Heat distribution of polymerisation temperature of bone cement on the spinal canal during vertebroplasty

Bernd Wegener · Nicole Zolyniak · Mehmet F. Gülecüüz · Andreas Büttner ·
Christoph von Schulze Pellengahr · Veronika Schaffer · Volkmar Jansson ·
Christof Birkenmaier

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Abstract

Purpose In the last 15 years, vertebroplasty and kyphoplasty have become established operative procedures for treating osteoporotic vertebral-body fractures and vertebral bodies afflicted with metastases. These procedures are quickly performed with few personnel and material resources and have a low rate of complications. However, cases of neurological impairment are reported in the scientific literature. We analysed whether potentially harmful heat is radiated/conducted by the polymerisation temperature of polymethylmethacrylate (PMMA) bone cement in the spinal canal. **Methods** We performed vertebroplasty on 25 vertebral bodies and measured the temperature distribution during polymerisation of bone cement within the spinal canal

using heat probes placed in the respective areas. The vertebral bodies were located in a circulating water bath at 37°C.

Results During polymerisation of the bone cement, a temperature rise was measured. The peak temperature was reached after few minutes. Temperature curves differed; a maximum temperature of up to 43.16°C was detected for a few seconds only.

Conclusion When vertebroplasty is performed correctly, there is no temperature development that could eventually damage the spinal cord or spinal nerves.

Introduction

In the last 15 years, vertebroplasty has become an established operative procedure for treating osteoporotic vertebral-body fractures and vertebral bodies afflicted with metastases. The procedure is quick, requires few personnel and material resources and has a low complication rate. However, cases of neurological impairment are reported [1–4]. There are various mechanisms of damage to be considered. Apart from direct nerve injury caused by instruments, compression by bleeding or tissue displacement, cement leakage and consequently heat radiated from the cement must be considered as a possible cause of neural damage. During polymethylmethacrylate (PMMA) bone-cement polymerisation, temperatures up to 100°C can develop in several minutes. Quite often, an analgesic effect is attributed to the destruction of nerve endings through heat development. Generally, there is no difference in heat development from cement polymerisation during vertebroplasty or kyphoplasty. So far, the questions of if and to what extent heat can possibly damage the spinal cord, cauda equina or spinal nerves has attracted little scientific

B. Wegener (✉) · M. F. Gülecüüz · V. Schaffer · V. Jansson ·
C. Birkenmaier
Department of Orthopaedics, Campus Großhadern,
Ludwig-Maximilians-University Munich,
Marchioninstraße 15,
81377 München, Germany
e-mail: bernd.wegener@med.uni-muenchen.de

N. Zolyniak
Department of Physical Medicine and Rehabilitation, Campus
Großhadern, Ludwig-Maximilians-University Munich,
München, Germany

A. Büttner
Institute of Legal Medicine,
Ludwig-Maximilians-University Munich,
München, Germany

A. Büttner
Institute of Legal Medicine, University of Rostock,
München, Germany

C. von Schulze Pellengahr
St. Joseph-Hospital, University of Bochum,
München, Germany

Fig. 1 Measuring station showing the vertebra within the thermal bath with a rotating stir bar. Probes were connected to the thermometer and the computer

attention. The aim of this study was to measure heat development in the spinal canal during vertebroplasty and to assess the danger potential to neural structures.

Material and methods

The study was performed on human cadaveric vertebral column specimens. The study was approved by the Institutional Ethical Review Board of the Institute of Legal Medicine. Twenty-five vertebral bodies of nine cadavers were evaluated. Specimens were dissected from newly deceased patients with an average age of 61.4 (range 44–76) years. As the collective of specimens was heterogenic regarding age, a normal distribution of bone mineral density could be assumed. Only vertebral bodies of specimens without malignancy, with no fracture (four vertebral bodies were excluded) and no fluoroscopically visible bone metastases were used. Only specimens from L1–L5 were used. Soft tissue and structures from the spinal canal were removed from the bone. In total, we investigated data of heat distribution gained during 25 correctly performed vertebroplasties. We excluded seven measurements in which vertebroplasty or measurements were not performed appropriately. This included extravasation of bone cement from the vertebral body in five cases, regardless of direction. Extravasation *in vitro* occurred more frequently compared with a clinical application. This is explained by the fact that we always inserted a defined amount (10 ml) of

cement into each intact vertebra under high pressure to ensure constant distribution of cement within the vertebral body. During clinical application of vertebroplasty, we typically use a smaller amount of cement. Furthermore, blood agglutination in cancellous bone, even after thorough rinsing, led to a higher expenditure of force during cement application. We also excluded two vertebrae in which more than half of the thermal sensors showed an objective measurement error, such as irrational fluctuations in the measurement or solitary recording failures. If a failure occurred in one to three thermal elements, only these elements were excluded from evaluation.

Specimens were positioned in an 18 L water bath at $37^{\circ}\text{C} \pm 1^{\circ}\text{C}$. The temperature was kept constant using a heating plate. To simulate blood and liquid flow, a magnetic stirrer was used to create a current. Sensors consisted of ten thermal elements with an interval of 1 mm between them. These were positioned in a ventrodorsal line inside the spinal canal starting from the posterior edge of the vertebra (Fig. 1).

The thermometer we used was the Testo 454 (Company: Testo AG, Lenzkirch Deutschland). A mantled thermal element type K, class 1, with a probe length of 400 mm and a diameter of 0.25 mm was connected to the thermometer. Temperatures with an accuracy of 10^{-2}C at a frequency of 1/3 Hz were recorded for 20 min, i.e. 400 solitary measurements per thermal element. Measurements were started five min after mixing the bone cement (Biomet Bone Cement V, Biomet Deutschland GmbH, Berlin, Germany), which was stored at room temperature. Through

Fig. 2 Ten thermal elements were placed in a row starting at the posterior edge of the vertebral body inside the spinal canal with a distance of 1 mm between each from anterior to posterior

Fig. 3 Binomial formula for calculating the probability of a potentially harmful single event occurrence ($P_e=0.1$), respective to the probability of nonoccurrence ($1 - P_g=0.93$) with $n=25$

a pedicle entrance, 10 ml PMMA bone cement was injected into the vertebral body after the cannula was placed in the anterior medial third of the vertebral body (Fig. 2). We used the single pedicle entrance because it showed efficient cement distribution within the vertebral body. Cannula (150-mm long, 3.2-mm diameter) position was confirmed using biplanar fluoroscopy.

Temperature progression dependent on time was statistically evaluated. The probability of a single event (P_e) in which a potentially harmful event (temperature $>50^\circ\text{C}$) could occur was determined, respective to the probability ($1 - P_g$) that it does not occur (Fig. 3).

Results

Recorded temperatures were up to 43.16°C . Temperature exceeded 43°C for only about three minutes. Maximal values of all measurements are displayed in Fig. 4 and divided into two separate diagrams for a better overview. In Fig. 5, for example, three measurements are represented where the temperature distribution in three different vertebrae is depicted. Curves indicate a highly heterogenic temperature distribution. Heat development begins at

different time points. Temperature progression is also variable. With increasing distance to the posterior edge of the vertebrae, the temperature decreases. For comparative purposes, two measurements were prepared in which bone cement leaked out of the vertebrae into the spinal canal. The highest recorded temperature there was 68.11°C in the first measurement and 65.52°C in the second (Fig. 6).

Discussion

Heat sensitivity of various tissues depends on tissue type, absolute temperature and application duration. The Arrhenius-equation describes this coherence and indicates that the velocity of a chemical reaction and speed of cell destruction increases with rising temperature. Graphically, the logarithmic rate of cell destruction is presented as a function of the inverse absolute temperature. This biphasic curve is equal in mammals. The curve progression is represented by the following equation according to Dewey [5]: $t_2 = t_1 \times R^{(T_1 - T_2)}$.

If heat damage of biological tissue is expected to occur in the temperature threshold $<43^\circ\text{C}$, an increase of 1°C and an application duration to the factor of six would be equivalent to

Fig. 4 Temperature development at the posterior edge of vertebrae dependent on time. To achieve a better overview, the curves were divided into three diagrams, which show a very different temperature development regarding time progression and maximum values

Fig. 5 Exemplary depiction of temperature development in the spinal canal in three characteristic vertebral bodies. A decreasing distance to the posterior edge of the vertebrae leads to an increase in temperature

an increase of 1°C at a temperature threshold >43°C and application duration to the factor of two to bring attain the same results [6]. This means that between 43°C and 45°C, a temperature increase of 1°C would be enough to halve the tolerated application duration [7].

Limitations

Temperature distribution depends on the distribution of the bone cement within the vertebral body, which will never be completely identical between individual experiments. Blood and liquid flow can only be simulated in an in vitro experiment. Numerous studies involving temperature-dependent necrosis development in cemented endoprosthesis have been conducted. It was demonstrated that bone trabecula exposed to temperatures up to 70°C showed necrotic areas [8]. However, temperatures of 50°C were not tolerated by osteoblasts [34]. Even during therapy for malignant tumours, thermal effects during bone-cement hardening is only considered because tumour tissue is more thermosensitive than comparable healthy tissue [7, 9]. Polymerisation heat from bone cement in vertebral bodies is precarious because of the close proximity to neural structures in which damage could result in dramatic functional impairment [10]. Paralysis as a complication of vertebroplasty has often been described, and realistically, it is certainly possible to thermally damage spinal nerves and

the spinal cord [11, 12]. In a study on rats, dose- and time-dependent damage to peripheral nerves at temperatures between 43°C and 45°C has been demonstrated [7]. Whole-body hyperthermia on dogs was performed by Takahashi in which the animals were exposed to temperatures of $42.0 \pm 0.1^\circ\text{C}$. In the histological evaluation seven days later, no damage was evident. On the contrary, Sminia et al. observed neurological deficiencies resulting death of rats after thermally exposing their brains and spinal cords temperatures up to $42.9^\circ\text{C} \pm 0.4^\circ\text{C}$ for >38 min. Histologically, damage to the gray and white matter was evident, along with an immigration of leucocytes and macrophages. Animals surviving the experiment showed scar tissue on histology. Heating the cauda equina, which has similarities to peripheral nerves, showed no indication of neurological deficiencies [13]. Franken et al. showed in rats that exposure to temperatures >43°C for one hour leads to motor dysfunction. At 43.8°C for one hour, loss of tail tonus, loss of sensibility in the lower extremities and nerve necrosis was observed [14]. The higher the chosen temperature, the higher the potential for damage. Uchiyama et al. showed alterations in the nerve amplitudes in dogs where their spinal cord was exposed to 45°C for over 30 minutes [15]. In a study conducted by Konno et al., neural damage to 20 pigs was examined after local hyperthermia was induced. Application of 40°C for >30 min resulted in no damage, whereas an application of 60°C for five minutes showed histological neural damage and of 70°C for five minutes resulted in nerve dysfunction [16]. Fajardo et al. defined thermal damage threshold on the central nervous system at 42°C for more than 60 min [17]. During vertebroplasty, the temperature increase during cement polymerisation is not solely dependent on chemical reaction. The surrounding temperature, mixing, cement hardening, amount of cement and pressure applied during application and cement dispersion in the surrounding tissue influences the temperature's affect on nerves [18–21]. The difference in thermal conduction in dry and moist bones, as described by Leeson and Lippit [20], was considered in our experimental setup. Li et al.'s studies resulted in a hardening temperature of approximately 100°C when a bone cement cylinder with an inner diameter of 60 mm and a cement thickness of 6 mm was used to answer a question raised in relation to hip arthroplasty [21].

Fig. 6 Temperature development after cement extravasation into the spinal canal in two different vertebral bodies. A peak value of 68°C was recorded. These measurements were excluded from analyses

In our experiment, we used a standardised amount (10 ml) of cement. Other study groups applied amounts between 1.5 and 12 ml [22, 23]. This comparatively large amount, which is even exceeded by some authors during therapeutic use, was used to simulate temperature development generated by larger amounts of cement. It is assumed that smaller amounts generate lower temperatures. The highest temperatures registered in our study were in the posterior edge of vertebral bodies. The peak value of 43.16°C was recorded for only a few seconds. Therefore, it can be assumed that an appropriate application of bone cement does not cause thermal damage to the spinal cord or spinal nerves. The results obtained when measuring temperatures created by cement extravasation were different. We measured temperatures up to 68.11°C, which surely possess the capability to induce thermal damage. Such a case is described by Wilkes et al. of a 63-year-old patient in whom damage was created by bone-cement leakage into the spinal canal via posterior edge, which eventually led to severe neural impairment [11]. Deramond et al. examined two different types of bone cement with a different setup to address the question of whether polymerisation heat and destruction of neural tissues explains the analgesic effect of vertebroplasty [12]. The authors recorded temperatures of 50°C within the vertebral body and up to 41°C in the posterior edge, leading to the conclusion that spinal-cord damage by polymerisation heat does not occur. In a study conducted by Belkoff and Malloy using 24 osteoporotic vertebrae filled with 6–10 ml of bone cement, a peak temperature of 113°C was measured [24]. Potentially harmful temperatures >50°C at the posterior edge were only registered when the cement approached this area. Aebli et al. simulated human physiological conditions in a sheep model [25]. They attempted to determine whether polymerisation heat was responsible for pain relief during vertebroplasty and whether damage to the spinal cord or spinal nerves occurred. In each of 12 vertebral bodies, 4 ml of cement was used. Temperatures over 40°C were measured within a time span of up to 1.5 min, and the authors concluded that thermal damage should not be expected. The cited studies attained similar results as determined in our study. Polymerisation heat caused by bone cement does not lead to damage of nerves when vertebroplasty is performed correctly.

Conclusion

In this study, we showed that heat emitted during PMMA bone-cement polymerisation during correctly performed vertebroplasty does not exceed temperature values described in the literature as being potentially harmful over an extended

period of time. Therefore, we assume that this heat does not lead to nerve damage.

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References

1. Birkenmaier C, Seitz S, Wegener B, Glaser C, Ruge MI, von Liebe A (2007) Acute paraplegia after vertebroplasty caused by epidural hemorrhage. A case report. *J Bone Joint Surg Am* 89:1827–1831
2. Gangi A, Dietemann JL, Guth S, Steib JP, Roy C (1999) CT- and fluoroscopy- guided Vertebroplasty: Results and Complications in 187 Patients. *Semin Intervent Radiol* 16:137–142
3. Harrington KD (2001) Major neurological complications following percutaneous vertebroplasty with polymethylmethacrylate: a case report. *J Bone Joint Surg Am* 83:1070–1073
4. Ratliff J, Nguyen T, Heiss J (2001) Root and spinal cord compression from methylmethacrylate vertebroplasty. *Spine* 26:E300–E302
5. Dewey WC (1994) Arrhenius relationship from the molecule and cell to the clinic. *Int J Hyperthermia* 10:457–483
6. Field SB, Morris CC (1983) The relationship between heating time and temperature: its relevance to clinical hyperthermia Radiotherapy and oncology. *Radiother Oncol* 1:179–186
7. De Vrind HH, Wondergem J, Haveman J (1992) Hyperthermia-induced damage to rat sciatic nerve assessed in vivo with functional methods and with electrophysiology. *J Neurosci Methods* 45:165–174
8. Stanczyk M, van Rietbergen B (2004) Thermal analysis of bone cement polymerisation at the cement- bone interface. *J Biomech* 37:1803–1810
9. Li S, Chien S, Branemark PI (1999) Heat shock- induced necrosis and apoptosis in osteoblasts. *J Orthop Res* 17:891–899
10. Toksvig-Larsen S, Johnsson R, Strömquist B (1995) Heat generation and heat protection in methylmethacrylate cementation of vertebral bodies. *Eur Spine J* 4:15–1
11. Wilkes RA, Mackinnon JG, Thomas WG (1994) Neurological deterioration after cement injection into a vertebral body. *J Bone Joint Surg Br* 76:155
12. Deramond H, Wright NT, Belkoff SM (1999) Temperature elevation caused by bone cement polymerization during vertebroplasty. *Bone* 25(Suppl 2):17–21
13. Sminia P, Hendriks JJ, van der Kracht A, Rodernand H, Honvemmann J, Jansen W (1995) Neurological observations after local irritations and hyperthermia of rat lumbosacral spinal cord. *Int J Radiat Oncol Biol Phys* 32:165–174
14. Franken NA, De Vrind HH, Sminia P, Havemann J, Troost D, Gonzalez Gonzalez D (1995) Neurological complications after 434 MHz microwave hyperthermia on the rat lumbar region including the spinal cord. *Int J Radiat Biol* 62:229–238
15. Uchiyama S, Yashiro K, Takahashi H, Homma T (1989) An experimental study of spinal cord evoked potentials and histologic changes following spinal cord heating. *Spine* 14:1215–1219
16. Konno S, Olmarker K, Byrod G, Nordborg C, Strömquist B, Rydevik B (1994) Acute thermal nerve root injury. *Eur Spine J* 3:299–302
17. Fajardo LF (1984) Pathological effects of hyperthermia in normal tissues. *Cancer Res* 44(Suppl):4826s–4836s
18. Brown SA, Bargar WL (1984) The influence of temperature and specimen size on the flexural properties of PMMA bone cement. *J Biomater Res* 18:523–536

19. Dunne NJ, Orr JF (2002) Curing characteristics of acrylic bone cement. *J Mater Sci Mater Med* 13:17–22
20. Leeson MC, Lippit SB (1993) Thermal aspects of the use of polymethylmethacrylate in large metaphyseal defects in bone: a clinical review and laboratory study. *Clin Orthop Relat Res* 295:239–245
21. Li C, Mason J, Yakimicki D (2004) Thermal characterization of PMMA-based cement curing. *J Mater Sci Mater Med* 15:85–89
22. Gangi A, Guth S, Imbert JP, Marin H, Dietemann JL (2003) Percutaneous vertebroplasty: Indications, Technique and results. *Radiographics* 23:e10
23. Muto M, Muto E, Izzo R, Diano AA, Lavanga A, Di Furia U (2005) Vertebroplasty in the treatment of back pain. *Radiol Med* 109:208–219
24. Belkoff SM, Molloy S (2003) Temperature measurements during polymerisation of polymethylmethacrylate cement used for vertebroplasty. *Spine* 28:1555–1559
25. Aebi N, Goss BG, Thorpe P, Williams R, Krebs J (2006) In vivo temperature profile of intervertebral discs and vertebral endplates during Vertebroplasty: an experimental study in sheep. *Spine* 31 (15):1674–1678