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REVIEW ARTICLE

Image-guided spine surgery: state of the art and future directions

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Abstract Navigation technology is a widely available tool in spine surgery and has become a part of clinical routine in many centers. The issue of where and when navigation technology should be used is still an issue of debate. It is the aim of this study to give an overview on the current knowledge concerning the technical capabilities of image-guided approaches and to discuss possible future directions of research and implementation of this technique. Based on a Medline search total of 1,462 publications published until October 2008 were retrieved. The abstracts were scanned manually for relevance to the topics of navigated spine surgery in the cervical spine, the thoracic spine, the lumbar spine, as well as ventral spine surgery, radiation exposure, tumor surgery and cost-effectivity in navigated spine surgery. Papers not contributing to these subjects were deleted resulting in 276 papers that were included in the analysis. Image-guided approaches have been investigated and partially implemented into clinical routine in virtually any field of spine surgery. However, the data available is mostly limited to small clinical series, case reports or retrospective studies. Only two RCTs and one metaanalysis have been retrieved. Concerning the most popular application of image-guided approaches, pedicle screw insertion, the evidence of clinical benefit in the most critical areas, e.g. the thoracic spine, is still lacking. In many other areas of spine surgery, e.g. ventral spine surgery or tumor surgery, image-guided approaches are still in an experimental stage. The technical development of image-guided techniques has reached a high level as the accuracies that can be achieved technically meet the anatomical demands. However, there is evidence that the interaction between the surgeon (‘human factor’) and the navigation system is a source of inaccuracy. It is concluded that more effort needs to be spend to understand this interaction.

Keywords Spine surgery · Image-guided surgery · Navigation · Computer-aided surgery · Computer-assisted surgery

Introduction

The complex demands of spine surgery patients are complemented by the complex three-dimensional micro and macro anatomy of the spine, which is only incompletely visible to the surgeon during the operation. Due to the sensibility of the neuro-vascular structures surrounding the spine accuracy and surgical approach has always been a key issue in all types of spinal surgery. In ventral spine surgery much effort has been spent to reduce the surgical trauma, resulting in the development of thoracoscopic techniques, retractor systems for lumbar surgery and ventral fusion techniques via dorsal approaches, e.g. PLIF. Especially the accuracy of pedicle screw placement has been lively discussed as misplacement rates of up to 30% in the lumbar spine and up to 55% in the thoracic spine have been reported [30, 107, 110]. Different techniques of pedicle screw placement have been described in the past. However, none of these techniques reduced the incidence

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of malpositioned pedicle screws significantly. New ways to address the issue of accuracy of spinal procedures were explored since powerful computer systems allowing real time image processing and implementation of smart tools using instrument-tracking techniques became available in the early 1990s. The technical problems of integrating image information, spinal anatomy, and the action of surgical instruments in a computer system operating in a real time mode were solved by 1995 resulting in the first report on the successful clinical application of an image guidance system for pedicle screw placement in the lumbar spine [70, 71]. Since than image-guided technologies became a leading topic in all branches of spine surgery. The critical issues in the life cycle of technological innovations in surgery are feasibility, accuracy and efficacy.

Not only in medicine the life cycle of an innovative technique or procedure is characterized by a steep increase of its application after feasibility and accuracy have been proven. With the widespread application of the innovative technique its limitations become obvious resulting in a more critical perception. Parallel to the increased use of the innovative technique scientific evidence becomes available providing the information necessary for more precise indications. With this process the range of indications is usually reduced and sometimes the new technique vanishes from clinical practice. While the feasibility of navigated spine surgery could be proven for virtually any application, the question of accuracy needs a more detailed evaluation. The demands concerning the accuracy of image-guided procedures vary depending on the type of procedure, e.g. ventral or dorsal, pedicle screw placement or deformity surgery, and the level of the spine subjected to surgery. With the more widespread application of image-guided techniques issues like reduction of radiation exposure, the impact of image-guided procedures on operating time and their cost-effectiveness need to be addressed as well. Given the life cycle of technological innovations mentioned above the application of image-guided techniques is currently in the phase of constantly increasing application. The field is highly dynamic and first generation technologies, i.e. CT based navigation, are more and more substituted by recent technological advances like 3D fluoroscopy based techniques. However, thirteen years after the first clinical application of image-guided spine surgery [71] there is a significant body of scientific evidence available. Therefore, it is the aim of this paper to analyze the scientific evidence with respect to the achievements made so far and to identify issues that need to be addressed to ensure a sustainable implementation of image-guided techniques in spine surgery before this innovation enters the consolidation phase of the innovation cycle.

Methods

Literature Database

A literature search was performed in the PubMed database. As search terms 'spine and navigation', 'spine and computer-assisted surgery' were used. A total of 1,462 publications published until October 2008 were retrieved. The abstracts were scanned manually for relevance to the topics of navigated spine surgery in the cervical spine, the thoracic spine, the lumbar spine, as well as ventral spine surgery, radiation exposure, tumor surgery and cost-effectivity in navigated spine surgery. Papers not contributing to these subjects were deleted resulting in 276 papers that were included in the analysis.

Results

Cervical spine

A total of 23 publications on the application of navigation technologies in cervical spine surgery were identified (Table 1). Six case reports [4, 42, 47, 60, 80, 105] reporting 15 patients were identified. The pathologies reported were heterogeneous ranging from one case of basilary impression operated via a transoral approach to a fracture/luxation of the segment C6/7. Within these case reports a total of 55 screws have been implanted with image-guided technology. In five cases a CT matching procedure was applied [4, 42, 47, 60, 105] and in one case a 3D fluoroscopy based approach [80]. Six publications referred to cadaver experiments [11, 12, 36, 38, 85, 86]. 279 screws (64 cadavers) implanted from C1–C7 segments are reported. All navigation modalities are applied, with one study [38] focusing solely on the comparison of two registration techniques (paired point registration versus paired point registration combined with surface matching). Five publications present a retrospective work-up of 224 patients treated for atlantoaxial instability, odontoid fracture, odontoideum mobile with dorsal stabilisation procedures [2, 13, 14, 18, 48]. In all studies CT based registration algorithms were applied. The main target of these studies was the accuracy of navigation procedures (5 studies) beneath the issue of feasibility (2 studies). Finally six studies with a prospective study protocol were identified [39, 40, 43, 50, 58, 96]. None of these studies reaches the level of a randomized controlled trial. A total of 434 navigated screws (61 patients) are reported. Two studies [39, 40] applied a 3D fluoroscopy based approach while the remaining four studies used CT matching algorithms. The information of one study [58] is based on the medline abstract only as the original article is published in Chinese language.

Table 1 Studies relating to the application of navigation technology in the cervical spine

Author (Ref.)	Study design	Vertebral bodies	Pathology	Surgical approach	Image acquisition	Endpoint	*n*		Result/conclusion
							Patients	Screws	
Battaglia et al. [11]	Cadaver	C2	Odontoid fracture	Dorsal	2D Fluoroscopy	Feasibility	22	22	A significant reduction in fluoroscopy time was noted with the computer-based fluoroscopy technique, whereas the surgical time was not found to differ significantly
Reinhold et al. [85]	Cadaver	C3–C7	n/a	Dorsal	2D Fluoroscopy vs. aiming frame	Accuracy	6	60	Aiming frame (AF) technique achieved a significantly smaller number of screws in contact with neurovascular structures compared with the virtual fluoroscopy (VF) (Grade I:15/64.3% AF vs. 13/43.3% VF and Grade III:2/7.1% AF vs. 10/33.3% VF)
Richter et al. [86]	Cadaver	C0–C5	n/a	Dorsal	CT matching (paired point)	Accuracy	13	50[b]/ 26[c]	96% of pedicle drill holes were placed accurately (4 pedicle breaches due to technical problems with DRB), 100% of C1/C2 K-wires were placed accurately
Holly et al. [36]	Cadaver	C1–C7	n/a	Dorsal	3D Fluoroscopy	Accuracy/ feasibility	3	42	41/42 (97.6%) screws were accurately placed. The transarticular atlantoaxial and subaxial lateral mass screws showed no evidence of foramen transversarium, neural foramen, or facet joint violation
Bloch et al. [12]	Cadaver	C1/C2	n/a	Dorsal	CT matching	Accuracy	17	30	All 30 screws were judged on CT scans and by visual inspection to be well positioned, with no perforations or VA injuries
Holly et al. [36]	Cadaver		n/a	Dorsal	CT matching (paired point vs. Surface + paired point)	Accuracy	3	75	Mean registration error paired point + surface matching (0.5 mm) signif. < paired point alone (1.2 mm). Navigational error (1.3 mm vs. 1.4 mm) insignificant
Rajasekaran et al. [79, 80]	Case report	C1–C4	Hangman Fracture	Dorsal	3D Fluoroscopy	Feasibility/ accuracy	1	8	Dorsal instrumentation is feasible and safe
Isenberg [42]	Case report	C1/C2	Atlanto-axial instability	Dorsal	CT matching	Feasibility	1	2	Navigated C1/C2 spondylodesis can be performed safely in the presence of atypic anatomy of the vertebral arteries
Veres et al. [105]	Case report	C1/C2	Basilary Impression	Transoral	CT matching (Fiducials)	Feasibility/ accuracy	3 Pat.		Neuronavigation and fluoroscopy-controlled transoral surgery is feasible. Registration accuracy was 1.5, 2.7, and 3.1 mm respectively

Table 1 continued

Author (Ref.)	Study design	Vertebral bodies	Pathology	Surgical approach	Image acquisition	Endpoint	n		Result/conclusion
							Patients	Screws	
Arand et al. [3, 4]	Case report	C2	Mixed	Dorsal	CT matching	Accuracy	2	4	Possibility for movement should be taken into account when procedures such as CT-based insertion of image-guided screws into patients with fractures of the isthmus C2 are performed
Kamimura et al. [47]	Case report	C2–C7	Model + Clinical study	Dorsal	CT matching	Accuracy	9	36	All 36 pedicle screws appear to have been inserted accurately by postoperative CT examination
Mahadeva et al. [60]	Case report	C6–C7	C6 fracture, C6/7 luxation	Dorsal	CT matching (Fiducials)	Feasibility	1	5	Navigation reduces the risk of complications
Liu et al. [58]	Prospective	–	–	Dorsal	CT matching	Accuray/ feasibility	–	159/ 145^a	Nav.: 155 (97.5%) accurately placed; conv.: 133 (91.7%) accurately placed, no serious complications in either group (Abstract only, article in chinese)
Hott et al. [39, 40]	Prospective	C1–Th1	Mixed	Dorsal	3D Fluoroscopy	Accuracy/ efficacy	30	96	Misplacement rate: 2/96 (2%)
Seichi et al. [95, 96]	Prospective	C1–Th4	Mixed	Dorsal	CT matching	Accuracy	10	51	Rate of cortical perforation of screws was high [5/10 (50%)] when the DRB could not be attached to the relevant vertebra compared with the rate when the DRB was attached to the relevant vertebra [6/37 (16%)]
Ito et al. [43]	Prospective	C2–C6	Mixed	Dorsal	CT matching (surface)	Efficacy	$5/5^a$	$25/27^a$	Misplacement rate (conv.): 15% lat., 7% med. Misplacement rate (nav.): none
Hott et al. [39, 40]	Prospective	C2–C7	Mixed	Dorsal	3D Fluoroscopy	Efficacy	6	25	Misplacementrate: 4%
Kotani et al. [50]	Prospective	C3–C7	Mixed	Dorsal	CT matching (paired point + surface)	Accuracy	$17/180^a$	78/ 669^a	Pedicle perforation nav.: 1.2% and conv.: 6,7% ($p < 0.05$)
Borm et al. [14]	Retrospective	C0–C3	Mixed	Dorsal	CT matching (surface)	Accuracy	14/17		The presented system is technically comfortable and allows safe percutaneous screw application as well as inclusion of computed navigation with high accuracy
Acosta et al. [1, 2]	Retrospective	C1/C2	Atlanto-axial instability	Dorsal	CT matching (paired point?)	Accuracy	20	36	33 (92%) screws were well positioned. Normal C1-C2 alignment was achieved in 17/20 (85%) patients. In 4/20 cases screw implantation was considered impossible but was actually accomplished with surgical navigation

Table 1 continued

Author (Ref.)	Study design	Vertebral bodies	Pathology	Surgical approach	Image acquisition	Endpoint	*n*		Result/conclusion
							Patients	Screws	
Kelleher et al. [48]	Retrospective	C1/C2	Atlanto-axial instability	Dorsal		Accuracy	60	109	Frameless stereotaxy can be applied safely in a clinical setting for transarticular screw fixation
Bolgerand Wigfield [13]	Retrospective	C1/Th12	Mixed	Dorsal	CT matching (paired point)	Feasibility	120	368	Image-guidance systems are useful intraoperative tools that can be applied accurately to spinal surgery
Chibbaro et al. [18]	Retrospective	C2	Type II odontoid fracture	Dorsal	CT matching	Feasibility	10	10	A safe, effective, elegant and fast form of treatment

The studies are stratified into the subgroups case report, cadaver experiments, prospective and retrospective studies. There are no randomized controlled trials investigating the application of navigated approaches to the cervical spine ([a] navigated vs. conventional, [b] only pedicle drill holes were evaluated, [c] only C1/C2 K-wires were evaluated)

Thoracic spine

A total of 24 studies relate to image-guided procedures of the thoracic spine (Table 2). Three case reports [7, 73, 95] referring to the question of feasibility of ventral navigated procedures were identified. Two case reports investigated the application of image-guided strategies for disc surgery in the thoracic spine [7, 73] and one case report featuring three patients describes an image-guided approach to the resection of an ossified posterior longitudinal ligament [95]. All studies apply CT based procedures using a paired point registration algorithm. The levels treated range from Th2 to L2. 7 cadaver studies report on navigated procedures. All studies focus on the accuracy of either dorsal instrumentation [9, 35, 67, 89] with one study referring to extrapedicular screw positioning [51], and two studies referring to ventral procedures namely the accuracy of ventral vertebral body screw placement [103] compared to standard fluoroscopy guided screw positioning. Additionally, one study compares the accuracy of either paired point CT matching or a combined registration algorithm with paired point matching plus surface matching [7]. 5 studies report on clinical investigations with a prospective study protocol. These studies refer to dorsal instrumentation [5, 24, 94, 108] with one study referring to navigated kyphoplasty [74]. The registration algorithms range from 2D fluoroscopy [24, 74] to CT matching algorithms [3, 94] and 3D fluoroscopy [108]. All levels of the thoracic spine from Th1 to Th12 are instrumented. The studies report on a total of 124 patients (while one study [3] only refers to the number of pedicle screws inserted, 6 patients received a kyphoplasty procedure) resulting in the placement of 380 navigated pedicle screws.

Lumbar and thoracolumbar spine

24 studies report on the application of image-guidance techniques in the lumbar and thoracolumbar spine (Table 3). Eight studies report on cadaver experiments. Among these 7 studies focus on the accuracy of navigated pedicle screw placement [16, 23, 31, 37, 84, 91]. While one study [89] reports on the 2D fluoroscopy based insertion of 10 translaminar facet screws with a misplacement rate of 50%. Additionally there is one study [56] comparing the radiation exposure in 2D fluoroscopy based navigation and the conventional approach. Here a statistically significant reduction of both radiation time and radiation dose is reported if screws are inserted with a navigation system. Five studies evaluated the misplacement rate of pedicle screws. Generally there is a tendency toward a higher accuracy if navigated approaches are chosen. However the range of accuracy is very broad and the data do not suggest a superiority of one of the registration algorithms that have

Table 2 Studies relating to the application of navigation technology in the thoracic spine

Author (ref.)	Study design	Vertebral bodies	Pathology	Surgical approach	Image acquisition	Endpoint	n		Result/conclusion
							Patients	Screws	
Assaker et al. [7, 8]	Cadaver	n/a	n/a	Ventral	CT matching (paired point (fiducials) + surface	Accuracy	1	n/a	Registration error: 0.96 mm Navigation error: 1.6 mm
Mirza et al. [67]	Cadaver	Th1–Th10	n/a	Dorsal	2D Fluoroscopy vs. CT matching	Accuracy	20	70/99/74	Perfect screws: fluoro nav. (multi references) 60 (86%); fluoro nav. (single reference): 31 (31%); standard fluoroscopy: 70 (74%); CT based navigation: 51 (69%)
Hart et al. [35]	Cadaver	Th1–Th10	n/a	Dorsal	CT matching (paired points + surface)	Accuracy	8	128	No significant differences in the overall exit rates. Significant difference in exit rates between the middle (47%), compared with the upper (9%) and lower (16%) thoracic regions, respectively ($p < 0.001$)
Sagi et al. [89]	Cadaver	Th1–Th12	n/a	Dorsal	2D Fluoroscopy	Accuracy	4	48/48[a]	Misplacement rate nav. vs. convent. 8%/10%. Average degree of perforation was 1.7/2.4 mm (nav./convent., $p = 0.055$). X-ray time: per screw was 3.6/5.9 s/screw (nav./convent., $p = 0.045$). Insertion time per screw was 2.98/4.35 min/screw ($p = 0007$)
Kothe et al. [51]	Cadaver	Th2–Th8	n/a	Dorsal (extrapedicular)	CT matching (paired points + surface)	Accuracy feasibility	4	54	Mean registration error ± SD: 1.0 ± 0.94 mm for the distance to the medial pedicle wall and 1.9 ± 1.44 mm for the distance to the anterior cortex. Angular measurements: 1.6° ± 1.1° for the transverse screw angle and 2.1° ± 1.6° for the sagittal screw orientation
Austin et al. [9]	Cadaver	Th6, 8, 10, 12	n/a	Dorsal	CT matching (paired point)	Accuracy		8	
Vaccaro et al. [103]	Cadaver	Th9–Th11	n/a	Ventral open	2D Fluoroscopy vs. conv. fluoroscopy vs. 3D fluoroscopy vs. FluoroNav EM	Accuracy	4	16	Standard fluoroscopy: tended to aim anterolaterally by 18°. Image-guidance systems: more accurate in the transverse plane compared with standard fluoroscopy. Significant difference in coronal plane screw angulation (angle of divergence with the superior endplate) between any of the imaging methods
Ohmori et al. [73]	Case report	Th12–L1	Mixed	Ventral	CT matching (paired point)	Feasibility	3	n/a	The tip of the standard probe and the angled rongeur could be monitored on 3D images during surgery, the retropulsed fragments within the spinal canal could be safely and completely removed under computer assistance
Seichi et al. [95, 96]	Case report	Th3–L2	Ossification of the posterior longitudinal ligament	Ventral	CT matching	Feasibility	3	n/a	Mean registration error: 0.5–0.8 mm
Assaker et al. [7, 8]	Case report	Th8–Th9	Calcified disc herniation	Ventral (thoracoscopic)	CT matching (paired point)	Feasibility	1	n/a	Navigation was reliable and a helpful monitoring device to achieve the surgical goals through endoscopic approaches

Table 2 continued

Author (ref.)	Study design	Vertebral bodies	Pathology	Surgical approach	Image acquisition	Endpoint	*n*		Result/conclusion
							Patients	Screws	
Kosmopoulos and Schizas [49]	Meta analysis	Th1–Th12	Mixed	Dorsal	Mixed	Accuracy		717/343[a]	Navigation provides a higher accuracy in the placement of pedicle screws for most subgroups analysed except for the thoracic levels (in vivo and cadaveric populations), where no advantage in the use of navigation was found
Wendl et al. [108]	Prospective	Th1–Th12	Mixed	Dorsal	3D Fluoroscopy	Accuracy	13	70	Misplacement rate: 0.71%, lowest average fluoroscopy time (1.28 ± 0.56 min) with Iso-C3D navigation at a comparable average OR time (103.26 ± 23.3 min)
Schnake et al. [94]	Prospective	Th2–Th12	Mixed	Dorsal	CT matching	Accuracy	85	211/113[a]	Misplacement rate: navigated: 7.5% (1.9% of the navigated screws perforated the pedicle wall by more than 4 mm) conventional: 31.9%
Arand et al. [3, 4]	Prospective	Th3–Th12	n/a	Dorsal	CT matching	Accuracy		45	Misplacement rate: navigated: 20% conventional: 21%
Fritsch et al. [24]	Prospective	Th4–Th12	Mixed	Dorsal	2D Fluoroscopy	Accuracy	20	54	Misplacement rates: medial: 1.8%, lateral 7.4%
Ohnsorge et al. [74]	Prospective	Th7–Th12	Vertebral compression fracture	Kyphoplasty	2D Fluoroscopy	Accuracy	6	n/a	The navigated drilling differed from the ideal trajectory by 1° to max. 4°. Conventional C-arm control led to a divergence of 4° to 8°. Radiation exposure was reduced by 76%, the operating time decreased by 40% if computer assistance was used
Rajasekaran et al. [79, 80]	RCT	Th1–Th12	Deformity	Dorsal	3D Fluoroscopy	Accuracy	17/16[a]	242/236[a]	Misplacement rate: conventional: 23% [non-navigation group: 4.61 ± 1.05 min (range 1.8–6.5)] navigated: 2%e [navigated: 2.37 ± 0.72 min (range 1.16–4.5)]
Johnson et al. [45]	Retrospective	n/a	Thoracoscopic discectomy	Ventral thoracoscopic	CT matching (paired point)	Accuracy	16	n/a	Mean registration error (calculated): 1.7 mm (range 1.4–2.0) Mean navigation errors (intraoperative): 1.2 mm (range 0.8–1.3)
Nottmeier and Crosby [72]	Retrospective	Th1–S1	Mixed	Dorsal	CT matching (paired points + surface)	Registration time	23 segments		Average registration time for a single vertebral segment (paired points and surface matching technique) was 117 s (1 min 57 s). Average accuracy obtained was 0.9 mm. Inaccurate registration occurred in 3/23 (13%) of the segments requiring a second attempt at registration. In 3/23 (13%) of segments, adequate navigation accuracy was maintained on an adjacent vertebral segment. Though associated with a learning curve, image-guidance can be used effectively and efficiently in spinal surgery
Lekovic et al. [54]	Retrospective	Th1–Th12	Mixed	Dorsal	3D Fluoroscopy vs. 2D Fluoroscopy	Accuracy	37	94/183[b]	Rate of unintended perforations is depend on pedicle diameter ($p < 0.0001$). No statistical differences between 2D and 3D fluoro matching related to rate or grade of cortical perforations

Table 2 continued

Author (ref.)	Study design	Vertebral bodies	Pathology	Surgical approach	Image acquisition	Endpoint	*n*		Result/conclusion
							Patients	Screws	
Ebmeier et al. [22]	Retrospective	Th1–Th12	Mixed	Dorsal	CT matching	Accuracy	112	365	Misplacement rate: 6.3% (11.5% with a minimal lateral perforation (<2 mm) of the pedicle wall)
Youkilis et al. [111]	Retrospective	Th1–Th12	Mixed	Dorsal	CT matching (paired points ± surface)	Accuracy	65	266	Reviewed: 224 screws, 19 cortical violations (8.5%). 11(4.9%) Grade II (<2 mm), 8 (3.6%) Grade III (>2 mm). 5 screws (2.2%) were thought to exhibit unintentional, structurally significant violations. Significantly higher rate of cortical perforation in the midthoracic spine (T4–T8, 16.7%; T1–T4, 8.8%; and T9–T12, 5.6%)
Rampersaud et al. [82]	Retrospective	Th2–Th12	Mixed	Dorsal	2D Fluoroscopy	Accuracy	n/a	79	Misplacement rate: thoracic: 31.6% (72% of pedicle breaches were lateral) lumbar: 10.6%
Arand et al. [5]	Retrospective	Th2–Th12	Tumor	Dorsal	CT matching (paired points ± surface)	Accuracy	8	26	Misplacement rate: 14% 3D vs. 2D

The studies are stratified into the subgroups case report, cadaver experiments, prospective and retrospective studies. There is one randomized controlled trial (RCT) investigating the application of navigated approaches to the thoracic spine and one metaanalysis ([a] navigated vs. conventional[b] 3D vs. 2D fluoroscopy)

been applied. Three case reports [2, 17, 90] relating to the feasibility of navigated pedicle screw insertion have been identified. All case reports conclude that image guided pedicle screw insertion in the thoracolumbar spine is clinically feasible using different registration approaches. Two retrospective studies report on the use of image guidance approaches in the lumbar spine [55, 92]. Both studies focus on specific pathologies. One study [92] compares the operating time in navigated procedures and finds a significant reduction of operating time if an image-guided approach is chosen, while the second retrospective study [55] is focused on the application of image-guided surgery in spinal revision procedures in 35 patients (231 pedicle screws). The accuracy rates achieved in this patient population with an altered anatomic situation are comparable to those reported for primary surgery. Twelve studies prospectively investigate image-guided procedures. The main focus of these studies is the accuracy of pedicle screw placement. Most studies relate to the accuracy of pedicle screw position within the pedicle [6, 25, 34, 64–66]. The misplacement rates range between 7 and 14% if the screws were inserted using a navigation system, with a tendency toward a higher misplacement rate in the thoracic spine [6]. One study systematically compares different registration algorithms [6] and describes a slight advantage of CT based registration algorithms over 2D fluoroscopy based navigation. Two studies [15, 46] analyzed the accuracy of screw position based on distance measures of the actual screw position compared to the preplanned screw trajectory. Both studies used CT based registration algorithms. Although the overall accuracy was within a tolerable range (2 mm) [15] there was a wide range especially in the sagital plane with up to 10 mm deviation. Another study relates to the feasibility of CT based navigation for preoperative planning of wedge osteotomy procedures in M. Bechterew patients [87] and reports that preoperative planning and intraoperative navigated osteotomy is feasible and resulted in excellent reconstruction of the sagital profile in all nine patients.

Ventral procedures and disc replacement surgery

Ventral procedures have been mainly reported for the thoracic spine. Two publications report on cadaver experiments [7, 103] focusing on the accuracy of either point identification on the ventral spine [7] or the placement of vertebral body screws. Additionally three case reports on the feasibility of clinical application of navigated ventral approaches have been published [8, 73, 95, 96]. Finally, there is one retrospective series of 16 patients subjected to thoracoscopic discectomy focusing on the accuracy of the procedure [45].There is only one case report on image-guided ventral surgery of the lumbar spine relating to the

Table 3 Studies relating to the application of navigation technology in the thoraco-lumbar spine

Author	Study design	Vertebral bodies	Pathology	Surgical approach	Image acquisition	Endpoint	n		Result/conclusion
							Patients	Screws	
Glossop et al. [31]	Cadaver	n	n/a	Dorsal	CT matching (paired point + surface)	Accuracy	1	8	Average navigational error: 1.2 mm (6°)
Sagi et al. [89]	Cadaver	L1–L5	n/a	Dorsal	2D-fluoroscopy vs. conv. Fluoroscopy vs. anatomic. landmarks	Accuracy			Misplacement rate: 17% anatomic landmarks: 17% conv. Fluoroscopy: 22% 2D-fluoroscopy: 5%
Sasso et al. [91]	Cadaver	L1–L5	n/a	Translaminar facet screws	2D Fluoroscopy	Accuracy	n/a	10	Misplacement rates: 50% Grade I breaches (<1/2 the screw through lamina) 50% Grade 0 screw placements (screw contained completely within the lamina)
Foley et al. [23]	Cadaver	L1–S1	n/a	Dorsal	2D Fluoroscopy	Accuracy	n/a	12	Mean probe tip error: 0.97 ± 0.40 mm Mean trajectory angle difference (virtual and fluoroscopically displayed probes): 2.7° ± 0.6°
Carl et al. [16]	Cadaver/ model	L1–L5	n/a	Dorsal	CT matching (surface)	Accuracy	n/a	44	Misplacement rate: 0%
Sakai et al. [90]	Case report	L4–S1	n/a	Dorsal	CT-fluoro matching	Accuracy	1	n/a	Misplacement rate: 0% (Abstract only, article in Japanese)
Acosta et al. [1, 2]	Case report	L4–L5	Deg. Spondylolisthesis	Dorsal	3D Fluoroscopy	Accuracy, feasibility	1	4	3D fluoroscopy navigated percutaneous pedicle screw placement is feasible
Mac Millan [59]	Prospective	L5–S1	n/a	Transsacral	CT matching (fiducials)	Accuracy, feasibility	17	n/a	Percutaneous fusion of the lumbosacral spine appears safe and provides excellent clinical results with a minimal amount of associated tissue trauma
Sasso and Garrido [92]	Retrospective	L5–S1	Isthmic Spondylolisthesis	Dorsal	2D Fluoro	Operating time	59/46[a]	n/a	Image-guided surgery requires significantly less operating time compared to the conventional approach
Lim et al. [55]	Retrospective	L1–S1	Revision surgery	Dorsal	CT matching (paired point + surface)	Accuracy	35	231	Misplacement rate: 4.8% Mean registration error: 0.65 mm (range 0.4–0.9 mm)
Holly and Foley [37]	Cadaver	Th1–L5	n/a	Dorsal	3D Fluoro	Accuracy/ feasibility	3	102 (64/30)[d]	Misplacement rate: 5.3% (thoracic screws: 8%, lumbar screws: 0%)
Reichle et al. [84]	Cadaver	Th12–L4	n/a	Dorsal	CT matching vs. 2D Fluoroscopy	Accuracy	n/a	26/24/25	Misplacement rates: CT navi: 19.23% 2D-Fluoro: 58.33% Convent.: 28.0%
Linhardt et al. [56]	Cadaver	Th8–L5	n/a	Dorsal	2D Fluoro vs. conv.	Radiation exposure	10	20/20[a]	0.041 mSv/2screws (conv.), 0.029 mSv/2 screws (nav.). Fluoroscopy time: 34 s (conv.), 25 s (nav.), (radiation dose $p = 0.00044$, fluoroscopy time $p = 0.00039$)

Table 3 continued

Author	Study design	Vertebral bodies	Pathology	Surgical approach	Image acquisition	Endpoint	*n*		Result/conclusion
							Patients	Screws	
Chappell et al. [17]	Case report	Th12–L1	Potts disease	Ventral open	CT matching (paired point)	Feasibility	1	n/a	The procedure is feasible. Registration accuracy: 0.7 mm
Kamimura et al. [46]	Model prospec.	n/a	Mixed	Dorsal	CT matching (paired point ± surface)	Accuracy	29/44′	169/88″	Mean navigational error: 1.78 ± 0.81 mm, mean angular deviation: 2.28° ± 1.92°. 51 thoracic screws and 118 lumbar screws. All screws correctly passed through the pedicles
Ruf et al. [87]	Prospective		Morbus bechterew	Dorsal (wedge osteotomy)	CT matching (paired point/CT fluoro matching)	Feasibility	9	n/a	Precise preoperative planning and correction osteotomy exactly according to this planning allow for an excellent correction of the sagittal profile even in severe ankylosing spondylitis
Fu et al. [25]	Prospective	Th9–S1	Mixed	Dorsal	2D Fluoroscopy	Accuracy, feasibility	12	66	Misplacement rate: 8% (5 screws showed structural violations: 4 (medial), 1 (lateral). Accuracy was higher in the sagittal plane than in the axial plain. Average time for registration and screw insertion (1 segment/4 screws) was 48 (24–90) min
Carl et al. [15]	Prospective	n/a	Mixed	Dorsal	CT matching (paired point)	Accuracy	11	32	Overall accuracy: ±2 mm (11 patients); Errors in three planes (mm): coronal 1.1 (0.3–3.0), transverse 1.9 (0.1–4.3), sagittal 5.2 (2.7–10.0)
Merloz et al. [66]			n/a	Dorsal	2D Fluoroscopy	Accuracy	26/26[a]	140/138[a]	Cortex penetration rate: Navigated: 5% Conventional: 13%
Grutzner et al. [34]	Prospective	n/a	Trauma	Dorsal	3D Fluoroscopy	Accuracy	61	302	Misplacement rate: 1.7% (misplacements of ≥2 mm) Average fluoroscopy time: 1.28 ± 0.56 min
Merloz et al. [64, 65]	Prospective	Th10–L5	Mixed	Dorsal	CT matching	Accuracy	26/26[a]	52/52[a]	Misplacement rate: navigated: 8% conventional: 42%
Arand et al. [6]	Prospective	Th2–L4	n/a	Dorsal	CT matching (paired point) vs. 2D Fluoroscopy	Accuracy	n/a	82(53/29)/ 74(38/36)[c]	Misplacement rate: CT navigated: thoracic 13%, lumbar 7% 2D fluoroscopy: thoracic 26%, lumbar 11%
Schaeren et al. [93]	Prospective	Th6–S1	Mixed	Dorsal	CT matching vs. conv. Fluoro	Radiation exposure	20	n/a	Mean effective dose for the CT model: 7.27 mSv, fluoroscopic dose: 0.48 mSv (factor 15)

Table 3 continued

Author	Study design	Vertebral bodies	Pathology	Surgical approach	Image acquisition	Endpoint	*n*		Result/conclusion
							Patients	Screws	
Laine et al. [53]	RCT	Th8–S1	Mixed	Dorsal	CT matching (surface)	Accuracy	91	219/277[a]	Misplacement rates: Conventional: 13.4% (Pedicle perforations >4 mm: 1.4%, mean operating time: 160 ± 73 min). Navigated: 4.6% (Pedicle perforations >4 mm: 0%, mean operating time: 179 ± 74 min (nav.) (NS)

The studies are stratified into the subgroups case report, cadaver experiments, prospective and retrospective studies. There is one randomized controlled trial (RCT) investigating the application of navigated approaches to the thoracic spine. [[a] navigated vs. conventional, [b] 3D vs. 2D fluoroscopy, patients/vertebral body models, pedicle screws inserted in patients/pedicle screws inserted into models, [c] CT matching (torac./lumb.)/2D fluoroscopy (thorac./lumb.), [d] thoracic screws/lumbar screws]

feasibility of image-guided vertebrectomy in a patient suffering from Pott's disease [17].Two groups reported image-guided approaches to lumbar disc replacement. One cadaver study investigating the accuracy of navigated versus conventional imaging [99] and a clinical series of 20 patients operated either with or without image-guided assistance [62].

Tumor surgery

Six publications report on image-guided tumor surgery. Two papers report on a total of 5 patients with benign tumors of the subaxial and cervicothoracic spine [68, 106]. Rajasekaran et al. [78] report a series of four patients treated for osteoid osteoma in the cervical, thoracic and lumbar spine. Van Royen et al. report on the extirpation of osteoid osteoma in the thoracic and lumbar spine using an image-guided high speed drill in five patients [104]. Image-guided surgery for dorsal instrumentation in 8 patients with metastatic disease of the thoracic spine was analyzed by Arand et al. [5] and Gebhard et al. [26] who reports on 12 patients. Both studies focus on the issues of feasibility and accuracy.

Radiation exposure

Six papers refer to the issue of radiation exposure in image-guided spine surgery. All papers published so far analyze the impact of image-guided techniques on the radiation exposure in pedicle screw placement. The impact of image-guided approaches in other areas of spine surgery has not been studied until now. Most recently Gebhard et al. [28] report on a prospective clinical study comparing different types of image-guided techniques versus the conventional approach to pedicle screw placement in a group of 38 patients. Linhardt et al. [56] compare the radiation dose and fluoroscopy time of fluoroscopic computer-assisted pedicle screw implantation versus the conventional approach in a cadaver experiment and found a significantly lower radiation dose and fluoroscopy time with fluoroscopic computer-assisted pedicle screw implantation compared with the conventional technique. In a combined clinical and experimental study Gebhard et al. [27] compared the radiation dose in image-guided and conventional spine surgery in 28 patients and found a significantly reduced radiation dose if image-guided approaches were applied both experimentally as well as clinically. Schaeren et al. [93] analyzed the overall radiation doses applied in patients that were operated using CT based image-guidance technique. Compared to the conventional technique CT based navigation results in higher radiation exposure if the preoperative CT scan is taken into account as well. A similar observation was reported by Slomczykowski et al. [98], however, they found that with an optimized sequential CT scan protocol the effective dose was 40% lower than in non-optimized sequential scanning.

Cost-effectiveness

Currently there are no studies published concerning the cost effectiveness of image-guided procedures in spine surgery.

Discussion

The amount of scientific literature concerning the clinical application of image-guided techniques in spine surgery is constantly growing. Meanwhile sufficient data is available to address the key questions relating to the clinical application of image guidance techniques in spine surgery, namely: ‘Can we navigate?’, ‘Shall we navigate?’, ‘Do we have to navigate?’ and ‘What’s next?’. As image guidance technology is constantly evolving and the applications in spine surgery are in very different stages of development, ranging from experimental evaluation, like ventral procedures, to almost routine application like pedicle screw placement, these questions cannot be answered in general but need to be discussed separately.

Registration techniques

The registration process of virtual reality, based either on fluoro-images, MRI scans or computed tomography images, to physical reality is the cornerstone of any navigation system. In the past different registration algorithms have been developed. These algorithms differ in terms of the type of image data used by the navigation system, i.e. either preoperatively acquired CT images or intraoperatively acquired fluoroscopy images, and the way virtual and physical reality is matched, i.e. registered. Generally, registration procedures based on active intraoperative registration and automated registration procedures can be differentiated. Intraoperative registration relies on the identification of anatomical landmarks, surface contours or preoperatively implanted fiducial markers. In classical pair-point registration at least three points not located on a straight line are to be identified in the surgical situs and in the data set. To provide an optimal spatial resolution these points need to have the largest possible distance from each other and need to be located on different levels. The surface registration algorithm is based on a three dimensional model which is calculated from preoperative CT data. Intraoperatively several points of the bony surface are identified with a tracked pointer. The computer then matches these clouds of points to a 3D reconstruction of the CT data. Both registration algorithms can be used simultaneously as well to increase the accuracy of the matching process. Holly et al. [36] systematically analyzed whether the combination of both registration algorithms yields synergistic effects and found that paired point matching in conjunction with surface matching results in a lower mean registration error than paired point matching alone. Holly et al. conclude that paired point registration alone might be sufficient for routine cases provided that easily discernable landmarks are meticulously chosen. Fluoroscopy based registration is an alternative approach to CT based registration. Fluoroscopic images, either 2D or 3D, are acquired intraoperatively. The registration procedure is automated, since the fluoroscope is equipped with traceable markers Additionally a reference base is attached to the patient (usually to a posterior process in the direct vicinity of the vertebral body to be operated). The susceptibility of reference arrays to accidental manipulation during the operation has been an issue of concern, as any change in position of a reference base during the operation will inadvertently result in a navigational error. This problem has been investigated experimentally by Citak et al. [19]. They used a femur model and the reference array was fixed with a single Schanz screw, thus the results cannot be directly transferred to the spine. However, relevant loosening occurred after only 2–3 cycles within a minimum force of 2 Nm applied. Thus care must be taken to avoid any accidental displacement of the reference arrays. In 2D-fluoroscopy based navigation conventional fluoroscopic images in two planes are acquired. The major disadvantage of 2D-fluoroscopy based navigation is the limited quality of fluoroscopic images in the thoracic spine as well as in obese and/or osteoporotic patients [40]. 3D-fluoroscopy based navigation uses a set of intraoperatively acquired rotational images. Usually a 270° scan with 256 images is done. The automated registration process with reference arrays fixed to the patient and the fluoroscope is identical to 2D-fluoroscopy based navigation.

From the methodological point of view there is no clear evidence as to which registration technique is superior. In a experimental comparison of CT based and 3D fluoroscopy based registration techniques, Geerling et al. [29] found no statistical difference between both modalities, however there was a tendency toward a higher accuracy if the 3D fluoroscopy based registration algorithm was applied. Intraoperative 3D fluoroscopy obviates the need for additional preoperative CT imaging, additionally the image data are acquired in the final position of the patient, e.g. prone, such that less artifacts due to different positions during imaging and intraoperatively are to be expected.

However, 3D fluoroscopy is also susceptible to systematic errors that need to be taken into account. Quinones-Hinojosa et al. [77] performed serial measurements of accuracy at different distances from the DRB and at different time points during the operation in lumbar surgery. They found an increasing inaccuracy with increasing distance between the DRB and the vertebral body actually being operated on, and increasing duration of the surgery. An inaccuracy of more than 3 mm in 9% of the cases at a distance of three levels below the level of DRB fixation and an inaccuracy of more than 3 mm in 17% of the cases 60 min after beginning of the procedure was found (although the inaccuracy had no tendency to further increase with a longer duration of the surgical procedure).

Remains the question how much accuracy is needed for biomechanically reliable pedicle screw implantation. Although there is an abundant number of classification systems for pedicle screw placement [49] there is no systematic investigation concerning the biomechanical effect of different degrees of pedicle screw misplacement. Additionally, the automated nature of 3D fluoroscopy based registration offers the advantage of being less time consuming and thus easier to integrate into the intra operative workflow, as no iterative interaction with navigation system is necessary. With respect to the trend toward a reduction of the invasiveness of surgical procedures 3D fluoroscopy is the only registration technique that supports minimally invasive approaches as the DRB can be clamped to a spinous process via a small incision of 1 cm length.

Generally it can be expected that 3D-fluoroscopy based image acquisition and registration will substitute CT based registration algorithms because of the less demanding logistics and the reduced radiation exposure [56] of the patient. Another problem, at least if multi-segmental instrumentation is considered, is the limited scan volume of 3D fluoroscopes might be overcome with the advent of flat-panel technology [97].The technical development of registration procedures has reached a point where further groundbreaking developments are not to be expected. The work of Holly et al. [36] clearly demonstrates that the overall accuracy of a navigated procedure is only partially influenced by the registration algorithm, as they found a significant difference between the registration error and the actual navigation error in their experimental study comparing different registration techniques. Most interestingly the navigational error, being a result of the interaction between the technology and the human factor, remained the same independent of the accuracy of the registration algorithm.

Pedicle screw placement

The methodological quality of the evidence available on pedicle screw positioning using image guidance techniques is rather sparse. Since 1995 only two randomized controlled trials [53, 79] and one meta-analysis [49] have been published. The remaining body of literature consists of case reports and smaller series with retrospective or prospective study design. This may be explained by the dynamical evolution of new and/or better technologies in the field of image-guided surgery. Thus new technologies became available and were applied clinically within a short period of time. Consequently the pace of technological innovation obviates a thorough evaluation, e.g. randomized controlled trials, of last generations' technologies. The meta-analysis presented by Kosmopoulos and Schizas [49] generally confirms the impression suggested by the literature that the use of image guidance techniques improves the accuracy of pedicle screw placement in spinal surgery. The major shortcoming of this study is that there is no subgroup analysis with respect to the navigation techniques that have been applied. The impact of the navigation technique on the outcome in terms of accuracy of pedicle screw placement needs to be discussed separately with respect to the level of the spine being operated on.

Cervical spine

The evidence available is very heterogeneous. According to the historical development of image-guided spine surgery the majority of studies relates to CT based navigation. The overall accuracy is very good with a maximum displacement rate of 8% reported by Acosta et al. [1], compared to 22% [43] of misplaced screws if a conventional technique was applied. Compared to the thoracic and the lumbar spine the anatomy of the cervical spine is more complex due to the unique proximity of neural and vascular structures. Morphometric studies have shown a relevant degree of anatomic variability especially in the C1 and C2 vertebrae. Paramore et al. [75] reviewed a population of 94 patients and found that in 18–23% of the patients posterior C1-2 transarticular screw fixation may not be feasible due to anatomic restraints. While the impossibility to safely place a screw should be anticipated preoperatively there appears to be a relevant number of cases where the individual anatomy reduces the number of possible screw trajectories to a minimum, necessitating a high accuracy of the screw placement process. Acosta et al. [1] report that in their series 8/33 (24%) screws could not have been safely placed without intraoperative image guidance. Thus, image guidance techniques might not only be a feasible but also a necessary adjunct for instrumentation of the cervical spine. However, given these spatial restraints of cervical vertebrae, the crucial step of any image guided surgical procedure, i.e. the registration process, has to be highly accurate. With respect to the cervical spine only Holly et al. [36] have systematically analyzed different registration algorithms for CT based image-guided surgery. They found a mean registration error of 0.5 mm if paired point and surface matching were combined, while paired point matching alone resulted in a mean registration error of 1.2 mm. Interestingly the actual navigational error of both registration protocols differed only slightly (1.3 vs. 1.4 mm). Concerning the more recent developments of 3D-fluoroscopy based image guidance no data referring to the accuracy of the registration process have been published so far. However, in the cervical spine the anatomical necessities and the technical capabilities are very close to one another. Thus a thorough understanding and handling of navigation technology is the prerequisite for its successful and safe application. In this context special attention has to be paid to the problem of intra-operative motion, relative or absolute, of the spinal segments being operated on as described by Arand et al. [4]. But also technical pitfalls have to be accounted for as Seichi et al. [96] report on high misplacement rates (50%) if the DRB could not be attached to the relevant vertebra. Generally the application of 3D image-guidance techniques in the cervical spine appears to increase the accuracy with misplacement rates ranging from 2% [40] to 40% [39]. The major advantage of intra-operative image acquisition is that the aforementioned problems of the registration process due to motion artifacts are avoided as the images are acquired after the patient has been positioned for surgery.

Thoracic spine

Like the cervical spine the thoracic spine is a high-risk area for surgery. Even minor medial pedicle breaches might result in clinically relevant symptoms. Generally, in the thoracic spine lateral pedicle breaches appear to be more common [22, 24, 82] than medial pedicle violation. Alternatively an extrapedicular approach to screw placement might be chosen. Concerning the biomechanical stability White et al. [109] found that transpedicular screws display a higher mechanical stability than extrapedicular screws although the differences were not overwhelming yet statistically significant. They conclude that extrapedicular screws are a biomechanically sound alternative to transpedicular screws only in case where the anatomy precludes a safe placement using the traditional transpedicular approach. Using image guidance techniques for pedicle screw placement misplacement rates as low as 1.8% (medial pedicle breach) and 7.4% (lateral pedicle breach) in a clinical study [24] or even no pedicle violations in a cadaver study [51] have been reported. Concerning the question which navigation technology should be applied Lekovic et al. [54] found comparable results for either 2D- or 3D-fluoroscopy based registration procedures. However, given the results of the meta analysis conducted by Kosmopoulos and Schizas [49] the application of image guidance technology does not improve the overall accuracy of pedicle screw implantation in the thoracic spine.

Lumbar spine and thoraco-lumbar junction

Concerning the incidence of pedicle screw misplacements in the lumbar spine and the thoraco-lumbar junction image-guided procedures appear superior to the conventional approach. In a cadaver study Sagi et al. [89] compared anatomical landmarks, 2D- and conventional fluoroscopy-guided techniques. They report that the misplacement rate of pedicle screws is lowest (5%) in the 2D-fluoroscopy group. Comparable observations are reported by Fu et al. and others [25, 66] with 8% of misplaced screws. Here there was a tendency toward medial displacement of the pedicle screws. With respect to the forgiving anatomical situation in the lower lumbar spine concerning the risk of neurological complications this accuracy is acceptable to recommend the clinical application of image-guided procedures in the lumbar spine. However, there is no data concerning the biomechanical tolerance of pedicle screws toward malpositioning. In the majority of studies CT based registration procedures have been applied. The accuracy of CT based registration algorithms appears comparable to the technically less demanding 2D-fluoroscopy based navigation procedures. Carl et al. [15] report an overall accuracy of ±2 mm using a paired point CT based registration algorithm. Foley et al. [23] found a probe tip error of 0.97 ± 0.40 mm in a cadaver study. In their combined experimental and clinical analysis Kamimura et al. [46] found comparable deviations of navigated pedicle screw placement. However, all pedicle screws (51 thoracic screws and 118 lumbar screws) were placed within the pedicle. Given this observation the accuracies achieved with either 2D fluoroscopic registration or CT based registration provide a satisfactory safety margin for navigated pedicle screw instrumentation in the lumbar spine.

Ventral spine surgery

The requirements of ventral procedures concerning the accuracy are comparable to the navigated placement of pedicle screws. However, due to the even more restricted access to the ventral spine, especially if minimal invasive strategies are applied, the implementation of image-guided techniques faces several technical challenges. Assaker et al. [7] were the first to describe a ventral image-guided procedure in a thoracic spine cadaver model in 2001. In the same year they also described the clinical application in a case of a calcified thoracic disc herniation that was removed thoracoscopically [8]. Chappell et al. [17] report on a case of open reconstruction in a case of Pott's disease at the thoracolumbar junction and Seichi et al. [95] used an image-guided approach to resect an ossified posterior longitudinal ligament in the thoracic spine in three patients. Ohmori et al. [73] reported the application of an image-guided approach to ventral decompression and corporectomy in three cases of thoracolumbar vertebral collapse. All cases reported so far used CT based registration procedures with registration errors ranging from 0.5 to 0.96 mm. Thus the accuracies achieved in the anatomically difficult environment with few anatomically distinct landmarks are remarkably good. However, here too the preoperative acquisition of CT data and postural change of the patient on the operating table might introduce systematic inaccuracies and subject the patient to additional radiation exposure. Maier et al. [61] described a ventral procedure based on 2D-fluoroscopy image acquisition. They analyzed the accuracy with which a predefined volume of the vertebral body could be resected using an image-guided approach and found a mean error between planned and actual resection volume of 0.98 mm which is comparable to the results described for CT based image-guided procedures. This approach meets the demands for an easy to perform on table image acquisition, a low radiation exposure for the patient and the operating room personnel and accuracy in the submillimeter range.

Apart from the mode of image registration, i.e. 2D fluoroscopy, 3D fluoroscopy or computed tomography, the optimal fixation of the DRB to the spine remains an unsolved problem. Among the options to be chosen from is fixation to the iliac crest, to a spinous process or transthoracically on a long stylus directly to a vertebral body. Any of these approaches carries its own risks and problems, e.g. the problem of motion artifacts with the DRB fixed to the iliac crest, the problem of limited visibility for the navigation system if fixed to a spinous process or the problem of a disturbing object in the thoracic cavity if the DRB is fixed to a vertebral body. Thoranaghatte et al. [101, 102] present a possible solution to this problem. They suggest using the endoscope as the tracking device by what they call a hybrid navigation system. A fiducial marker is fixed to the spine and the position and orientation of the marker in space is determined by means of image analysis. This information is then correlated to the position of the endoscope, which is equipped with a DRB. This technique, which is still under evaluation, could obviate the need for a DRB, which is fixed to the bone separately. So far there are no reports on the application of 3D fluoroscopy based imaging techniques in ventral spine surgery. In trauma cases where dorsal instrumentation is usually performed prior to ventral stabilization it can be expected that 3D fluoroscopy cannot be implemented successfully unless intraoperative 3D fluoroscopy provides a scan quality that is comparable to conventional computed tomography. However, so far this problem has not been addressed in experimental or clinical studies.

Disc replacement surgery

Artificial discs are implanted in increasing numbers in the cervical and the lumbar spine. Reliable functioning of the implant depends on the optimal positioning in the sagittal and the frontal plane. Additionally there is a very small margin for rotational misplacement. In a clinical series of 100 cases McAfee et al. [63] report that 17% of the cases showed a suboptimal (3–5 mm deviation) or bad (>5 mm deviation) position of the implants. The clinical follow up of this patient population showed that revision surgery was necessary in those cases with suboptimal or bad implant position. If the implant is placed to far ventrally subluxation will eventually occur. Technical pitfalls, namely the parallax effect of image intensifiers [76], contribute the difficulties in finding the correct position of the implant. In a cadaver study Smith et al. [99] compared standard fluoroscopy-guided implantation of an artificial disc with 2D and 3D fluoroscopy based navigation. Concerning the correct midline centering of the implant 3D fluoroscopy-assisted implantation was superior to 2D fluoroscopy or standard fluoroscopy (mean 4.18, 10.25 and 10.07%, respectively). With respect to the rotational alignment of the implant the performance of 2D fluoroscopy and 3D fluoroscopy was comparable with an angle of rotation relative to the posterior vertebral body axis of 87.67° (SD 1.53) and 86.67° (SD 1.53), respectively, while standard fluoroscopy resulted in a angle of 82° (SD 5.20). However, these results did not reach statistical significance. In a clinical study with 6 disc arthroplasties performed with and 14 disc arthroplasties performed without image-guidance Marshman et al. [62] report on significantly better results of the image-guided approach with respect to the parameters off-center malplacement, axial rotational malplacement and coronal tilt, while the operating time did not differ between the groups. These positive results led the authors to the conclusion that image guidance should be considered for routine use in artificial disc arthroplasty. The feasibility of image-guided technologies in disc arthroplasty has been proven. However, there is no strong data defining the degree of accuracy that is necessary in disc arthroplasty, although the observation of McAfee et al. [63] (XY) that artificial discs with a degree of malplacement that might have been avoided by application of an image-guided approach resulted in revision surgery strongly suggests a benefit of image-guided implantation.

Tumor surgery

Oncologic spinal procedures are among the most complex procedures in spine surgery. Generally primary tumors of the spine have to be differentiated from metastatic spinal disease. If the tumor has invaded the surrounding tissues of the spine resection according to oncologic criteria becomes either extremely complex or impossible. Additionally oncologic procedures often require a simultaneous anterior and posterior approach. If oncologic resection is indicated image-guided techniques are confronted with technical challenges that have not yet been resolved. The key problem is that for successful navigation both soft tissues and osseous structures need to be registered simultaneously. As long as soft tissues are contained within a rigid anatomic structure like the skull secure registration is feasible, e.g. in navigated brain surgery. In spinal tumor surgery this prerequisite is not met. A possible solution to this problem is the development of smart tools (navigated tools) that interact with soft tissues only in the direct vicinity of the dissection without changing the spatial distribution of the surrounding tissue. Otherwise a mismatch between anatomic and virtual reality would result in an intolerable navigational error. In metastatic spinal disease surgical therapy is usually palliative, i.e. prevention or alleviation of spinal cord compression and support or restoration of spinal stability. In cases of biomechanically relevant instability usually a dorsal instrumentation is performed. Gebhard et al. were among the first to report on the application of image-guided pedicle screw placement in tumor cases [26]. While the accuracy of pedicle screw placement met the results known from non tumor cases, accurate registration turned out to be a problem in 6 screws where the tumor destabilized the vertebral body to such an extend that a safe fixation of the DRB was not possible. In these cases the DRB was fixed to a more distal vertebral body. Thus image guided approaches should only be chosen in those cases where the DRB can be attached close to the vertebra being operated as too far away fixation might result in significant registration errors [77].The rational in the surgical therapy of benign spine tumors is to completely remove the tumor and to keep the collateral damage as small as possible. However, often a wide resection is performed due to difficulties to exactly localize the tumor in the surgical situs. This might result in destabilisation of the spine necessitating an additional fusion procedure.

Navigated surgery of primary tumors of the spine has been reported in a cumulative case report by Rajasekaran et al. [78]. Here, image-guided technology was used to locate and percutaneously resect the nidus of an osteoid osteoma. Rajasekaran et al. demonstrated that with the high accuracy achieved with an image guidance system the nidus could be precisely targeted thus avoiding a destabilizing wide resection. The efficacy of this procedure was confirmed by van Royen et al. [104] who controlled the complete removal of a radionuclide enhanced osteoid-osteoma after 3D image-guided extirpation. Generally, image-guided approaches offer the advantage to target the tumor more precisely, thereby reducing the collateral damage and the risk of consecutive spinal instability, but it has to be realized that there is currently no systematic data available on the application of navigated approaches in this patient population.

Radiation exposure

Compared to other procedures in musculoskeletal surgery spine surgery is radiation intensive [100]. For example the amount of radiation exposure needed to adequately visualize the lumbar spine in lateral projection is significantly greater than in other musculoskeletal sites [57]. As the biological effects of repeated radiation are unknown it should be an ultimate goal to reduce the occupational exposure of the operating room personnel and especially the primary surgeon. In a cadaver experiment with fluoroscopically assisted thoracolumbar pedicle screw placement Rampersaud et al. [81] found that radiation exposure is up to 10–12 times greater than in other, nonspinal musculoskeletal procedures.In a comparative study Gebhard et al. [28] showed that image-guided approaches generally reduce the radiation exposure of the operating room personnel independent of the registration mode, i.e. CT matching, 2D- or 3D-fluoro matching, compared to standard fluoroscopy-assisted surgery. The best results were found for 3D-fluoroscopically assisted approaches with a tenfold reduction of radiation exposure compared to standard fluoroscopy-assisted procedures. A comparable result was achieved by Linhardt et al. [56] when comparing 2D-fluoroscopically assisted pedicle screw instrumentation with the conventional fluoroscopic approach to pedicle screw insertion. If CT based image-guidance is compared to standard fluoroscopy based approaches there is a clear advantage for standard fluoroscopy as the preoperative CT scan significantly contributes to the overall radiation exposure of the patient. Schaeren et al. [93] documented a 15-times lower radiation dose for fluoroscopically controlled pedicle screw insertion compared to the CT guided approach. They concluded that image-guided pedicle screw instrumentation should be limited to carefully chosen indications. However, the occupational radiation exposure of the operating room personnel is significantly reduced by CT based image-guidance compared to standard approaches. Thus image-guided surgery significantly reduces the occupational radiation exposure of the operating room personnel. The overall radiation exposure of the patient is most significantly reduced if intraoperative 3D fluoroscopy based image-guidance systems are applied. In terms of radiation exposure the constant and defined amount of radiation necessary to perform a 3D scan is a major advantage of 3D fluoroscopy based image-guidance, while in standard fluoroscopy the amount of radiation depends to a relevant degree from exogenous factors like the surgeon, the bone quality etc. [27].

Future directions

The state of the art of image-guided spine surgery is very heterogeneous in the different branches of spine surgery. The technical aspects of image-guided spine surgery for the most common applications, i.e. pedicle screw placement, are sorted out, and the clinical benefit in terms of increased accuracy and reduced exposure to ionizing radiation has been clearly proven for cervical and lumbar instrumentation. Other applications like ventral approaches to the spine, spinal tumor surgery or disc replacement surgery are still being developed. However, the ultimate consequence of the implementation of new technologies generally means that traditional approaches vanish from daily routine and finally, when the cycle of innovation is closed, the knowledge about these techniques is lost. While this development is the key process of technical innovation in many areas, in surgery the loss of technical knowledge and practice might put patients at risk, because traditional procedures often serve as rescue procedures. Today navigated spine surgery is not yet a routine procedure, and thus can be considered as one technical approach amongst others. In order to avoid the development described above the question ‘Who should be allowed to navigate?’ needs to be asked. The use of image guidance systems for pedicle screw placement might induce a sense of security and ease in the surgeon resulting in ignorance against inconsistencies between virtual and physical reality. Furthermore, in case an inconsistency is recognized the surgeon has no means to resolve the situation adequately if the traditional techniques, e.g. anatomical landmark-based pedicle screw insertion, are not properly trained. Currently there are no concepts to resolve this conflict. However, to achieve a permanent implementation of image-guided approaches a framework that ensures a thorough understanding of image-guidance technology and an appropriate level of routine in traditional (rescue) procedures is mandatory.

The work of Rampersaud et al. [83] raises another intriguing question concerning the neuropsychological basis of image-guided surgery, i.e. why does image-guided surgery actually improve surgical performance. In a theoretical analysis of pedicle anatomy Rampersaud et al. came to the conclusion that there is no safety margin at certain levels of the spine, namely the cervical spine, the mid-thoracic spine and the thoraco-lumbar junction. Furthermore, the accuracy required according to the model analysis exceeds the accuracy achieved in the clinical application of image-guided systems. Thus the question has to be raised how and why image-guided surgery actually works. In the first instance this observation has to be understood as a clear hint that image-guided surgery does only function in conjunction with the human factor, i.e. the surgeon. It has to be stated that at the current stage of knowledge this question cannot be answered. However, several hypotheses can be developed. Interestingly the meta-analysis analysing the accuracy of pedicle screw placement presented by Kosmopoulos and Schizas [49] found no advantage of image-guided implantation of pedicle screws compared to conventional implantation in the thoracic spine. The authors clearly point out that these results have to be interpreted with caution, as there is only a very small group of studies (6 with and 6 without image-guidance) that explicitly report on the thoracic spine. Additionally it is hypothesized that the individual comfort and skills level of the surgeons participating in the studies might have influenced the outcome. To confirm the hypothesis that the anatomy of the pedicles in distinct levels of the spine precludes correct placement of pedicle screws a detailed database relating pedicle anatomy to the operative technique applied, the skills level of the surgeon and the incidence of misplacement needs to be implemented. As a matter of fact these data are currently not available. Alternatively it can be hypothesized that the insufficiencies of the human factor, the surgeon, when performing a complex task with reduced visual control (screw tip is inside the vertebral body and cannot serve as a visual feed back) are compensated for by image-guided techniques. This issue was first raised by Cleary et al. [20] who identified the cognitive modeling of human performance, especially the role of spatial cognition in image-guided spinal procedures, as a high priority research issue. This hypothesis is supported by the findings of Holly et al. [36] who described a constant navigational error independent of the registration algorithm that has been applied, thus giving an important hint concerning the relevance of the human factor in image-guided spine surgery. From anatomical [88], electrophysiological [10, 32, 33, 41], and neuropsychological [21, 44, 52, 69] investigations is it known that our representation of the space surrounding us is based upon the integration of many different sensory inputs, including both vision and somato-sensation. There appears to be no single, supra-modal map of space that is used to guide our movements, e.g. to reach or direct an object. Instead, movements appear to be planned and controlled within multiple coordinate systems, each one attached to a different part of the body. This multitude of reference coordinate systems might well turn out to interfere with the high demands of accuracy defined by Rampersaud et al.

[83]. If this assumption is true the positive effect of image-guidance systems in spine surgery is to visualize the object being manipulated, i.e. the pedicle screw, in its own Euclidian coordinate system, while providing direct visual feed back of the manipulation thereby providing an instance of integration of the different coordinate systems involved in motion control. In this case it can be assumed that image-guidance systems reduce the perceptive and locomotive complexity of the surgical procedure.

Given this assumption navigation systems might become an important cornerstone in spinal surgery education. While today spinal surgery education takes place in the OR and to a lesser degree in cadaver and hands-on workshops the systematic development of education and training modules using navigation technology might offer a new way to develop and improve the perceptive and locomotive capabilities necessary to perform surgery on an organ that has a complex three-dimensional anatomy which is to a large extent hidden from direct visual perception. A major advantage of image-guidance system based education modules, if systematically applied in a skills lab setting, is that they allow a trial-and-error based approach of education. With every iteration of a surgical procedure, or of individual steps of a procedure, that is performed under direct visual feedback provided by the navigation system a training effect of the eye-brain-hand axis can be expected. However, while the clinical applications of image-guidance systems have reached a high standard, the opportunities image-guidance systems offer as educational tools have not been investigated systematically so far.

The development of image-guidance techniques for ventral procedures is ongoing. Interesting developments are to be expected from the integration of image analysis techniques and endoscopy.

Summary and conclusion

Since the advent of high-speed computer workstations allowing the integration of 3D image processing and real time tracking of smart tools the feasibility of image-guided approaches of virtually any application in spine surgery has been proven. Thus image-guided spine surgery is a reality—yes, we can navigate. However, the mere technical feasibility does not justify the clinical application of a technique. Clinical data that strongly suggest the application of image-guidance techniques have so far only been published for pedicle screw implantation in the cervical and lumbar spine. However, due to the unique anatomical circumstances in the cervical spine and with respect to the data published so far the application of image-guidance systems might be suggested as compulsory. However, image-guided surgery is technically demanding and a learning curve has to be completed. Minor inaccuracies in the handling of the technical equipment might translate into major surgical errors. These errors, once implemented are systemic errors that propagate through the whole procedure. Thus not only ‘difficult’ cases should be navigated, but any case to establish a proper routine in the handling of the navigation system by all members of the team involved in the care of the spine patient in the OR. Apparently the margin between technical capabilities of image-guidance systems and the anatomical demands in terms of accuracy is very small. Current data suggest that a relevant amount of accuracy is lost in the interaction of the surgeon and the image-guidance system. Thus future research in the field of image-guided surgery should strife for a better understanding of these interactions.

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