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ORIGINAL ARTICLE

Cardiovascular changes after PMMA vertebroplasty in sheep: the effect of bone marrow removal using pulsed jet-lavage

Lorin M. Benneker · Jörg Krebs · Vanessa Boner · Andreas Boger · Simon Hoerstrup · Paul F. Heini · Armando Gisep

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Abstract Clinically, the displacement of intravertebral fat into the circulation during vertebroplasty is reported to lead to problems in elderly patients and can represent a serious complication, especially when multiple levels have to be treated. An in vitro study has shown the feasibility of removing intravertebral fat by pulsed jet-lavage prior to vertebroplasty, potentially reducing the embolization of bone marrow fat from the vertebral bodies and alleviating the cardiovascular changes elicited by pulmonary fat embolism. In this in vivo study, percutaneous vertebroplasty using polymethylmethacrylate (PMMA) was performed in three lumbar vertebrae of 11 sheep. In six sheep (lavage group), pulsed jet-lavage was performed prior to injection of PMMA compared to the control group of five sheep receiving only PMMA vertebroplasty. Invasive recording of blood pressures was performed continuously until 60 min after the last injection. Cardiac output and arterial blood gas parameters were measured at selected time points. Post mortem, the injected cement volume was measured using CT and lung biopsies were processed for assessment of intravascular fat. Pulsed jet-lavage was feasible in the in vivo setting. In the control group, the injection of PMMA resulted in pulmonary fat embolism and a sudden and significant increase in mean pulmonary arterial pressure. Pulsed jet-lavage prevented any cardiovascular changes and significantly reduced the severity of bone marrow fat embolization. Even though significantly more cement had been injected into the lavaged vertebral bodies, significantly fewer intravascular fat emboli were identified in the lung tissue. Pulsed jet-lavage prevented the cardiovascular complications after PMMA vertebroplasty in sheep and alleviated the severity of pulmonary fat embolism.

Keywords Vertebroplasty · Pulmonary fat embolism · Cardiovascular changes · Pulsed jet-lavage · In vivo study

L. M. Benneker · P. F. Heini
Department of Orthopedic Surgery, Inselspital, University of Bern, Bern, Switzerland

J. Krebs
rH realHealth International, Nottwil, Switzerland

V. Boner · A. Gisep
AO Research Institute, Davos, Switzerland

A. Boger
Synthes GmbH, Oberdorf, Switzerland

S. Hoerstrup
Department for Cardiovascular Surgery Research, University Hospital of Zurich, Zurich, Switzerland

A. Gisep (✉)
icotec AG, Industriestrasse 12, 9450 Altstätten, Switzerland
e-mail: armando.gisep@icotec.ch

Introduction

Osteoporotic fractures of vertebral bodies are most commonly treated by percutaneous vertebro- or kyphoplasty, injecting viscous polymethylmethacrylate (PMMA) cement into the vertebral bodies. The treatment is reported to lead to immediate and long lasting pain relief in 80–93% of patients [1]. Percutaneous cement augmentation of vertebral bodies may therefore become more popular in the future, as demographic changes will lead to a dramatic increase in vertebral fractures needing stabilization. The incidence of vertebral fractures for women above the age of 80 may increase above 50% [2]. The increased local stiffness after vertebral augmentation in an otherwise

osteoporotic spine bears the risk of a higher incidence of fractures of the adjacent vertebrae and thus prophylactic reinforcement of adjacent vertebrae with a high fracture risk is advisable in certain cases [3, 4]. Due to the risk of fat embolism, the number of augmented vertebrae during prophylactic multisegmental vertebroplasty should be limited to six levels per session or 25–30 cc of PMMA or flushed out bone marrow, respectively [5]. This empirical limitation is based on the increasing incidence and severity of pulmonary complications when injecting larger volumes. Pulmonary fat embolization during vertebroplasty may lead to arterial hypotension, oxygen desaturation and arrhythmia [6–9]. Cardiovascular changes resulting from fat embolism are often transient, but may be fulminant, resulting in cardiac arrest and even death [10–12]. Aebli et al. [13] have demonstrated the embolization of bone marrow fat and the associated cardiovascular changes during vertebroplasty in a sheep model. There was a cumulative increase of fat emboli in lung biopsies of sheep after multiple level augmentations [14]. Reducing the severity of pulmonary fat embolization may alleviate the severity of subsequent cardiovascular changes.

In a previously published human cadaveric study [15], we have shown that pulsed jet-lavage (irrigation) is suitable for removing intravertebral fat or bone marrow. Pulsed jet-lavage was therefore used to remove intravertebral in an in vivo sheep model in order to reduce the embolic load and alleviate subsequent cardiovascular complications. Lavage and drainage of the bone marrow cavity before cement injection may also reduce the risk of cement leakage by facilitating the penetration of the cement between the bone trabeculae, thus preventing cement leakage through blood vessels as a way of least resistance [15]. Furthermore, the decreased local resistance may reduce injection forces allowing the use of higher viscous cement with an advantageous flow behavior [16].

The safety of pulsed jet-lavage prior to PMMA vertebroplasty and its use for preventing or alleviating fat embolization and subsequent cardiovascular changes were investigated in a sheep model.

Materials and methods

Investigations were carried out in 11 skeletally mature mixed-bred ewes (4 ± 1 years old, mean body weight 69 ± 10 kg) according to Federal and State guidelines for experimental surgery. The study was approved by the Animal Ethics Committee (Kantonales Veterinäramt Zürich KEK-No: 204/2007). The animals were divided into two groups: one group ($n = 5$) was subjected to conventional bipedicular percutaneous vertebroplasty and the second group ($n = 6$) underwent vertebroplasty after pulsed jet-lavage of the vertebrae for intravertebral fat removal. In each animal, three lumbar vertebrae were treated.

Anesthesia was induced with propofol (6 mg kg^{-1}) and maintained with isoflurane (2–3%) in oxygen (50%). Analgesia and muscle relaxation were achieved by administrating buprenorphine (0.005 mg kg^{-1}) and pancuronium (0.06 mg kg^{-1}). Lungs were ventilated mechanically for maintaining normal end-tidal and arterial carbon dioxide tension prior to cement injection. End-tidal carbon dioxide tension was measured with an infrared capnometer. Ventilation settings were not altered after cement injection. A drip infusion of Ringer's lactate solution was maintained via the left cephalic vein at 4 ml kg^{-1} h^{-1}. Electrodes were placed on the skin for electrocardiogram (ECG) conduction.

Animals were positioned in dorsal recumbence for cardiovascular instrumentation. The right carotid artery was cannulated (multiple lumen catheter, Quinto, B. Braun Medical AG, Sempach, Switzerland) for measuring arterial blood pressure (ABP) and taking blood samples. An introducer (8 FG; Intro-Flex, Edwards Critical-Care Division, Irvine, CA, USA) for a Swan-Ganz catheter was inserted into the right jugular vein. Subsequently, a Swan-Ganz standard thermodilution pulmonary artery catheter (7.5 FG, length 110 cm, CCO/VIP, Edwards Critical-Care Division, Irvine, CA, USA) was floated into the pulmonary artery for measuring central venous pressure (CVP), pulmonary arterial pressure (PAP) and cardiac output. The correct position of the catheter was confirmed by recording typical pressure waves. Catheters were connected to pressure transducers (Uniflow, Baxter, Volketswil, Switzerland) via pressure tubing filled with Ringer's lactate solution. Heart rate was derived from the electrocardiogram. Cardiovascular pressures and electrocardiogram were digitized at 1 Hz using an analog/digital converter (Hellige Messturm, Marquette-Hellige GmbH Medizintechnik, Freiburg, Germany) and stored on a computer for offline analysis. Bolus thermodilution method was used for measuring cardiac output at certain time points. Cooled Ringer's lactate solution (<10°C; 5 ml) was injected through the Swan-Ganz catheter and values were calculated by a cardiac output machine (COM-2, Baxter, Volketswil, Switzerland).

The animals were then placed and fixed in a prone position on a radiolucent table. After a 1 cm stab incision, 2.0 mm K-wires were placed bilaterally in the dorsolateral cortex of the vertebral body in the projection of the pedicles under ap-fluoroscopic and tactile control. It was necessary to prepare the insertion path for the biopsy needle with a 3.2 mm high-speed drill, because the cortical bone of ovine vertebrae is much harder due to the higher bone mineral density compared to osteoporotic human vertebrae. Therefore, a trocar system was slid over the K-wire and

after removing the K-wire, the drill was advanced under fluoroscopic and tactile control. As soon as the medial border of the pedicle was reached, the depth was controlled in lateral view before advancing the drill to the center of each hemivertebra. After having removed the drill and reinserted the K-wire, a standard 8-gauge biopsy needle (outer diameter 4.2 mm, length 150 mm; MD Tech, Gainesville, FL, USA) was inserted over the K-wire into the vertebral body, tightly sealing the predrilled canal.

In the lavage group, vertebral bodies were flushed with saline solution (B. Braun Medical AG, Sempach, Switzerland) after needle placement. For this purpose, a lavage hand unit (ScandiMed, Biomet Merck, Switzerland) was attached to one biopsy needle using a custom made adaptor. Suction (−500 mmHg) was applied to the contralateral biopsy needle before starting the lavage process using a vacuum pump (Medela Vario V18, Medela, Switzerland). Figure 1 shows a schematic illustration of the setup.

The vertebral bodies were flushed with 100 ml of saline solution in increments of 10 ml. After the lavage process, a constant flow (180 ml/h) of diluted heparin (5,000 IU/L) into the vertebral body was established through one biopsy needle in order to avoid blood clotting during the time between lavage and cement injection (15 min). Vertebral bodies were filled bipedicularly with PMMA cement formulated for vertebroplasty (Vertecem Mixing Kit, Synthes GmbH, Oberdorf, Switzerland) under fluoroscopic control using 1 ml syringes (Viscosafe Injection Kit, Synthes GmbH, Oberdorf, Switzerland). Injection started at a viscosity of 35 Pa s controlled by parallel theometer measurement (RheolabQC, Anton Paar, Graz, Austria) (Boger, Wheeler, Schenk et al. Clinical investigations of PMMA cement viscosity during vertebroplasty and related in vitro measurements. E-Pub, European Spine Journal). In order to maximize the embolic load, maximal filling of the vertebral bodies was the goal and cement leakage was deliberately accepted to some degree (no pulmonary cement embolism).

Blood pressures and ECG activity were continuously recorded until 60 min after beginning the last (i.e. third) cement injection. Cardiac output and blood gas parameters were measured before the placement of the biopsy needles (baseline), before the lavage (pre-lavage) and the injection (pre-injection) process and 10 min after having started the first injection, 10 min after having started the second injection and 10, 30 and 60 min after having started the third injection. Cardiac output measurements were taken three times and averaged. Arterial blood gas analysis was carried out immediately.

At the end of the protocol, the animals were killed by intravenous injection of pentobarbital (1 g sheep^{-1}) and potassium chloride (2 mmol kg^{-1}), while the animals were still under anesthesia. After killing, the lumbar spines were explanted and underwent qCT analysis at a resolution of 123 μm (Xtreme CT, Scanco Medical, Switzerland). The CT data (DICOM images) were then transferred to Amira 4.1 software for segmentation and determination of cement volume in the vertebral bodies. Lung tissue biopsies were harvested from each of the five lung lobes, stained with oil-red O (fat stain) and subjected to high resolution confocal laser scanning microscopy (Axiovert200 M, Zeiss, Goettingen, Germany). The digital images of the lung sections (2 sections per lung lobe, $n = 110$) were analyzed using a macro (KS400, Zeiss, Goettingen, Germany) to determine the number of intravascular fat droplets present in an area of 2.5 mm × 3.0 mm of lung tissue.

In order to obtain pre-injection values of continuously recorded parameters (i.e. blood pressures and heart rate), data were averaged over 5 min. For post-injection values, data were averaged over 20 s.

An increase or decrease in a cardiovascular variable of more than 15% present for more than 20 s was considered a cardiovascular response.

The chosen sample size was sufficient to detect clinically relevant changes of blood pressure and blood gas variables from pre-injection and post-injection values, with the power ranging from 80 to 95%. Data were calculated and presented as the mean ± standard deviation of the mean (±SD). Statistical analysis included a two-way ANOVA for repeated measures and Student's *t* test to test for inter- and intra-group differences of the pooled cardiovascular data per animal. Post hoc analyzes were achieved using the Newman–Keuls test. Statistical analysis of the histology included a Mann–Whitney *U* test to compare the number of

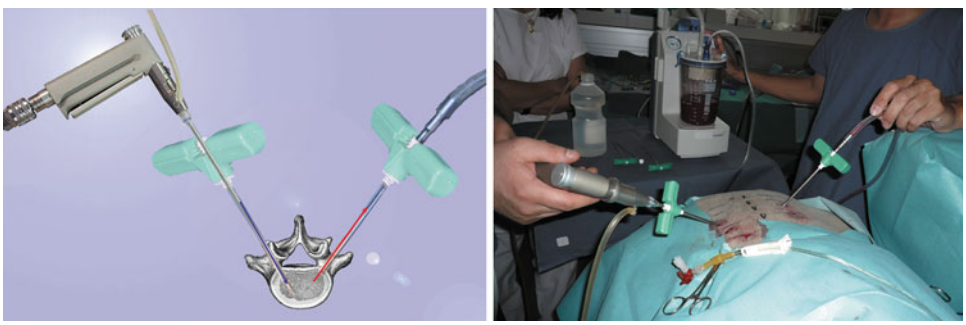

Fig. 1 Schematic illustration of the setup with two biopsy cannulas placed in the vertebral body (*left*). The intra-operative setup is shown on the *right*. Suction is applied to remove the intravertebral fat together with the saline solution

Table 1 Baseline cardiovascular parameters

	Control group ($n = 5$)	Lavage group ($n = 6$)
MABP (mmHg)	96 ± 14	94 ± 15
MPAP (mmHg)	24 ± 4	25 ± 5
MCVP (mmHg)	6 ± 2	5 ± 3
HR (bpm)	90 ± 5	90 ± 11
CI (L min^{-1} m^{-2})	5.8 ± 1.5	5.1 ± 1.0
pH	7.39 ± 0.03	7.41 ± 0.02
pCO_2 (kPa)	5.7 ± 0.2	5.5 ± 0.5
pO_2 (kPa)	27 ± 4	25 ± 4

MABP mean arterial blood pressure, *MPAP* mean pulmonary arterial pressure, *MCVP* mean central venous pressure, *HR* heart rate, *CI* cardiac index, pCO_2 arterial carbon dioxide tension, pO_2 arterial oxygen tension

fat droplets divided by the amount of cement inside the vertebral bodies between the two groups. Differences in the number of fat droplets in the lung lobes of single animals were analyzed using a Friedman two-way analysis of variance. Intergroup differences of the injected cement volume were assessed using a *t* test. All differences tested were considered significant at $P < 0.05$.

Results

Percutaneous insertion of the biopsy cannulas and intravertebral lavage under vacuum was feasible in this in vivo setting. In most cases, a good flow of saline solution through the vertebral body was achieved. Placement of biopsy cannulas and the lavage process took for each vertebral body 12.3 ± 4.7 and 1.7 ± 1.1 min, respectively ($n = 33$).

There were no significant ($P > 0.05$) difference in the cardiovascular parameters between the control and the lavage group at baseline (Table 1).

Data of the continuously recorded parameters (i.e. invasive pressures and heart rate) from the three lavage and injection events were pooled for statistical analysis, because there were no significant ($P > 0.05$) differences among the pre-event values and the post-event cardiovascular changes. The lavage process elicited no cardiovascular changes (Table 2).

In the control group, cement injection elicited a sudden (1 min after injection) increase in mean pulmonary arterial pressure (MPAP) of more than 50% that lasted for 9 min (Fig. 2).

In the lavage group, there was no significant change in MPAP. 10 of 18 cement injections (56%) elicited a cardiovascular response (increase) in MPAP whereas in the control group all injections ($n = 15$) resulted in an increase in MPAP (Fisher exact test for intergroup difference: $P = 0.004$). There were no other cardiovascular changes in both groups (Tables 3, 4).

Evaluation of the CT images showed significantly ($P = 0.022$) more cement in the irrigated vertebrae compared to the control vertebrae (3.45 ± 0.81 vs. 2.75 ± 0.87 cc).

Intravascular fat and bone marrow cells were present in all lung lobes of both groups (Fig. 3).

There were no significant ($P = 0.78$) differences in the count of fat emboli among the different lung lobes (Table 5). The count of fat emboli in all five lobes was significantly ($P = 0.003$) higher in the control compared to the irrigation group.

Discussion

Summary

The safety of pulsed jet-lavage prior to PMMA vertebroplasty and its use for preventing or alleviating fat

Table 2 Cardiovascular parameters before and after vertebral lavage

	Pre-lavage ($n = 18$)	1 min ($n = 18$)	3 min ($n = 15$)	5 min ($n = 15$)	10 min ($n = 15$)
MABP[a] (mmHg)	81 ± 17	80 ± 17	83 ± 21	80 ± 20	77 ± 21
MPAP[a] (mmHg)	21 ± 4	24 ± 5	21 ± 4	20 ± 4	20 ± 4
MCVP[a] (mmHg)	5 ± 3	6 ± 4	5 ± 3	4 ± 3	4 ± 2
HR[a] (bpm)	89 ± 12	88 ± 11	89 ± 11	90 ± 11	90 ± 12
CI[b] (L/min/m^2)	5.9 ± 1.4				5.7 ± 1.4
pH[b]	7.41 ± 0.03				7.41 ± 0.02
pCO_2^b (kPa)	5.6 ± 0.3				5.3 ± 0.3
pO_2^b (kPa)	25 ± 4				25 ± 4

1, 3, 5 and 10 min represent time after lavage

MABP mean arterial blood pressure, *MPAP* mean pulmonary arterial pressure, *MCVP* mean central venous pressure, *HR* heart rate, *CI* cardiac index, pCO_2 arterial carbon dioxide tension, pO_2 arterial oxygen tension

[a] Pooled cardiovascular data of continuously measured parameters

[b] Cardiovascular parameters measured before and 10 min after lavage

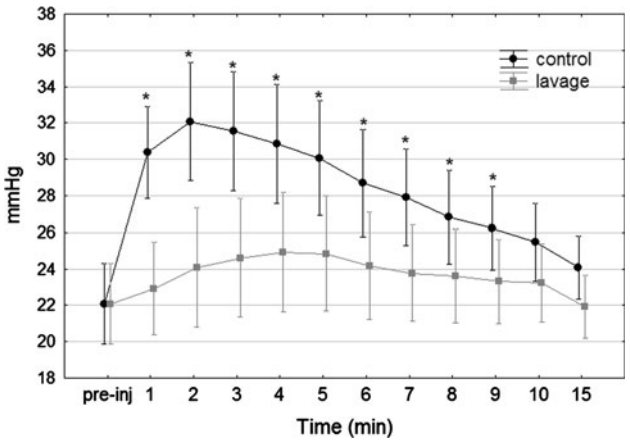

Fig. 2 Mean pulmonary arterial pressure after cement injection (pooled data). *Asterisk* indicates a significant ($P < 0.02$) difference from the pre-injection value

embolization and subsequent cardiovascular changes were investigated in a sheep model. Lavage of the vertebral bodies prevented the increase in pulmonary arterial pressure after PMMA injection and significantly reduced the severity of pulmonary bone marrow fat embolism. Furthermore, it was possible to inject significantly more cement into lavaged vertebrae compared to the control group.

Effect of Lavage

The cardiovascular reaction to PMMA injection, i.e. pulmonary bone marrow fat embolization, was characterized by a sudden (within 60 s after injection) and considerable (>50%) increase in pulmonary arterial pressure which is in accordance with previous investigations [13, 17]. Pulmonary hypertension lasted for 9 min. In the lavage group, there were no significant cardiovascular changes after cement injection. This seemed to be the result of the reduced embolic load. Intravertebral lavage was effective in removing bone marrow fat prior to cement injection, evident by the significantly lower count of fat emboli. In a previous study, drilling a vent hole contralaterally to the cement injection site also reduced the embolic load (by 50%), but only alleviated the cardiovascular changes after injection of PMMA into vertebral bodies [14]. Lavage under vacuum seemed to be more effective than the passive escape route via the vent-hole. Even though lavage did not

Table 3 Cardiovascular parameters measured continuously before and after cement injection (pooled cardiovascular data)

		Pre-injection	1 min	3 min	5 min	10 min	30 min	60 min
MABP (mmHg)	Ctrl	88 ± 12	84 ± 10	92 ± 14	92 ± 15	87 ± 13	78 ± 10	71 ± 9
	Lav	76 ± 16	71 ± 18	77 ± 19	80 ± 17	70 ± 13	60 ± 6	60 ± 7
MPAP (mmHg)	Ctrl	22 ± 2	29 ± 5*	31 ± 4*	29 ± 3*	25 ± 3	21 ± 1	22 ± 1
	Lav	22 ± 5	24 ± 7	27 ± 10	26 ± 8	23 ± 4	22 ± 3	22 ± 2
MCVP (mmHg)	Ctrl	5 ± 3	6 ± 3	6 ± 2	6 ± 2	5 ± 3	4 ± 2	4 ± 3
	Lav	6 ± 3	6 ± 3	7 ± 4	6 ± 4	5 ± 3	4 ± 2	4 ± 3
HR (bpm)	Ctrl	97 ± 8	96 ± 9	97 ± 7	98 ± 8	98 ± 8	99 ± 12	100 ± 15
	Lav	88 ± 12	87 ± 11	92 ± 15	89 ± 10	88 ± 11	87 ± 9	92 ± 13

1, 3, 5, 10, 30 and 60 min represent time after cement injection

Ctrl control group, *Lav* lavage group, *MABP* mean arterial blood pressure, *MPAP* mean pulmonary arterial pressure, *MCVP* mean central venous pressure, *HR* heart rate

* Significantly ($P < 0.02$) different from pre-injection value

Table 4 Cardiovascular parameters measured periodically before and after cement injection

		Pre-injection	10 min after 1st injection	10 min after 2nd injection	10 min after 3rd injection	30 min after 3rd injection	60 min after 3rd injection
CI (L/min/m^2)	Ctrl	5.8 ± 0.7	6.2 ± 1.1	6.7 ± 0.3	6.9 ± 1.0	7.1 ± 0.9	7.2 ± 1.3
	Lav	5.9 ± 1.4	5.4 ± 0.4	5.2 ± 0.6	5.9 ± 1.0	5.5 ± 0.8	5.6 ± 0.8
pH	Ctrl	7.39 ± 0.02	7.37 ± 0.02	7.37 ± 0.03	7.37 ± 0.03	7.38 ± 0.03	7.37 ± 0.03
	Lav	7.41 ± 0.02	7.40 ± 0.03	7.40 ± 0.04	7.40 ± 0.04	7.41 ± 0.04	7.42 ± 0.04
pCO_2 (kPa)	Ctrl	5.9 ± 0.3	6.2 ± 0.3	6.2 ± 0.4	6.4 ± 0.5	6.2 ± 0.6	6.4 ± 0.5
	Lav	5.3 ± 0.3	5.9 ± 0.6	5.9 ± 0.5	5.8 ± 0.6	5.7 ± 0.5	5.8 ± 0.5
pO_2 (kPa)	Ctrl	27 ± 5	27 ± 5	25 ± 3	24 ± 3	25 ± 4	24 ± 3
	Lav	25 ± 4	23 ± 4	24 ± 4	24 ± 4	24 ± 4	24 ± 4

Ctrl control group, *Lav* lavage group, *CI* cardiac index, *pCO_2* arterial carbon dioxide tension, *pO_2* arterial oxygen tension

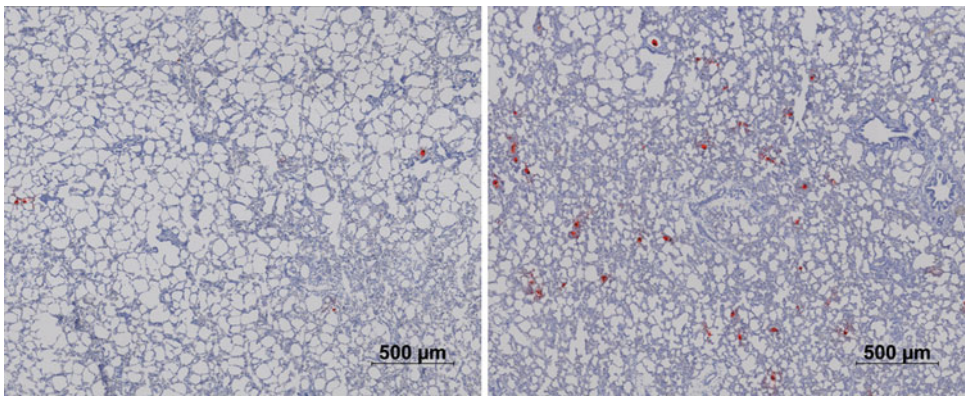

Fig. 3 Images of oil-red O stained lung sections, lavage (*left*) and control (*right*). There were significantly ($P = 0.022$) more fat droplets present in the control lung tissue

Table 5 Counts of intravascular fat emboli in the analyzed microscopic views of the lung tissue samples

	Control		Lavage	
	Median	95% CI	Median	95% CI
RCR ($n = 10/12$)	18	10–37	10	5–21
RMID ($n = 10/12$)	15	9–22	8	1–38
RCD ($n = 10/12$)	25	14–39	8	5–27
LCR ($n = 10/12$)	13	8–20	16	7–31
LCD ($n = 10/12$)	23	13–32	6	3–21
All lobes ($n = 50/60$)	17	16–24	9*	11–24

CI confidence interval, *LCD* left caudal lobe, *LCR* left cranial lobe, *RCR* right cranial lobe, *RMID* right middle lobe, *RCD* right caudal lobe, *n* number of analyzed microscopic views (control/lavage)

* $P < 0.05$ from the control group

remove all bone marrow fat and did not prevent fat embolization, it reduced the embolic load to a degree below the threshold for eliciting a cardiovascular response.

Lavage process

The used setup with a bipedicular access to the vertebral body applying pulsed jet irrigation and a vacuum on the contralateral side proved to be feasible. It was possible to remove a significant amount of fat from the vertebral body using this technique. The lavage process elicited no cardiovascular changes and therefore appears to be safe for tests in a clinical setting.

Cement injection

Removing bone marrow fat by lavage allowed injecting significantly more cement in this experimental setup and a more homogenous distribution.

Further, we could demonstrate reduced injection pressures after lavage in a human cadaveric study which again would allow the use of more viscous cement with a potential reduction of extravasations [16]. The same effect of injection pressure reduction could be shown as a side investigation of this study [18].

Another limitation of our experimental setup where we aimed for a maximal filling to increase the embolic load is that we deliberately accepted local cement leakage, thus not representing the clinical situation. The expected reduction of extravasations after lavage could therefore not be demonstrated with the present setup and needs to be verified in a clinical investigation, ideally in humans.

Clinical relevance

Results obtained from this animal study can only be extrapolated to clinical practice with caution. However, the range of baseline cardiovascular variables and the response to bone marrow fat embolism are comparable to those recorded in humans. The cardiovascular response to fat embolization in patients may be even more severe as a result of impaired cardiovascular function. Furthermore, the embolic load from osteoporotic vertebrae is potentially higher compared to ovine vertebrae as cancellous bone is replaced by bone marrow fat during the disease. Present results should be verified in a clinical setting. Pulsed jet-lavage of vertebral bodies before vertebroplasty may increase the safety of the intervention especially for elderly patients with impaired cardiopulmonary function, as pulmonary fat emboli are often a critical factor of the treatment. For multilevel vertebroplasty, there may be the possibility to treat higher numbers of levels, hence avoiding a second procedure. Krebs et al. [19] have demonstrated that the administration of a pulmonary vasodilator (sildenafil) prevented cardiovascular changes after fat embolization elicited by PMMA vertebroplasty. However, the treatment only prevented the consequences of fat embolization and not the cause (i.e. fat embolization) for the deterioration itself.

Animal model

Investigating cardiovascular complications after fat embolism during vertebroplasty and the prevention thereof

requires an animal model suited to inject a similar quantity of bone cement and thus forcing a similar quantity of bone marrow into the circulation as in the clinical situation. Previous studies have shown that the sheep model is suitable to elicit reproducible and well-defined fat embolism and subsequent cardiovascular changes [13, 14, 20]. The sheep was therefore chosen to investigate cardiovascular changes during percutaneous vertebroplasty, even though the sheep's vertebral bodies have a higher bone mineral density and therefore a lower quantity of bone marrow fat content compared to—especially osteoporotic—human patients (Benneker, Gisep, Krebs et al. Percutaneous vertebroplasty in sheep; development of an animal model. Submitted to Spine). Ideally such a study would have been conducted in osteoporotic sheep but currently, the adverse effects by the different induction regimes of large animal models for osteoporosis outbalances its advantages [21]. Theoretically, in osteoporotic bone, the technique would be easier to perform and the beneficial effects of lavage are expected to be greater.

Outlook

In the current study, we have been able to prove that the application of a pulsed jet-lavage in combination with a vacuum applied on the contralateral pedicle did not cause any cardiovascular reactions during and after the removal of intravertebral fat. It seems that this is a safe and efficient technique. Next studies should investigate the feasibility and details of a monopedicular system for parallel irrigation and application of vacuum via the same pedicle. This again would be an important step towards clinical application of the technique, as many cementations, mostly as prophylactic treatment of osteoporotic vertebrae, are done in a monopedicular manner. The technique presented here is only suited for interventions under general anesthesia as negative intraosseus pressure is relatively painful; again a monopedicular technique may overcome this limitation.

Conclusion

In conclusion, lavage of the vertebral bodies resulted in a significant reduction of the embolic load and thus prevented the increase in pulmonary arterial pressure after PMMA injection, even though significantly more cement was injected into the lavaged vertebrae potentially displacing more bone marrow fat into the venous system. Vertebral lavage for removing intravertebral fat prior to cement injection for multilevel vertebroplasty may be useful for preventing potentially life threatening complications in patients with impaired cardiopulmonary function.

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