H, Ido K, Matsuda Y et al (2000) Evaluation of bioactive bone cement in canine total hip arthroplasty. *J Biomed Mater Res* 49:273–288
- Galibert P, Deramond H (1990) La vertébroplastie acrylique percutanée comme traitement des angiomes vertébraux et des affections d'origines et fragilisantes du rachis. *Chirurgie* 116:326–335
- Galibert P, Deramond H, Rosat P, Le Gars D (1987) Note préliminaire sur le traitement des angiomes vertébraux par vertébroplastie percutanée. *Neurochirurgie* 33:166–168
- Garbarsky A, Mejdoubi E, Caratero C, Lacout JL (1995) Hydraulic phosphate cement for orthopaedic and dental applications. *Bull Inst Oceanogr Monaco* 14(3):35–41
- Guigui P, Plais P, Flautre B (1994) Experimental model of posterolateral spinal arthrodesis in sheep. 1. Experimental procedures and results with autologous bone graft. *Spine* 19:2791–2797
- Guigui P, Plais P, Flautre B (1994) Experimental model of posterolateral spinal arthrodesis in sheep. 2. Application of the model: evaluation of vertebral fusion obtained with coral (Porites) or with a biphasic ceramic (Triosite). *Spine* 19:2798–2803
- Heini PF, Kaufmann M, Angst M (1998) Effect of bone cement augmentation on the mechanical properties of human cadaveric vertebrae. Abstract presented at the Eurospine '98, Second Combined Meeting of the Leading European Spine Societies, Innsbruck, 24–27 June 1998
- Heini PF, Berlemann U, Kaufmann M, Lippuner K, Fankhauser Ch, van Landuyt P (2001) Augmentation of mechanical properties in osteoporotic vertebral bones – a biomechanical investigation of vertebroplasty efficacy with different bone cements. *Eur Spine J* 10(2):164–171

32. Heini PF, Walchli B, Berlemann U (2000) Percutaneous transpedicular vertebroplasty with PMMA: operative technique and early results. A prospective study for the treatment of osteoporotic compression fractures. *Eur Spine* 9(5):445–450
33. Heini PF (1998) Orthopedic aspects of vertebral metastases. *Ther Umsch* 55(7):418–22
34. Heise U, Osborn J, Duwe F (1990) Hydroxyapatite ceramic as a bone substitute. *Int Orthop* 14:329–338
35. Ikenaga M, Hardouin P, Lemaître J, Andrianjatovo H, Flautre B (1998) Biomechanical characterization of a biodegradable calcium phosphate hydraulic cement: a comparison with porous biphasic calcium phosphate ceramics. *J Biomed Mater Res* 40:139–144
36. Jensen ME, Evans AJ, Mathis JM, Kallmes DF, Cloft HJ, Dion J (1997) Percutaneous polymethylmethacrylate vertebroplasty in the treatment of osteoporotic vertebral body compression fractures: technical aspects. *Am J Neuroradiol* 18:1897–1904
37. Khairoun I, Boltong MG, Driessens FCM, Planell (1997) Effect of calcium carbonate on clinical compliance of apatitic calcium phosphate bone cement. *J Biomed Mater Res* 38(4):356–360
38. Khairoun I, Driessens FCM, Boltong MG, Planell JA, Wenz R (1999) Addition of cohesion promoters to calcium phosphate cements. *Biomaterials* 20:393
39. Knaack D, Goad ME, Aiolo M, Rey C, Tofighi A, Chakravarthy P, Lee DD (1998) Resorbable calcium phosphate bone substitute. *J Biomed Mater Res* 43(4):399–409
40. Krause WR, Park SH, Straup RA (1989) Mechanical properties of BIS-GMA resin short glass fiber composites. *J Biomed Mater Res* 23(10):1195–1211
41. Kurashina K, Kurita H, Hirano M, Kotani A, Klein CPAT, de Groot K (1997) In vivo study of calcium phosphate cements: implantation of an atricalcium phosphate/dicalcium phosphate dibasic/tetracalcium phosphate monoxide cement paste. *Biomaterials* 18:539–543
42. Lacout JL, Mejdoubi E, Hamad M (1996) Crystallization mechanism of calcium phosphate cements for biologic uses. *J Materials Sci Materials Med* 7:371–374
43. Le Henc J, Lesprit E, Delavigne C et al (1997) Tricalcium phosphate ceramics and allografts as bone substitutes for spinal fusion in idiopathic scoliosis: comparative clinical results at four years. *Acta Orthop Belg* 63:202–211
44. Lim T, Brebach GT, Renner SM, Kim WJ, Kim JG, An HS (2001) Effect of a new calcium phosphate cement on the compression strength of vertebroplasty. Transactions of the Orthopaedic Research Society, San Francisco, 25–28 February 2001
45. Moore D, Chapman M, Manske D (1987) The evaluation of a biphasic calcium phosphate ceramic for use in grafting long-bone diaphyseal defect. *J Orthop Res* 5:356–365
46. Passati N, Daculsi G, Rogez J, Martin S, Bainvel J (1989) Macroporous calcium phosphate ceramic performance in human spine fusion. *Clin Orthop* 248:169–176
47. Persson BM, Ekelund L, Lovdahl R, Gunterberg B (1984) Favourable results of acrylic cementation for giant cell tumors. *Acta Orthop Scand* 55(2):209–214
48. Saito M, Maruoka A, Mori T, Sugano N, Hino K (1994) Experimental studies on a new bioactive bone cement: hydroxyapatite composite resin. *Biomaterials* 15(2):156–160
49. Sandhu H, Kanim L, Toth J et al (1997) Experimental spinal fusions with recombinant human bone morphogenetic protein-2 without decortication of osseous elements. *Spine* 22:1171–1176
50. Sato T, Bourgeault C, Kyle R (2001) Calcium phosphate augmentation of screw fixation in femoral neck fracture. Transactions of the 47th annual meeting of the Orthopaedic Research Society, San Francisco, 25–28 February 2001
51. Schildhauer TA, Bennett AP, Wright TM, Lane JM, O'Leary PF (1999) Intravertebral body reconstruction with an injectable in situ-setting carbonated apatite: biomechanical evaluation of a minimally invasive technique. *J Orthop Res* 17:67–72
52. Turner A, Gillies R, Svehla M, Saito M, Walsh W (2001) Augmentation of pedicle screw fixation with a bioactive cement. Transactions of the 47th annual meeting of the Orthopaedic Research Society, San Francisco, 25–28 February 2001
53. Weill A, Chiras J, Simon JM, Rose M (1996) Spinal metastases: indications for and results of percutaneous injection of acrylic surgical cement. *Radiology* 199:241–247
54. Williams D (1996) Editorial. *Biomaterials* 17(1):1–2
55. Yamamuro T, Nakamura T, Iida H (1998) Development of bioactive bone cement and its clinical applications. *Biomaterials* 19:1479–1482
56. Zdeblick T, Ducker T (1991) The use of freeze-dried allograft bone for anterior cervical fusions. *Spine* 16:726–732
57. Zerwekh J, Kourosh S, Scheinberg R (1992) Fibrillar collagen-biphasic calcium phosphate composite as a bone graft substitute for spinal fusion. *J Orthop Res* 10:562–572