Immediate stabilization of pedicle screws: Preclinical pilot study of polymer-augmented pedicle screws

de Wild, Michael ; Zimmermann, Simon ; Klein, Karina ; Steffen, Thomas ; Schlottig, Falko ; Hasler, Carol ; von Rechenberg, Brigitte

DOI: https://doi.org/10.1515/cdbme-2023-1004

Michael de Wild*, Simon Zimmermann, Karina Klein, Thomas Steffen, Falko Schlottig, Carol Hasler and Brigitte von Rechenberg

Immediate stabilization of pedicle screws

Preclinical pilot study of polymer-augmented pedicle screws

https://doi.org/10.1515/cdbme-2023-1004

Abstract: This study was designed as proof of principle and safety test of the novel technique, the Immediate Stabilization System (ISS). The technique is designed to immediately stabilize polymer-augmented pedicle screws (PAS) in deficient bone and avoid complications of loosening pedicle screws at the bone-screw interface, especially in osteoporotic patients. A polymer sleeve was designed as augmentation to improve screw anchorage after drilling the screw hole. By applying ultrasonic energy, the polymeric tube was molded into the pores of the host bone forming a strong and uniform bond with the adjacent bone. The original screw was then implanted into the denser bony environment leading to an enhanced immediate stability. The ISS-treated implants were compared to conventionally placed pedicle screws in *ex-vivo* cadaver bones (2 sheep spines, n = 6 implants per spine, total 12 screws) and *in-vivo* in a spinal sheep model (Swiss alpine sheep, n = 5, 4 implants per animal, total 20 screws). The primary stability of ISS-treated pedicle screws was increased in *ex-vivo* bone (+24% insertion torque (IT)) and *in-vivo* (+32.9% IT) in sheep spine. Removal torque (RT) was lower in the in PAS tested for 8 weeks *in-vivo*. The ISS technology demonstrated improved anchorage of pedicle screws in *ex-vivo* cadaver bones as well as *in-vivo* studies in sheep spine.

Keywords: pedicle screw, screw anchorage, insertion torque, polymer sleeve, primary stability.

***Corresponding author: Michael de Wild:** University of Applied Sciences Northwestern Switzerland FHNW, School of Life Sciences HLS, Institute for Medical Engineering and Medical Informatics IM^2, Hofackerstrasse 30, 4132 Muttenz, Switzerland, michael.dewild@fhnw.ch
Simon Zimmermann, Falko Schlottig: NEXILIS AG, Gräubernstrasse 16, 4410 Liestal, Switzerland
Carol Hasler: Children's Hospital Basel, University UKBB, Orthopaedic Department, Spitalstrasse 33, 4056 Basel, Switzerland
Karina Klein, Thomas Steffen, Brigitte von Rechenberg: University of Zürich, Musculoskeletal Research Unit (MSRU), Center for Applied Biotechnology and Molecular Medicine (CABMM), Winterthurerstrasse 260, 8057 Zürich, Switzerland

1 Introduction

Insufficient screw anchorage in trabecular bone of poor quality leads to early implant failure. Osteoporosis is both, cause for frequent fragility fractures and, when internal fixation is attempted, the reason for compromised (screw) implant load bearing capabilities.[1] Implant loosening and failure are due to decreased bone density and impaired trabecular structure. This is especially critical in spine surgery, where good bone anchorage of pedicle screws is critical for sufficient primary stability in instrumented segmental fixation for reliably achieving posterolateral fusion.[2]

The gold standard for improved pedicle screw anchorage in osteoporotic bone is augmentation with polymethylmethacrylate (PMMA) bone cement.[2] However, PMMA cement is a permanent foreign body that cannot easily be removed. Its Young's modulus is higher than that of natural bone with the stiffness mismatch potentially resulting in bone resorption. In addition, the exothermal polymerization reaction of PMMA during insertion can cause bone necrosis due to heat and the monomer has potentially cytotoxic effects.[3] Also leakage during injection may cause life threatening cement emboli with a reported incidence rate up to 41%.[4] Therefore, new and less risky fixation methods for immediate stabilization of pedicle screws in the vertebral bodies are required.

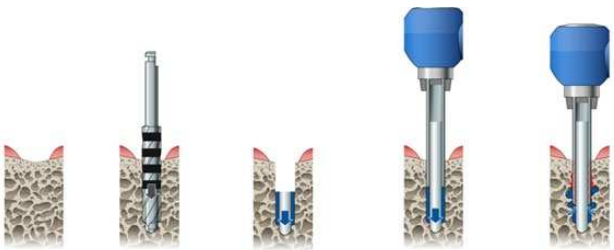

Figure 1: Immediate implant stabilization process: Polymeric sleeve and the central pin are placed on the floor of the drill hole. After the Sonotrode® probe is lowered to the rim of the sleeve, it is activated and gently pressed down, with the polymeric material melting into the pores of the surrounding trabecular bone (drawings courtesy of Nexilis AG).

A novel method was developed where a polymer sleeve is inserted into the drill hole in the bone and melted with ultrasound to augment bone fixation of pedicle screws

(PAS).[5,6] The size-matched thermoplastic polymer sleeve (based on polylactide) is inserted into a predrilled hole in the vertebral body and using an ultrasonic stylus probe melted and distributed into the pores of the surrounding cancellous bone (fig. 1). Ultrasonic energy shall be kept as low as possible to still warrant solubilisation of the polymer, yet the thermal impact on bone should be regional and temporally limited. Re-solidification initiates as soon as the supply of ultrasonic energy is stopped, when the resorbable polymer and surrounding cancellous bone is forming a strong bond. Thereafter, a pedicle screw of choice is inserted using the conventional surgical procedure. As a result, the primary stability of any pedicle screw inserted is expected to improve. Yet the polymer, which unlike PMMA is degradable over time, will eventually be replaced with newly formed bone. A previous preclinical study in the sheep using a similar method showed enhanced primary stability of generic dental implants.[6] In contrast to the ISS technology using hollow sleeves, the Bone Welding®, resp. SonicWeld® technology is based on massive polymer cylinder.[7] Quasi-static push-out tests and cyclic fatigue tests in bone analog material have demonstrated stronger fixation of the polylactide component than conventional screws in higher density foams, and comparable fixation in low-density foam.[8] Load applications in open-porous sawbone showed similar peak load forces compared with that of titanium screw fixation.[7]

2 Materials and Methods

For all experiments, the exact same custom-made titanium grade 4 screws were used (Thommen Medical AG, Grenchen, Switzerland), featuring a thread similar to commercially available pedicle screws (25 mm length single thread, ø4.3 mm core diameter, 1.75 mm thread pitch, $\phi = 22°$ apical opening angle). A custom screw head allowed easy connecting for implant placement including the torque measurement equipment (fig. 2).

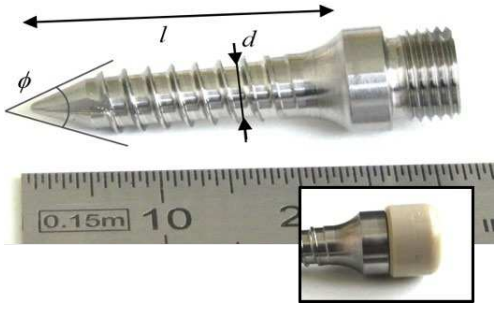

Figure 2: Custom-made pedicle screw. The inset shows the PEEK cap mounted to the screw head while implanted.

For the polymer-augmented custom screws (PAS) experimental groups, sterile (γ-sterilized at 25-40 kGy) cylindrical polymer sleeves of 12 mm length, 4 mm diameter and 0.3 mm wall thickness, consisting of 70:30 poly(L-lactide-co-D,L-Lactide) copolymer, were used (Samaplast, St. Margarethen, Switzerland).

For the *ex-vivo* study, the 12 screws were equally placed in two sheep cadavers, thereby instrumenting left and right pedicles in up to three consecutive lumbar vertebrae in a single animal. In the *in-vivo* study five adult female Swiss Alpine sheep with a mean age 2.9 years and a mean body weight 67 kg (ranging from 60.5 kg to 76.5 kg) were used. After sedation (xylazine, 0.1 mg/kg BW.), anaesthesia was induced with Diazepam (0.1 mg/kg BW iv), ketaminhydrochloride (2 mg/kg BW iv) in combination with propofol (0.3 – 0.3 mg/kg BW iv) and maintained with inhalation anaesthesia (max. 5 Vol% isoflurane in 100% oxygen) through tracheal intubation. Epidural morphine (0.1 mg/kg BW) was given for pain reduction. Postoperative management included Temgesic® (0.01 mg/kg BW iv) every four hours prior to surgery and three times thereafter. Rimadyl® (4 mg/kg BW SID) was given for four days after surgery. Prophylactic antibiosis consisted of penicillin (35'000 IU/kg BW BID iv) for four days and gentamycin (4 mg/kg BW SID iv) for four days.

The animal was placed in sternal recumbency and a dorsal surgical approach to the lumbar spine was made. The paraspinal muscles (*m. longissimus dorsi*) were split to get access to the posterior aspect of the L2 and L3 vertebrae, four transpedicular screw holes, angled at about 35° towards the midline, were predrilled. The correct position of the pilot-drill bit was verified (mainly for not breaching the medial pedicle wall) using fluoroscopy. After stepwise opening up the hole to ø4.3 mm diameter, a minimum of 25 mm drilling depth and closed drill hole floor was verified using a feeler probe. At each level, selecting sides randomly, a native (NS) and polymer-augmented screw (PAS) were placed. For the PAS group, a sleeve and guiding pin were pushed to the drill floor, the polymer was liquefied using the Sonotrode® probe and finally, in the NS and PAS groups, the custom screw was placed while the insertion torque (IT) was measured. No posterior connecting rods were used, but rather the screw heads were covered with PEEK caps with rounded edges (KETRON PEEK-CLASSIX LSG; biocompatibility according to USP Class VI, ISO-10993-4/5/10/11) to prevent engrafting of the screw head with bone complicating later RT tests, see insert in fig. 2. The lumbar fascia and subcutis were closed with absorbable suture material (Vicryl® 2-0). Staples were used for adapting the skin.

Animals were sacrificed after eight weeks. The surgery sites were macroscopically inspected. The lumbar spine was *en-*

bloc resected, vertebrae instrumented with screws had excessive soft tissue removed, were individually wrapped in moist gauze, sealed in plastic bags and transferred in a cool environment for biomechanical evaluation. All tests were performed within six hours of sacrifice.

The IT was measured with a biomechanical setup using a drag-indicator (Mark-10 STJ50, Mark-10 Corp., Coplague NY), intraoperatively with an extension that could be repetitively autoclaved. RT was measured with a more elaborate setup, always in the lab. A test frame (TSTMH-DC with DC4040 digital controller) was used to vertically mount the screw head for continuously measuring RT. Two different range sensors (Mark-10 STJ12 and STJ50) with either 137 Ncm (0.1 Ncm resolution) or 570 Ncm (0.5 Ncm resolution) maximum torque were used. A multiphase motor was used for turning a double-walled metallic container at a constant angular velocity (0.1°/sec). By filling the outer compartment with hot water, a low-temperature (T_m = 47°C) melting-point alloy was molten in the container. By immersing the mount specimen vertically in the container, with the bone already cast into a square block of plaster (to prevent soiling the alloy), screw axis alignment with the torque stand mechanical axis was guaranteed. RT data (angle and torque) were continuously recorded using proprietary software.

3 Results

Five animals (n = 10 screws each for the NS and PAS groups) were used for *in-vivo* torque data analysis. One pedicle screw was interfering with the tip of the opposite side screw. Another screw (in #52.06) had the hole drilled to deep, thereby perforating the vertebra's anterior wall with the polymer sleeve lost into the prevertebral muscle tissue. Fluoroscopic images in three orthogonal planes of individual vertebrae were reviewed (fig. 3). No screws breaching the medial pedicle wall were identified. After eight weeks implantation, no bone resorption in the proximity of any polymer-augmented screw was observed.

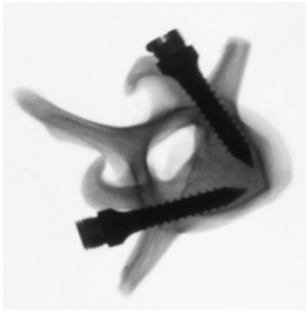

Figure 3: Sample of coronal view of single sheep lumbar vertebra with bilateral pedicel screws placed. Upon insertion the screw's first thread is level with the bone surface, screw tips do not interfere, and the medial walls of both pedicles are not perforated along the screw tracks. Ziehm Vision FD Vario 3D, 54 kV, Ziehm Imaging GmbH, Nuremberg, Germany.

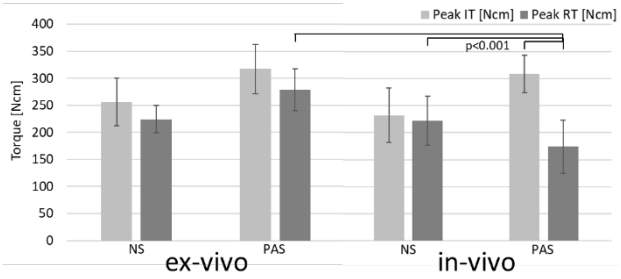

Figure 4: The graphs depict mean ± 1 SD insertion torque (IT, bright) and removal torque (RT, dark) values for native screws (NS) and the polymer-augmented screws (PAS) in sheep vertebrae, left *ex-vivo* (n = 12), right *in-vivo* (n = 20) data. Significant differences are indicated (unpaired t-test, $p < 0.001$).

In the *in-vivo* tests torque measured after 8 weeks implantation in the PAS group experienced a significant obvious drop in RT compared to the IT (from on average 308 Ncm to 174 Ncm), but not the NS control group (Tab. 1 and fig. 4). Table 1 compares peak strength for pedicle screws placed in the sheep lumbar spine under *ex-vivo* and *in-vivo* conditions. For the *in-vivo* condition test was conducted only after eight weeks implantation. Significant differences were found in the polymer-augmented screws for RT ($p = 0.001$), see Tab. 1. The biomechanical evaluation of implant fixation strength used the paired tests, where left and right pedicles of the same vertebra are directly compared. The PAS group always showed significantly higher IT values. However, in the *ex-vivo* condition the PAS group was significantly higher ($p = 0.012$), while for the *in-vivo* condition was significantly lower ($p = 0.040$). The RT compared to IT for the same NS were never statistically different (paired t-test, $p > 0.05$) while for the PAS, the RT was significantly lower in *ex-vivo* sheep ($p = 0.028$) and most obviously for *in-vivo* ($p < 0.001$). The latter drop was the largest at 43.6%.

The reason for this drop in torque in the *in-vivo* experiments could be the fact that the polymer had another eight weeks to creep into an optimally conforming shape. But it could also be a result of catalytic and hydrolytic effects on the screw-surface or of beginning sleeve resorption which *in-vivo* may be much faster than anticipated. Based on published data polylactide retains its mechanical strength for 8-12 weeks.[9] It can be assumed that the degradation starts on the surface of the polymeric structure. Therefore, the initial form-fit at the interface between the pedicle screw and the polylactide might already be affected after 8 weeks by

polymeric degradation. The vertebral body is highly vascularized, therefore promoting transport of body fluid and macrophages to the location which start with enzymatic degradation of the polymer. [10]

Table 1: Biomechanical results (mean ± 1 SD) on the comparison between *ex-vivo* and *in-vivo* data for IT and RT. Comparison between *ex-vivo* and *in-vivo* conditions (non-paired t-test, $p < 0.05$), run separately for NS or PAS groups. *In-vivo* data for RT recorded after 8 weeks implantation. Significant differences are highlighted red. Legend: Native screws: NS; polymer-augmented screws: PAS.

	NS			
	ex-vivo (n=6)	*in-vivo* (n=10)	% change	sign.
Peak IT [Ncm]	256.2 ± 43.6	232.3 ± 50.3	-9.3%	0.351
Peak RT [Ncm]	224.0 ± 25.2	221.6 ± 45.4	-1.1%	0.908
	PAS			
	ex-vivo (n=6)	*in-vivo* (n=10)	% change	sign.
Peak IT [Ncm]	316.8 ± 45.1	308.7 ± 34.4	-2.6%	0.690
Peak RT [Ncm]	**278.6 ± 38.8**	**174.1 ± 48.9**	**-37.5%**	**0.001**

4 Conclusions

Although results are still preliminary it can be concluded that PAS offer better *ex-vivo* fixation in the vertebral body compared to NS. The ISS technology proved to be safe to use with *in-vivo* experiments in sheep. As a platform technology, it could be used in dental, trauma, spinal and other orthopaedic applications without any change of original implants or surgical instruments. This novel technology has the potential to improve the treatment of osteoporotic bone fractures or situations with disturbed bone metabolism, clinically allowing for more time for fusion and mobilization. Future studies should elicit further the material degradation and bone remodelling pattern of PAS along with interconnecting rods. Histological follow-ups will further prove safety of the PAS system.

Author Statement

Research funding: This project was financially supported by the Swiss Commission for Technology and Innovation (CTI) under the project number 14929.1 PFLS-LS. We thank Th. Borter (EMS Electro Medical Systems S.A., 1260 Nyon) for his support with ultrasonic devices. Conflict of interest: All authors declare that they have no conflict of interest. Falko Schlottig is Co-founder of NEXILIS and member of the advisory board. Simon Zimmermann worked for Nexilis AG for several years. Ethical approval: All applicable international, national, and/or institutional guidelines for the care and use of animals were followed. Experiments were conducted according to Swiss Laws of Animal Welfare and protection (TSchG §455, licence number 47/2013). This article does not contain any studies with human participants performed by any of the authors.

References

[1] Goldhahn J, Suhm N, Goldhahn S, Blauth M, Hanson B. Influence of osteoporosis on fracture fixation--a systematic literature review. Osteoporos Int. 2008;19(6):761-772. doi:10.1007/s00198-007-0515-9

[2] Fransen P. Increasing pedicle screw anchoring in the osteoporotic spine by cement injec-tion through the implant. Technical note and report of three cases. J Neurosurg Spine. 2007;7(3):366-369. doi:10.3171/SPI-07/09/366

[3] Bettencourt A, Calado A, Amaral J, et al. In vitro release studies of methylmethacrylate liberation from acrylic cement powder. Int J Pharm. 2000;197(1-2):161-168. doi:10.1016/s0378-5173(99)00468-8

[4] Hulme PA, Krebs J, Ferguson SJ, Berlemann U. Vertebroplasty and kyphoplasty: a sys-tematic review of 69 clinical studies. Spine (Phila Pa 1976). 2006;31(17):1983-2001. doi:10.1097/01.brs.0000229254.89952.6b

[5] Spicher A, Lindtner RA, Zimmermann S, Stofferin H, Schmoelz W. Ultrasound melted polymer sleeve for improved primary pedicle screw anchorage: A novel augmentation technique. Clin Biomech (Bristol, Avon). 2019;63:16-20. doi:10.1016/j.clinbiomech.2019.02.007

[6] Stübinger S, Waser J, Hefti T, et al. Evaluation of local cancellous bone amelioration by poly-L-DL-lactide copolymers to improve primary stability of dental implants: a biome-chanical study in sheep. Clin Oral Implants Res. 2015;26(5):572-580. doi:10.1111/clr.12445

[7] Cho PWJ, Burton RG, Gratton D, Cho JH. Biomechanical study of SonicWeld Rx pin in cortical bone graft layering technique. J Oral Maxillofac Surg. 2011;69(5):1519-1524. doi:10.1016/j.joms.2010.05.016

[8] Ferguson SJ, Weber U, von Rechenberg B, Mayer J. Enhancing the mechanical integrity of the implant-bone interface with BoneWelding technology: determination of quasi-static interfacial strength and fatigue resistance. J Biomed Mater Res B Appl Biomater. 2006;77(1):13-20. doi:10.1002/jbm.b.30427

[9] Hutmacher DW. Scaffolds in tissue engineering bone and cartilage. Biomaterials. 2000;21(24):2529-2543. doi:10.1016/s0142-9612(00)00121-6

[10] Richert a, Dąbrowska GB. Enzymatic degradation and biofilm formation during biodegradation of polylactide and polycaprolactone polymers in various environments. Int J Biol Macromol. 2021;176:226-232. doi:10.1016/j.ijbiomac.2021.01.202