THE 3D-CT NAVIGATION TECHNOLOGY FOR SURGICAL TREATMENT OF IDIOPATHIC SCOLIOSIS IN CHILDREN*

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Objective. To study the application of the active optical 3D-CT navigation system during surgical treatment of idiopathic scoliosis in children.
Materials and Methods. The study included 12 children aged 14—17 years with thoracic and thoracolumbar idiopathic scoliosis. The magnitude of scoliotic deformity varied from 52° to 80° (average 70°). Correction of deformity was performed using multisegmental pedicle screw instrumentation inserted with the guidance of an active optical 3D-CT navigation system. The values of mean-square registration error for reference points were estimated according to anatomical landmarks and monitoring of time required for registration and formation of bone canals for pedicle screws was performed at the stage of navigation.
Results. In 96.6 % of cases the pedicle screws were placed in all preplanned vertebral pedicles. In other 9 vertebrae (3.4 %), the screw placement was complicated by pedicle fracture and deviation of screw trajectory. There were no cases of neurological or infection complications, as well as instrumentation loosening in all studied patients.
Conclusion. Active optical 3D-CT navigation using preoperative CT images and registration of anatomical guides is applicable for correction of idiopathic scoliosis in children. The use of multisegmental transpedicular fixation allows reducing the length of metal fixation zone and achieving maximum curve correction and reliable stability.
Key Words: idiopathic scoliosis, children, transpedicular fixation, navigation, computed tomography.

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Introduction

Multisegmental pedicle screw instrumentation is recently used more often for correction of idiopathic scoliosis due to several advantages it has over the conventional Cotrel-Dubousset instrumentation for scoliosis correction. The new method allows one to achieve higher degree of correction, ensures stability and reliable fixation during post-operative period, helps to reduce the length of the metal fixation zone and eliminates complications associated with the use of correction systems with hook stabilization elements. Moreover, this instrumentation prevents further progression of the residual deformity after the surgical procedure. Meanwhile, the total multisegmented pedicle screw instrumentation is associated with several difficulties, which are coming from the dramatic anatomical change in vertebrae that were involved into scoliotic curvature. Many researchers are forced to use laminar and pedicle hooks for instrumentation immobilization because of the technical problems associated with screw insertion and possible complications (such as perforation and fracture of the vertebral arch pedicle, spinal stenosis by implants, and neurological complications) [6, 7, 10, 13].

The use of navigation systems during surgical correction of idiopathic scoliosis in children is a new and promising method, which allows one to ensure screw insertion into deformed vertebrae that are located on the curvature and to significantly reduce the risk of complications during the surgery. According to the literature [4, 15], the use of navigation assistance during surgical procedures for spine correction resulted in a 1.3–1.7-fold increase in accuracy of pedicle screw installation.

Several methods of navigation assistance can be used during the spine surgeries today. The main ones include 2D fluoroscopy-based navigation, 3D fluoroscopy-based navigation, 3D-CT navigation with registration of reference points according to the anatomical landmarks, and intraoperative 3D-CT navigation [14]. The 2D fluoroscopy-based navigation is commonly used during surgical procedures for degenerative diseases in the lumbar spine in adults. However, it is capable of neither visualizing the walls of vertebral arch pedicles during bone canal formation nor controlling screw insertion in 3D coordinates, which limits its use in children with idiopathic scoliosis. An analysis of the literature indicates that the intraoperative 3D-CT-navigation is the most accurate method and can be regarded as the optimal method for screw installation during the surgical procedure [14, 16]. However, its use is limited by high cost of the equipment, low accessibility, an increased risk of contamination of the operating theater, and an increase in radiation exposure to the patient during multilevel registration. The use of 3D fluoroscope as a navigation system to control the insertion of pedicle screws provides images of poor quality, which affects the accuracy of screw placement into vertebral bodies.

The objective of this study was to investigate possible applications of the active optical 3D-CT navigation system using preoperative CT images and registration of the position of reference points on the anatomical landmarks on vertebrae during surgical treatment of idiopathic scoliosis in children.

Material and Methods

The study involved 12 children (11 females and 1 male) aged 14–17 years with thoracic and thoracolumbar idiopathic scoliosis. The magnitude of scoliotic deformity varied from 52° to 80° (average 70°). Correction of idiopathic scoliosis was performed using only multisegmental pedicle screw instrumentation for all patients.

A standard preoperative evaluation that includes multi-slice computed tomography (MSCT) of the deformed spinal segment with the patient lying on his stomach in prone position was performed. This position was used in order to closely mimic patient's position on the operating table. CT scan was performed at the T1–S1 level. Scanning parameters were as follows: slice thickness – 1.0 mm, CT matrix size – 512 × 512 pixels. The MSCT data were exported to the navigation system using "SpineMap 3D" software for further analysis.

The midpoints of spinous process and transverse processes of the analyzed vertebra and the midpoint of the spinous process of the upper vertebra were used as reference points in the thoracic spine (Fig. 1). The midpoint of spinous process and both midpoints of zygapophysial joints from both sides of the registered vertebra and midpoints of spinous processes of the upper vertebra were used as reference points in the lumbar spine. Fixation of the positions of reference points on the bone structures of the posterior side of the vertebral column is referred to as anatomical landmark registration. Preoperative planning in the thoracic spine was performed for all the vertebrae to be instrumented.

The navigation system was installed after performing surgical access and skeletonization of the posterior structures of spinal column. The tracking camera was mounted on the side of patient's lower limbs during the surgery procedures in all patients. Patient's tracker (zero tracker) was mounted on the spinous process of the vertebra located one or two vertebrae below the level of the planned formation of bone canals for pedicle screw installation (Fig. 2). The intraoperative anatomical landmark registration was subsequently carried out. Three or four reference points were used for registration: 4 points in 93 % of cases and 3 points in 7 % of cases. Prior to the bone canal formation in the vertebral bodies, additional testing of the registration accuracy was performed by determining the awl position on the surface of posterior bone structures. If considerable spatial deviations from the anatomical landmarks were detected during the test, re-registration on the adjacent vertebra was carried out. In the cases when the registration accuracy was estimated to be high (mean square error was less than 1.0 mm), the formation of bone canals on the instrumented vertebra was carried out. During the anatomical landmark registration, the time needed for validating instruments and placing the zero tracker was recorded in all patients. After the registration, the mean square error was estimated and the time needed for bone canal formation was recorded. The registration time was counted from the point of registration of the first reference point until the end of accuracy of anatomical landmark registration was verified. The time needed for bone canal formation was counted from the moment of mounting an awl into the pedicle screw insertion zone until the completion of the canal verification by bulbous-end probe. After the bone canals for supporting structural elements had been formed, vertebral

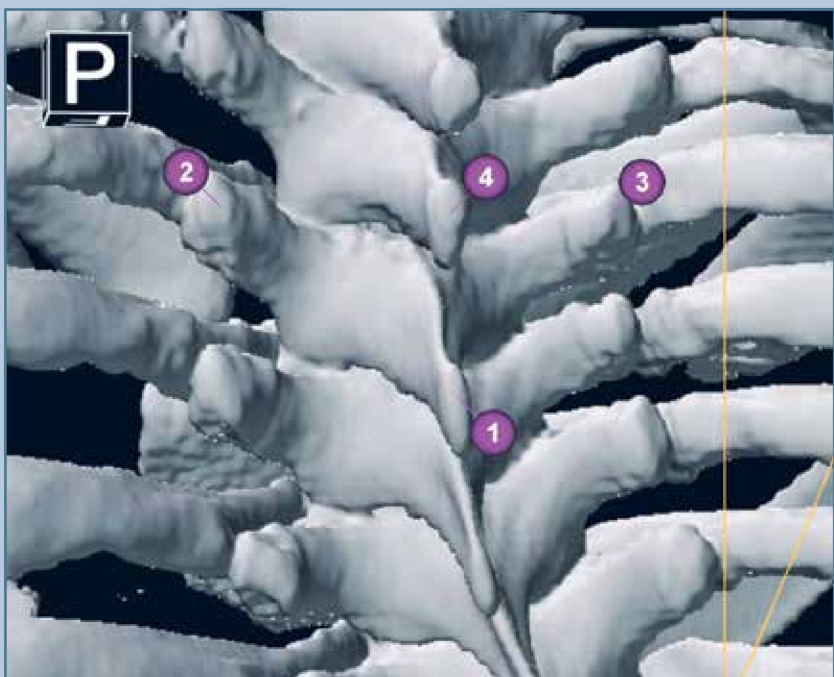

Fig. 1
Preoperative planning of reference points according to the anatomical landmarks

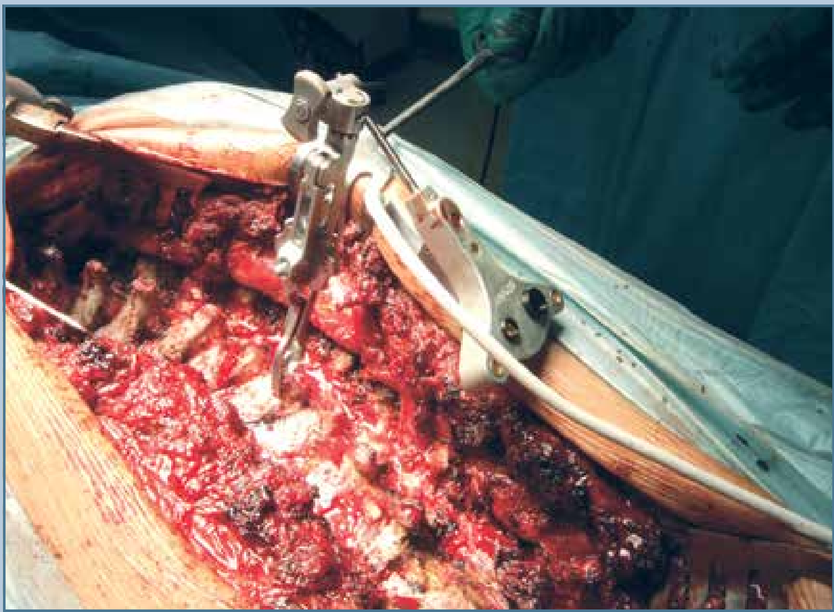

Fig. 2
Patient's tracker (zero tracker) is mounted on the spinous process in the thoracic spine

Table 1
Anatomical landmark registration time performed on a single vertebra (R), and bone canal formation time prior to pedicle screw mounting (C), s

Vertebrae	R		C	
	Average	N	Left side	Right side
T2	30.0	1	71	42
T3	49.0	3	106.4 (43–198)	120.6 (91–178)
T4	153.3	7	118.2 (52–285)	199.8 (183–238)
T5	114.9	10	94.5 (39–175)	182.9 (78–319)
T6	87.2	11	153.3 (46–341)	160.5 (97–270)
T7	128.6	10	146.1 (32–300)	146.3 (30–380)
T8	86.3	9	153.5 (71–356)	146.0 (35–299)
T9	144.5	4	137.8 (54–395)	103.3 (35–174)
T10	81.7	6	132.1 (50–328)	112.2 (45–200)
T11	176.3	6	92.9 (37–180)	158.6 (76–284)
T12	71.8	6	123.9 (43–234)	157.0 (71–310)
L1	–	0	129.7 (90–180)	137.8 (73–184)
L2	83.4	7	279.0 (108–589)	88.0 (40–140)
L3	75.3	3	135.4 (88–165)	98.0 (36–160)
L4	–	0	92.4 (51–112)	89.6 (43–115)
Average time, s	98.6		131.1	129.5

N – Number of registrations performed at this level;
the range of bone canal formation time for pedicle screw insertion is shown in parentheses.

bodies at all levels were labeled with Rg-marks and Rg-control was carried out in the coronal and sagittal planes. Then pedicle screws were inserted and the spinal deformity was corrected according to the developed procedures.

Results

Data obtained during 3D-CT navigation were analyzed for all 12 patients with thoracic and thoracolumbar idiopathic scoliosis. The total number of instrumented vertebrae was 136 and the total number of pedicle screws installed was 263. Fusion area boundaries localized between the T2 and L4 vertebrae. The cranial border for instrumented stabilization zone ended at the T2 vertebra in one case, at T3 in 2 cases, at T4 in 4 cases, and at T5 in 5 cases. The caudal border of instrumentation ended at L1 in 2 cases, at L2 in 5 cases, at L3 in 3 cases, and at L4 in 2 cases. The total amount of pedicle screws installed in the upper thoracic spine was 18; in the middle thoracic spine, 91; in the lower thoracic spine, 96; and in the lumbar spine, 58. Screws were installed in the direction starting from the lumbar towards the thoracic spine. The duration of zero tracker mounting ranged from 35 to 82 s (average 55 s). The duration of anatomical landmark registration ranged from 30 to 176 s (average 98.6 s). The time needed for bone canal formation for pedicle screw installation ranged from 32 to 589 s (average 131.1 s) for the thoracic curvature region and from 30 to 380 s (average 129.5 s) for the lumbar curvature (Table 1). Mean square error of registration varied from 0.3 to 1.2 mm (average 0.7 mm). The distribution of the mean error over specific spine regions was as follows: upper thoracic spine – 0.5 mm (0.3–1.1 mm), middle thoracic spine – 0.7 mm (0.3–1.1 mm), lower thoracic spine – 0.8 mm (0.3–1.2 mm), and lumbar spine – 0.8 mm (0.3–1.2 mm). During the formation of bone canals for pedicle screws in the lumbar and lower thoracic spine, supporting elements were installed in a single vertebral body from the same registration level only in 6.3 % of cases. In general, bone canals for supporting structures were formed in these spine regions within several different vertebral bodies from the same registration level. In 56.3 % cases, it was possible to install screws into two adjacent vertebrae; in 28.1 % cases, into 3 vertebrae; and in 9.4 % cases, in 4 vertebrae without loss of accuracy. The registration was carried out for each vertebra in 80 % cases during formation of canals for supporting elements of instrumentation, and in 20 % of cases bone canals were formed at two different levels. In the upper thoracic spine, the anatomical landmark registration was performed for each single level prior pedicle screw insertion procedure in 100 % of cases (Table 2).

In 96.6% cases, pedicle screws were installed at each preplanned level. In other 9 vertebrae (3.4% cases), installation of the supporting elements was complicated by pedicle fracture, which was associated with its smaller sizes (4 cases), pedicle sclerosis (3 cases), and the deviation of the trajectory during the screw installation procedure (2 cases). The latter type of complications appeared at the initial stage of using the navigation system and was associated with the initial experience accumulation for the installation of supporting elements.

No cases of neurological or infection complications, as well as destabilization of instrumentation, were reported in the early and late postoperative periods for each single patient.

Discussion

Patients with idiopathic scoliosis that require surgical treatment represent a group of patients with severe spinal deformity accompanied by variation in size of pedicles and vertebrae. These characteristics necessitate the development of novel surgical techniques that would enable more effective correction of the spine curvature and provide conditions for reliable and stable spine fixation after the surgery.

These requirements are completely addressed using the instrumentation with transpedicular supporting elements. This methodology requires special accuracy of surgical procedure during the pedicle screw placement and a reliable method to control the operator's manipulations. Meanwhile, the installation of screw instrumentation is hampered by the decreased diameter of pedicles, major distortion of the spinal anatomy, sclerotic processes in pedicles located primarily at the height of the pedicle arc curvature (in particular, in patients with scoliotic deformity in the thoracic spine). Under these conditions, pedicle screw placement is associated with significant technical difficulties and with elevated risk of trajectory deviation during insertion of supporting elements. This, in turn, could lead to severe undesired effects, such as damage of the spinal cord and roots, as well as instability of the spinal system.

Currently, the use of fluoroscopic control systems is the most common method for pedicle screw placement. This technology has found a widespread application due to its relative simplicity and availability. At the same time, the accumulated experience on the application of this method revealed several significant shortcomings that are typical for screw insertion under the control of image intensifier tubes (IIT). First of all, it delivers a very high radiation dose for patients and personnel. Besides that, the control over the placement of pedicle screws is performed only in the planar projection, which considerably lowers the accuracy and safety of the procedure. According to the studies by Belmont et al. [2], Amiot et al. [1], Nottmeier et al. [11], significant deviation in screw trajectories

Table 2

Mean square registration error for vertebrae instrumented from a single level for all patients

Vertebrae	Patients											
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th
T1	—	—	—	—	—	—	—	—	—	—	—	—
T2	—	—	—	—	—	—	—	—	—	0,7	—	—
T3	—	—	—	—	—	—	—	—	—	0,8	0,3	0,5
T4	0,4	0,6	—	0,4	—	—	—	0,6	—	1,1	0,4	0,6
T5	0,9	0,8	0,7	*	*	0,3	0,5	0,6	1,0	0,7	0,7	0,8
T6	1,0	0,8	0,8	0,7	0,9	0,8	0,7	0,9	0,5	*	0,4	0,6
T7	1,1	0,8	0,7	0,8	*	0,5	0,6	0,7	0,3	0,5	0,5	*
T8	0,5	0,7	*	*	1,0	0,6	0,9	0,5	*	0,4	0,7	0,4
T9	0,9	*	*	0,3	*	*	*	*	1,1	*	0,8	*
T10	*	*	0,9	*	1,2	0,6	0,9	*	*	0,9	*	0,7
T11	0,6	0,4	*	0,9	*	*	*	0,8	0,9	*	0,6	*
T12	*	*	0,7	*	1,2	0,7	1,0	*	*	0,8	*	1,0
L1	*	*	*	*	*	*	*	*	*	*	*	*
L2	*	0,7	0,5	*	0,9	0,8	*	0,6	1,1	—	1,0	—
L3	0,8	*	*	0,6	—	—	0,5	—	—	—	—	—
L4	*	—	—	*	—	—	—	—	—	—	—	—
L5	—	—	—	—	—	—	—	—	—	—	—	—

"—" — this vertebra was not instrumented;

"*" — registration was not performed at this level.

during 2D fluoroscopy may be as high as 7–54 %, while the occurrence rate of the neurological complications may reach the level of 5–7 %.

The use of optical navigation systems is one of promising directions to improve the surgical technique of pedicle screw insertion. 2D fluoronavigation is the one of simplest methods of navigation assistance. Its primary advantage is significant (10 to 12-fold) decrease in radiation dose [3], which is particularly important when performing surgical procedures in children and adolescents. Another advantage is the possibility to simultaneously control the pedicle screw insertion procedure in several projections, which ensures an increased accuracy of the surgical procedure. The fundamental shortcomings of the 2D fluoronavigation include the two-dimensional nature of the data obtained, which considerably lowers the possibility of pre- and intraoperative planning of insertion trajectories for structural supporting elements, and impossibility to control the insertion procedure in axial and coronal projections.

The 3D navigation methods, which provide more favorable environment for planning of pedicle screw insertion have recently become the most popular methods in clinical practice. According to the meta-analysis conducted by Tian, Xu [15] in 2011, the 3D-navigation methods have significant advantage over 2D fluoroscopic control in terms of accuracy of installation of pedicle supporting elements prior to screw insertion. In this study, the authors performed a retrospective analysis of the literature to analyze the results of screw insertion in pedicles of 7,533 lumbar and thoracic vertebrae. The accuracy of screw placement with 3D navigation assistance reached 96.7 % and was significantly higher than that for the conventional techniques using 2D fluoroscopic control [15].

The advantages of 3D navigation are most apparent for the procedures performed in the thoracic spine. Amiot et al. [1] have clearly demonstrated higher accuracy of the 3D navigation compared to the procedures under fluoroscopic control. This type of navigation assistance allowed accurate screw insertion in 95% cases, while the use of the fluoroscopic control resulted in a considerably lower accuracy rate (85 %) [1]. Laine et al. [9] performed data analysis of surgical procedures carried out in 100 patients with spinal disorders and disclosed that the use of 3D navigation assistance is capable of reducing the pedicle perforation rate from 13.4 to 4.6 %; according to studies by Kotani et al. [8], the perforation rate decreased from 11 to 1.8 %.

One of the most attractive methods of 3D navigation is the 3D fluoronavigation, which is based on simultaneous use of 3D-IIT and attached standard optical navigation system. The fundamental advantage of this technology is the possibility of obtaining 3D intraoperative images of the spinal column with subsequent control of pedicle screw insertion in axial, coronal and sagittal projections as compared to the standard 2D navigation. The major shortcomings of the 3D fluoronavigation inlcude poor quality of intraoperative images (in particular in patients with osteoporosis, high body weight and/or severe disorders of the spine anatomy) [5]. Furthermore, the small diameter of the detector requires multiple data registrations, especially during installation of larger instrumentation. For patients with scoliotic deformity it will result in increased operation time and significant radiation exposure, which is comparable to the dose received under fluoroscopic control of screw placement. It should be mentioned that the construction of 3D-IIT significantly hampers, and in many cases does not allow the data collection in 3D for patients with high body weight and significant spinal deformities (scoliosis and kyphosis with angles higher than 90°) [12].

Due to these reasons, the 3D navigation that uses the intraoperative CT data can be regarded as a kind of "gold standard" of all 3D assisted navigation types. During this procedure, a surgeon obtains the data that are characterized by the following advantages: images of high diagnostic quality; possibility of an automatic (without an operator) data collection; incredibly high accuracy of the procedure due to the use of images obtained directly on the operating table. In addition, 3D-CT navigation differs from the 3D fluoronavigation by a decreased radiation dose, lack of serious technical limitations, and reduced data collection time. Meanwhile, high cost, low availability, and stringent demands to the design features of operating rooms significantly limit the widespread use of the intraoperative 3D-CT navigation.

The 3D-CT navigation that uses the preoperative CT data of the spinal column can be regarded as an efficient alternative. However, the differences in patient' position on the operating table and in the CT scanner are considered to be a potential source of significant errors and, therefore, low accuracy of navigation assistance. The use of 3D navigation based on the pre-operative CT data necessitates mandatory registration by anatomical landmarks, which can significantly increase surgery duration. The data obtained during surgical procedures in the present study have demonstrated the incompetency of the assumption made above. The average installation time for zero tracker was less than 55 s. The average time spent on registration of four anatomical landmarks was 98.6 s for a single vertebra. The registration on a single vertebra in the lower thoracic and lumbar spine allowed accurate screw insertion at three and two levels in 28.1 % and 56.3 % of cases, respectively.

The data regarding the accuracy of anatomical registration based on the preoperative CT seems promising. The mean square error of registration in the thoracic spine was 0.3–1.1 mm (average 0.5 mm), in the lumbar spine 0.5–1.1 mm (average 0.7 mm). Meanwhile, navigation assistance that uses preoperative CT data has several fundamental advantages: it allows one to noticeably decrease the radiation dose; it does not increase the risk of infectious complications associated with contamination of the surgical field, in contrast to the intraoperative CT examination; and it is characterized by an extreme economy compare to all other types of 3D navigation.

Conclusion

The data obtained in the present work indicate the possibility of application and high accuracy of the active optical 3D-CT navigation method that uses preoperative CT images and anatomical landmarks registration for treatment of idiopathic scoliosis in children. The high registration accuracy allowed placement of two pedicle supporting elements in the body of each vertebra located on the spine curvature. This version of preoperative planning and placement of supporting elements throughout the spinal curvature allowed one to use modern technologies for surgical correction of idiopathic scoliosis. These techniques facilitate reducing the instrumentation length, correcting the substantial spinal curvature and providing stable fixation for the course of postoperative monitoring. The 3D-CT navigation method used in the present work is regarded as an efficient alternative to the intraoperative 3D-CT navigation, provides comparable registration accuracy, and is associated with lower economic expenses.

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