

Automated cement segmentation in vertebroplasty

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Abstract

Vertebroplasty is a minimally invasive procedure with many benefits. However, the procedure is not without risks and complications. Leakage of the cement out of the vertebral body and into the surrounding tissues is one of the most serious complications of vertebroplasty. Cement can leak into spinal canal, venous system, soft tissues, lungs and intradiscal space, causing serious neurological complications, tissue necrosis or pulmonary embolism. In this work we present a method for automatic segmentation and tracking of bone cement during vertebroplasty procedures, as a first step towards building a warning system to avoid cement leakage outside the vertebral body. We show that using active contours based on level sets the shape of the injected cement can be accurately detected. We have improved the model for segmentation proposed in our previous work, by including a term that restricts the level set function to the vertebral body. We have applied the method to a set of real intra-operative X-ray images and our results show that the algorithm can successfully detect different shapes with blurred and not well defined boundaries, where the classical active contours segmentation is not applicable. The method was positively evaluated by physicians.

Key words: Vertebroplasty, cement segmentation, level sets

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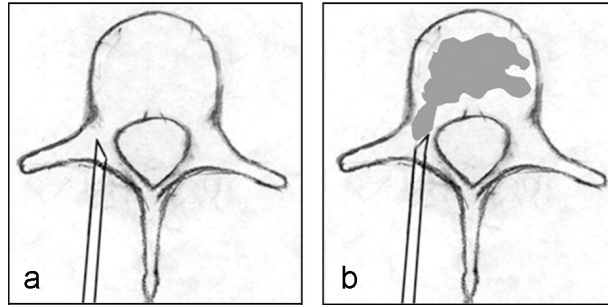


Fig. 1. Schematic drawings of vertebroplasty procedure: (a) Vertebroplasty needle is inserted through the pedicle of the vertebra. (b) Acrylic bone cement is injected into the vertebra, filling the cavity within the bone [4].

29 Introduction

30 Vertebroplasty is a minimally invasive image-guided procedure in which a bio-
31 material (bone cement) is injected into the spine in order to stabilize fractured
32 vertebra and relieve pain (Figure 1) [1–4]. Problems that could be treated by
33 this procedure include painful compression fractures resulting from osteoporosis,
34 fractures associated with cancer or benign blood vessel expansions, and
35 fractures from trauma. During image guided vertebroplasty procedures, ce-
36 ment injection is monitored using X-ray imaging. However, the visibility on
37 the screens of the operating room could be poor and it may be very difficult
38 and time consuming for the surgeon to detect the borders of the injected ce-
39 ment. Furthermore, especially when using old imaging equipment, only very
40 experienced physicians are able to accurately visualize the cement and distin-
41 guish it from bony structures.

42 Leakage of the cement out of the vertebral body and into the surrounding
43 tissues is one of the most serious complications in vertebroplasty (Figure 2)
44 [5–7]. In a large number of vertebroplasty cases, cement leakage is detected
45 only after the procedure. Most common problems include pulmonary embolism
46 [8] and fractures of adjacent vertebral bodies [9]. Leakage into the spinal canal
47 and nearby nerves may cause serious neurological complications potentially
48 leading to death if the cement enters the blood stream [10].

49 In certain cases, an intraosseous venography can be used, prior to cement
50 injection, to map the venous outlets from the vertebral body [1,3]. In this
51 way the surgeon can reposition the vertebroplasty needle, if injection of the
52 contrast agent shows a large direct venous connection. Although venography
53 can show sites of potential leakage, stagnant contrast agent makes the cement

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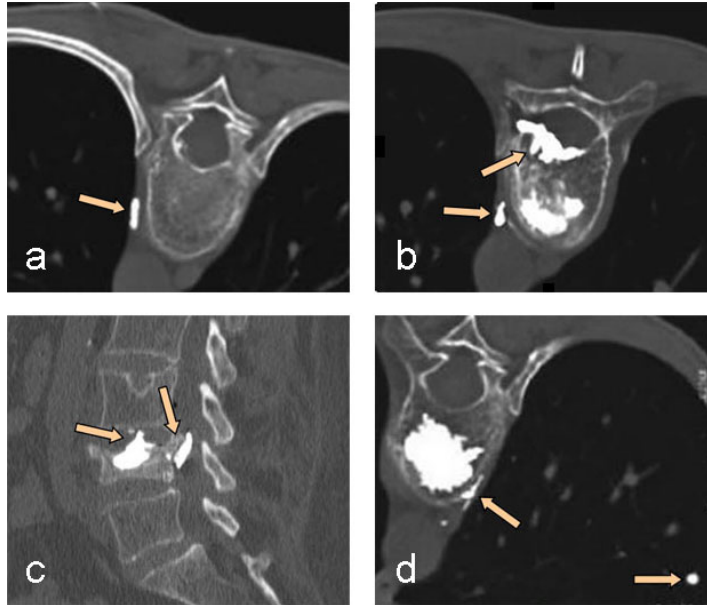


Fig. 2. Leakage of cement during vertebroplasty procedures: (a) Leakage through the vertebral venous system. (b) Leakage through epidural space. (c) Leakage into intervertebral discs. (d) Leakage in surrounding tissues (pulmonary). (images courtesy of The Interventional Radiology website and National Naval Medical Center - WebMedpix)

54 injection more difficult to monitor, and an allergic reaction to contrast agent
 55 remains a potential risk. Furthermore, it has been shown that venography does
 56 not significantly increase the effectiveness or safety of percutaneous vertebro-
 57 plasty [11,12] and opinions about the utility of venography to improve clinical
 58 outcomes or decrease complications during vertebroplasty are controversial.

59 Hence, it is of paramount importance to monitor the evolution of the injected
 60 cement. In this work, we propose a method for automated cement segmen-
 61 tation and tracking on fluoroscopic X-ray images, to help predict eventual
 62 leakage and stop the injection if necessary. The method was tested on a set of
 63 X-ray images obtained during real vertebroplasty procedures performed in the
 64 Radiology Department of University Hospital of Geneva, and was positively
 65 evaluated by physicians.

66 **Methods**

67 Segmentation techniques based on active contours [13], or deformable models,
 68 have been widely used in image processing for different medical applications,
 69 such as computer integrated surgery or computer aided diagnosis [14]. The idea
 70 behind active contours is to extract the boundaries of homogeneous regions
 71 within the image, while keeping the model smooth during deformation. In such

72 models, the initial contour, specified by the user, is evolved to the boundaries
73 of the object by balancing two energy forces. The first force, computed from
74 image data, represents external energy that attracts the curve towards image
75 features, while the second force, defined within the curve, represents the in-
76 ternal energy and affects the smoothness of the curve. Using classical active
77 contours with an edge-stopping function [15] can greatly affect the segmen-
78 tation of the model with diffuse and not well defined edges, especially if the
79 deformation involves splitting or merging of parts. In those cases, when the
80 image topologies are unidentified, segmentation should be performed using
81 an energy minimisation approach, which will be explained in the following
82 subsections.

83 *Mumford-Shah model*

84 One of the most extensively studied mathematical models for medical image
85 segmentation is the variational model of Mumford and Shah [16–18], which de-
86 tects an object via minimization of an energy functional involving a piecewise
87 smooth approximation of the image. The problem can be additionally reduced
88 by restriction of the segmented image to piecewise constant image functions
89 on each segmented region. This simplified case is called the minimal partition
90 problem, and in order to solve it Mumford and Shah propose to minimize the
91 following functional:

$$F^{MS} = \sum_i \lambda_i \int_{\Omega} |u_0(x, y) - c_i|^2 dx dy + \mu |C| \quad (1)$$

92 where C is a finite set of closed, smooth curves in a bounded region $\Omega \in \mathcal{R}^2$,
93 with total length $|C|$, $u_0 : \Omega \rightarrow \mathcal{R}$ represents the observed image and c_i is the
94 approximation to piecewise constant image functions, $c_i = \text{mean}(u_0)$, on each
95 segmented region $\Omega_i \subset \Omega$. λ_i and μ are positive parameters that regulate the
96 balance between energies.

97 *Cement segmentation based on level sets*

98 The energy functional proposed by Mumford and Shah is not easy to solve
99 because of the unknown set of complex contours C and unidentified image
100 topologies. The segmentation algorithm developed in this work is based on the
101 implicit representation of deformable models implemented within the frame-
102 work of level sets, as it is proposed by Chan and Vese [17]. This implicit rep-
103 resentation for evolving curves, introduced by Osher and Sethian [19], allows
104 automatic change of topologies without re-parametrization.

105 Let $\omega \subset \Omega$ be the region inside the curve. Using the level set formulation, the
 106 boundary $C = \partial\omega$ can be modelled as a zero level set of a Lipschitz function
 107 ϕ , defined on the entire image domain Ω as: $C = \partial\omega = \{x \in \Omega : \phi(x) = 0\}$,
 108 $inside(C) = \omega = \{x \in \Omega : \phi(x) > 0\}$ and $outside(C) = \Omega \setminus \omega = \{x \in$
 109 $\Omega : \phi(x) < 0\}$. Having the Heaviside function $H(\phi)$ defined on the whole
 110 image domain Ω , and its corresponding Dirac function $\delta(\phi)$, we can replace
 111 the unknown variable C by the level set function $\phi(x)$ as:

$$F(\phi, c_1, c_2) = \mu \int_{\Omega} \delta(\phi) |\nabla \phi| + \lambda_1 \int_{\Omega} |u_0 - c_1|^2 H(\phi) d\Omega \\ + \lambda_2 \int_{\Omega} |u_0 - c_2|^2 (1 - H(\phi)) d\Omega, \quad (2)$$

112 where the length value $|C| = \int_{\Omega} \delta(\phi) |\nabla \phi|$ is estimated directly from the level
 113 set function [20]. In Figure 3 we show how our segmentation algorithm works
 114 on X-ray scans during cement injection in vertebroplasty (see [21] for more
 115 detailed discussion on model implementation).

116 *Model restriction to vertebral shape*

117 In this work we propose a modification of the functional defined above by
 118 restriction of the level set function to the area of interest, which in our case is
 119 the vertebral body. Introducing a mask term in the functional, the performance
 120 of the model is improved. Segmentation of objects outside of the vertebral body
 121 is thus effectively avoided, by detecting when segmented cement approaches
 122 the borders of the vertebra (Figure 3).

123 Let m be a mask defined as $m(x, y) = 0$ inside the vertebral body and
 124 $m(x, y) = 1$ outside. Our energy functional can be modified as follows:

$$F(\phi, c_1, c_2) = \mu \int_{\Omega} \delta(\phi) |\nabla \phi| + \lambda_1 \int_{\Omega} |u_0 - c_1|^2 H(\phi) d\Omega \\ + \lambda_2 \int_{\Omega} |u_0 - c_2|^2 (1 - H(\phi)) d\Omega + \lambda_3 \int_{\Omega} m H(\phi) d\Omega \quad (3)$$

125 Finally, the boundary is updated by solving a nonlinear, model associated
 126 Euler-Lagrange equation:

$$\frac{\partial \phi}{\partial t} = \mu \delta_0(\phi) \operatorname{div} \left(\frac{\nabla \phi}{|\nabla \phi|} \right) \\ + \delta_0(\phi) \sum_{i=1}^2 (-1)^2 \lambda_i (u_0 - c_i)^2 + \lambda_3 \delta_0(\phi) m = 0 \quad (4)$$

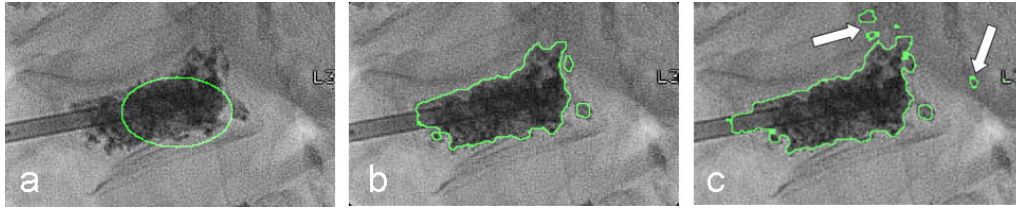


Fig. 3. (a) Original image with the initialization contour. b) Result after 400 iterations. c) Result after 700 iterations, showing that the segmentation incorrectly extends out of the vertebral body.

127 At each iteration step, a level set deformation is computed as a variation of
 128 mean curvature of the level set ϕ , the first term in Eq. (4), and as a piecewise
 129 smooth approximation of the image data inside and outside the contour, the
 130 second term in Eq. (4). The mask term penalizes the evolution of the contour
 131 outside of the region of interest and assures convergence of energy.

132 Results

133 We have applied our method to a set of X-ray images obtained during real ver-
 134 tebroplasty procedures performed in the Department of Radiology and Medi-
 135 cal Computing at the University Hospital of Geneva. The images were obtained
 136 using a Philips V5000 B-plane Integres C-arm and show sagittal scans of the
 137 vertebral body during cement injection. We have tested our method in a total
 138 of 13 scans, corresponding to 4 vertebrae (L2, L3 and L4), at different time
 139 steps during injection (between the 3rd and 8th minute), and depicting a va-
 140 riety of cement shapes. The images were filtered by anisotropic diffusion prior
 141 to segmentation, in order to reduce the noise of the low quality X-ray images
 142 and encourage smoothing in homogeneous regions while preserving edges [22].
 143

144 Initialization was performed by automatically selecting the center, as the mid-
 145 point of the image, and the radius of the initial curve, which in our case was an
 146 ellipse with the axes as 1/3rd of the image size (Figure 3a). The energy param-
 147 eter values are chosen empirically as follows: $\mu = 325$, $\lambda_1 = 0.3$, $\lambda_2 = 0.7$, and
 148 $\lambda_3 = 1000$. The algorithm was implemented in Matlab and the images shown
 149 here are obtained after 150 iterations, which approximately takes 7 seconds
 150 (CPU @1.7GHz, RAM 512MB).

151 We present the results on a third lumbar vertebra with osteoporosis in four
 152 different time points during injection of bone cement (Figure 4). In Figure 4a,
 153 we show the original images, in which we can observe the cannula inserted
 154 in the vertebral body and the injected cement. In Figure 4b we show the
 155 resulting segmentation contour in light green. The bottom row corresponds

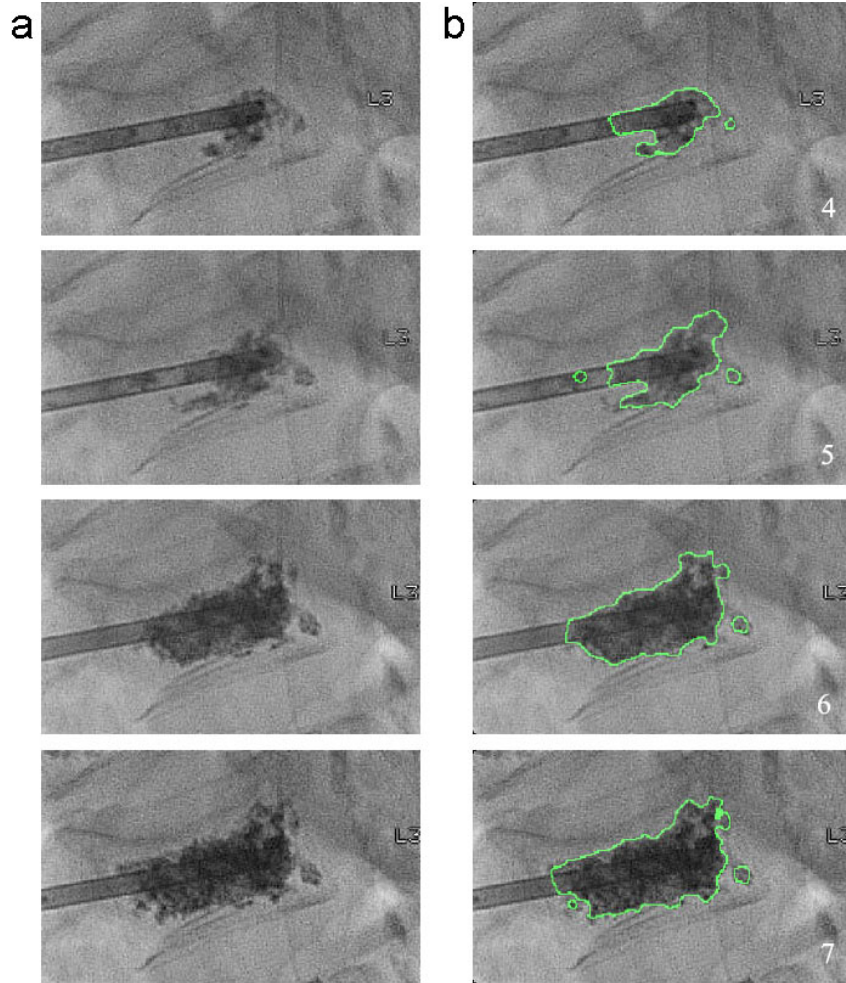


Fig. 4. (a) Image sequence during cement injection in lumbar vertebra L3. (b) Segmentation results.

156 to the same image as in Figure 3b, and it shows that our algorithm performs
 157 much better than the one without mask restriction (compare to Figure 3c).
 158 The convergence of the energy was observed after 500 iterations (25 seconds),
 159 as opposed to the case of the algorithm without mask restriction, which fails to
 160 converge. In all the tested images, no noticeable differences in contour shape
 161 were visible when comparing the result after 500 iterations with that after 150
 162 iterations, which only takes 7 seconds.

163 Our results have been evaluated by the interventional radiologist that per-
 164 formed the operations. The scale, based on clinical usability, was as follows:
 165 1-very bad, 2-bad, 3-satisfying, 4-good and 5-very good. The physician would
 166 evaluate the result as bad even if the overall segmentation was correct, but
 167 even a small particle of the cement was not detected, since this can potentially
 168 lead to leakage and serious complications. Based on this evaluation scale, the
 169 segmented sequence in Figure 4, obtained during cement injection in third
 170 lumbar osteoporotic vertebra, was evaluated as 5, 4, 5 and 5 top-down. We

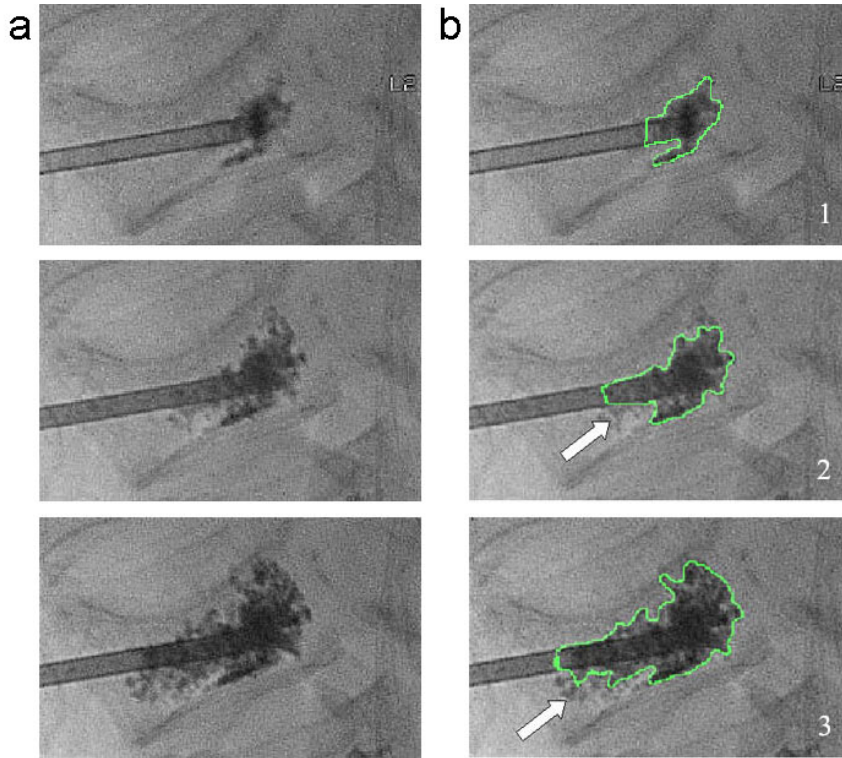


Fig. 5. (a) Image sequence during cement injection in lumbar vertebra L2. (b) Segmentation results.

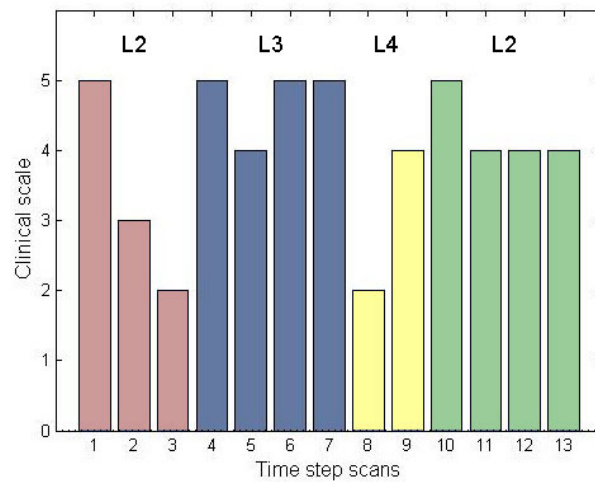


Fig. 6. Evaluation of cement segmentation on 13 X-ray images (time step scans), corresponding to 4 vertebrae (shown in different colors). The scale, based on clinical usability, was: 1-very bad, 2-bad, 3-satisfying, 4-good and 5-very good.

171 show another example of algorithm performance on an osteoporotic second
 172 lumbar vertebra (Figure 5). This sequence was evaluated as 5, 3 and 2, since
 173 a certain amount of cement (indicated by arrows) was not detected. Clinical
 174 evaluation of all 13 cement segmentations is shown in Figure 6.

175 Discussion

176 Leakage of the cement outside of vertebral body may lead to serious postop-
177 erative problems for the treated person and it is of paramount importance
178 to correctly monitor the evolution of injected cement. We have developed a
179 method for automatic cement segmentation during vertebroplasty procedures.
180 The algorithm performs very well, in terms of speed and accuracy, on objects
181 with blurred and not well defined boundaries, as is the case of the cement,
182 where the classical active contours segmentation is not applicable. Validation
183 of the results by the surgeon proves the utility of this technique.

184 One of the strengths of this method is that it can detect several contours in
185 one image, thus tracking cement particles that spread out of the main cement
186 cloud. This is very important for detecting the leakage of cement during the
187 surgery and it can be a signal to the physician to stop the injection. We show
188 as well one of the drawbacks of our algorithm (Figure 5b). In these cases
189 the distribution of cement is more spread out than in other cases and there
190 is a higher gradient close to the cannula edges which affects internal energy
191 and curve evolution. One of the possible solutions for resolving this problem
192 would be to segment the cannula, subtract it from the images and smooth the
193 intensities around cannula.

194 The incorporation of the mask term significantly improves the performance of
195 the algorithm, but it naturally leads to the need for an automatic segmentation
196 of vertebrae. This is a focus of our future research. The method has now
197 been applied to a set of static images extracted from real injection sequences,
198 but further evaluation on real-time dynamic sequences using GPU-enabled
199 technologies is currently in progress.

200 We believe that the development of an automatic warning system for cement
201 leakage will improve the safety of vertebroplasty and minimize potential com-
202 plications.

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