临床论著

椎弓根螺钉系统固定对椎体生长发育的影响

仉建国[1], 张延斌[2], 王升儒[1], 杨 阳[1], 林莞峰[1], 杜 悠[1]

(1 中国医学科学院北京协和医院骨科 100032; 2 北京积水潭医院骨科 100035 北京市)

【摘要】**目的:**探讨椎弓根螺钉系统固定对 5 岁以下婴幼儿椎体生长发育的影响。**方法:**回顾性分析 2000 年 1 月~2016 年 12 月在我院行双侧椎弓根螺钉固定的先天性脊柱侧凸患儿, 年龄≤5 岁, 随访时间至少 5 年。在术前与末次随访时, 于 CT 轴位图像上测量患者固定椎和邻近非固定椎的椎体及椎管相关参数(椎体及椎管前后径和横径、椎管面积及双侧椎弓根长度)。计算各项参数的生长值(末次随访数值-术前数值)和生长百分比(增长值除以末次随访值)。将胸椎和腰椎的参数进行分组比较。采用统计学的方法比较组间差异。**结果:**本研究共纳入 13 例患者, 接受手术时的平均年龄为 3.4±1.1 岁(2~5 岁), 平均随访 7.2±2.2 年(5~11 年)。所有患者均接受半椎体切除、椎弓根螺钉固定、短节段融合。研究共纳入 69 个椎体, 包括 43 个固定椎以及 26 个非固定椎。在末次随访时, 所有椎体的各项参数均得到明显增加。固定椎椎管前后径的生长值(2.2±1.7mm)与椎管面积(72.8±48.5mm^2)明显大于非固定椎(1.1±1.3mm, 39.2±26.3mm^2), 固定椎椎管前后径的生长百分比[(11.2±7.1)%]与椎管面积生长百分比[(21.3±11.6)%]明显大于非固定椎[(6.0±6.0)%, (13.4±8.1)%], 固定椎椎体前后径的生长值(3.8±2.5mm)明显小于非固定椎(6.1±3.0mm), 生长百分比[(20.5±12.1)%]也明显小于非固定椎[(28.1±11.0)%], 差异均具有统计学意义(P<0.05)。在腰椎椎体中, 结果类似。在随访过程中, 非固定腰椎椎管形状发生了明显的变化, 而在固定腰椎体中此形状变化不明显。**结论:**椎弓根螺钉系统固定可能会减缓椎体的生长发育, 间接加速椎管的生长发育, 可能阻止或减缓腰椎椎管形状的演变。但其影响较小, 椎弓根螺钉固定的椎体较术前均有明显的生长。所以, 在小于 5 岁的婴幼儿中应用椎弓根螺钉系统固定对椎体生长发育并无严重影响。

【关键词】椎弓根螺钉; 中央神经骺板; 椎体; 椎管; 生长发育

doi:10.3969/j.issn.1004-406X.2018.12.02

中图分类号:R687.3, R336 **文献标识码** A **文章编号:**1004-406X(2018)-12-1060-07

Influence of pedicle screw instrumentation on growth potential of the immature vertebra/ZHANG Jianguo, ZHANG Yanbin, WANG Shengru, et al//Chinese Journal of Spine and Spinal Cord, 2018, 28 (12): 1060-1066

【**Abstract**】**Objectives:** To explore the influence of pedicle screw instrumentation on the growth of immature spine at a very young age. **Methods:** Between January 2000 and December 2016, individuals who had bilateral pedicle screw instrumentation were reviewed. Patients younger than 5 years old with a minimal follow-up of 5 years were included. Anteroposterior diameter of vertebral body, pedicle length of both sides, anteroposterior diameter, transverse diameter and area of spinal canal were measured on CT images before surgery and at final follow-up. Parameters of instrumented vertebrae and adjacent non-instrumented vertebrae were compared. Growth value was calculated as: preoperative value - postoperative value, and growth percentage were calculated as: growth value divided by the final follow-up value. Subgroups of thoracic vertebrae and lumbar vertebrae were compared, respectively. Statistical analyses were performed. **Results:** 13 patients with congenital spinal deformity were enrolled. The average age at surgery was 3.4±1.1(range, 2-5) years old, and the average follow-up was 7.2±2.2(range, 5-11) years. Osteotomy and short instrumentation with pedicle screws were performed on each case. A total of 69 segments was measured, including 43 instrumented vertebrae and 26 adjacent non-instrumented vertebrae. Significant increases of all parameters were noted at final follow-up. The growth value(2.2±1.7mm vs 1.1±1.3mm), the area of spinal canal(72.8±48.5mm^2 vs 39.2±26.3mm^2), the growth

第一作者简介:男(1967-), 教授, 研究方向: 脊柱外科

电话: 18813019313 E-mail: ybzhang_jsth@163.com

共同第一作者: 张延斌 E-mail: zhangyanbinshuai@163.com

percentage of anteroposterior diameter[(11.2±7.1)% vs (6.0±6.0)%] and area of the spinal canal[(21.3±11.6)% vs (13.4±8.1)%], the anteroposterior diameter of vertebral body(3.8±2.5mm vs 6.1±3.0mm) and its growth percentage[(20.5±12.1)% vs (28.1±11.0)%] had significant differences between instrumented vertebrae and non-instrumented vertebrae (P<0.05). Similar results were noted in lumbar region. Shape-change phenomenon was found in non-instrumented vertebrae and not apparent in instrumented vertebrae. **Conclusions:** Pedicle screw instrumentation may slow down the growth of vertebral body, indirectly speed up the growth of spinal canal and hinder the shape-change phenomenon of lumbar spinal canal. But the influence is quite slight and the significant development occurs in instrumented vertebrae. So pedicle screw instrumentation may not make a great difference on the growth of immature vertebrae in children younger than 5 years old.

【Key words】 Pedicle screw; Neurocentral synchondrosis; Vertebral body; Spinal canal; Growth

【Author's address】 Orthopaedic Department of Peking Union Medical College Hospital(East), Beijing, 100034, China

近几十年脊柱椎弓根螺钉系统逐渐流行[1~3]。相比其他脊柱内固定系统，椎弓根螺钉系统固定具有矫形率高、翻修率低、融合节段短以及手术时间短等优点[4-6],因此它在脊柱矫形手术中得到广泛应用。虽然很多研究已经证实了椎弓根螺钉系统在婴幼儿患者中应用的安全性及有效性[7~10],但是很多医生仍担心它是否会影响椎体及椎管的生长发育。既往研究表明，成对的中央神经骺板(neurocentral synchondrosis,NCS) 位于椎体和椎弓根的交界处[11]。它是一种双向生长的软骨板,对椎体和椎管的生长发育至关重要。NCS 的闭合时间仍不确定,可能位于 3~16 岁之间[12~14]。椎弓根螺钉的置入可能会损伤 NCS。很多动物实验已经证实椎弓根螺钉固定可能会影响脊柱的生长发育,甚至是医源性椎管狭窄[15~17]。但是,关于该方面的临床研究相对较少。少数国外临床研究发现椎弓根螺钉固定不会对患儿脊柱的生长发育造成负面影响,与动物研究的结论相矛盾。本研究的目的就是探究在 5 岁以下婴幼儿患者中应用椎弓根螺钉系统固定是否会影响未成熟椎体的生长发育。

1 资料与方法

1.1 一般资料

获得伦理委员会批准后，回顾分析于我院行椎弓根螺钉固定的患儿。入组标准为:(1)先天性脊柱畸形,(2)接受初次手术时年龄≤5 岁,(3)行后路双侧椎弓根螺钉固定,(4)随访至少 5 年,(5)末次随访时行低剂量 CT 检查。

共纳入 13 例患者。2 例患者有相关发育畸形;1 例为内脏逆位,另 1 例为室间隔缺损。所有患者均行后路一起半椎体切除、椎弓根螺钉固定、短节段融合术。所有手术均由同一脊柱外科医生完成。患者接受手术时的平均年龄为 3.4±1.14(2~5)岁,平均随访 7.2±2.17(5~11)年。研究共纳入 69 个椎体,包括 43 个固定椎体以及 26 个非固定椎体。每个节段的固定椎体和非固定椎体数量详见表 1。

1.2 手术方法

全身麻醉后患者俯卧于体位垫上，标准背部正中切口。骨膜下暴露后方结构,根据解剖结构定位椎弓根螺钉进钉点,打孔、攻丝后,小心置入万向椎弓根螺钉，透视确认椎弓根螺钉位置及长度满意。常规方法切除半椎体,若截骨间隙无法通过

表 1 固定椎与非固定椎分布

Table 1 Distribution of the instrumented and non-instrumented vertebrae

	固定椎 Instrumented vertebra	非固定椎 Non-instrumented vertebra
T3	0	0
T4	1	0
T5	0	3
T6	2	1
T7	4	0
T8	2	0
T9	2	3
T10	3	2
T11	3	5
T12	4	2
L1	7	2
L2	5	0
L3	5	3
L4	3	4
L5	2	1

加压闭合,则置入填充自体骨的钛笼。适当加压后临时锁紧。术中透视确认半椎体完全切除,矫形效果满意,最后锁紧螺母,行后外侧融合。术中均行神经诱发电位监测。患者手术后佩戴支具下地行走。

1.3 观测指标

对患者术前及末次随访时 CT 影像进行测量。CT 轴位图像均经过矢状位校正,使之与椎体上终板平行(图 1a)。所有椎体分为椎弓根螺钉固定组和邻近的非固定组。术前及末次随访时测量参数如下:(1)椎体前后径(A-P diameter of vertebral body,VAP);(2)双侧椎弓根长度(PL);(3)椎管前后径 (A-P diameter of the spinal canal, CAP);(4) 椎管横径 (transverse diameter of the spinal canal,CLAT);(5) 椎管面积 (area of the spinal canal,AREA)(图 1b)。所有图像均使用 Surgimap(version 2.6.6.9,Nemaris Inc.)测量。

分别对两组术前和末次随访时的参数进行比较分析。用各个参数的变化值来反映椎体和椎管的生长幅度,计算公式为:末次随访数值-术前数值。增长百分比计算方式为增长值除以末次随访值。此外有研究表明, 椎体从近端到远端逐渐增大,且胸腰椎间的椎体大小存在明显差异[18]。为了减少椎体位置的影响, 我们对胸椎和腰椎的参数进行分组比较。

1.4 统计分析

对具有正态分布和方差齐性的变量进行 t 检验分析。对不适用于 t 检验的变量则进行 u 检验分析。所有的统计测试均使用 SPSS 19.0 进行。bonferroni 校正(α/n)被用来减少Ⅰ类误差。当 $P<0.01$ 时,我们认为有统计学差异(α=0.05,n=5)。

2 结果

两组间术前和末次随访时各个参数比较有显著统计学差异($P<0.05$,表 2),这表明了随访期间椎体有明显生长发育。固定椎的椎弓根长度、椎管前后径和椎管面积的生长值和生长百分比明显高于非固定椎, 而固定椎椎体前后径的生长值和生长百分明显低于非固定椎, 差异有统计学意义($P<0.05$,表 3、图 2)。

胸椎和腰椎的分组比较详见表 4、5。腰段固定椎和非固定椎见比较的结果较前类似。在腰椎

表 2 脊椎各个参数术前及末次随访比较

Table 2 Comparisons of parameters before surgery and at final follow-up

	术前 Preoperative		末次随访 Final follow-up	
	NIV	IV	NIV	IV
PLL(mm)	15.8±1.9	16.4±2.4	17.8±3.0①	18.4±2.6①
PLR(mm)	16.5±2.0	17.1±2.7	18.3±3.1①	18.9±2.7①
VAP(mm)	16.1±2.5	15.6±2.9	21.3±4.5①	18.4±3.5①
CAP(mm)	16.7±1.7	16.9±2.0	17.7±2.3①	18.9±2.7①
CLAT(mm)	19.1±3.5	19.0±3.5	21.3±3.7①	22.1±3.6①
AREA(mm^2)	252.9±60.5	264.8±72.2	289.7±70.6①	330.7±96.4①

注:NIV,非固定椎;IV,固定椎;PLL,左侧椎弓根长度;PLR,右侧椎弓根长度;VAP,椎体前后径;CAP,椎管前后径;CLAT,椎管横径;AREA,椎管面积;①与术前比较 $P<0.01$

Note: NIV, non-instrumented vertebrae; IV, instrumented vertebrae; PLL, left of pedicle length; PLR, right of pedicle length; VAP, A-P diameter of vertebral body; CAP, A-P diameter of the spinal canal; CLAT, transverse diameter of the spinal canal; AREA, area of the spinal canal; ①Compared with preoperative, $P<0.01$

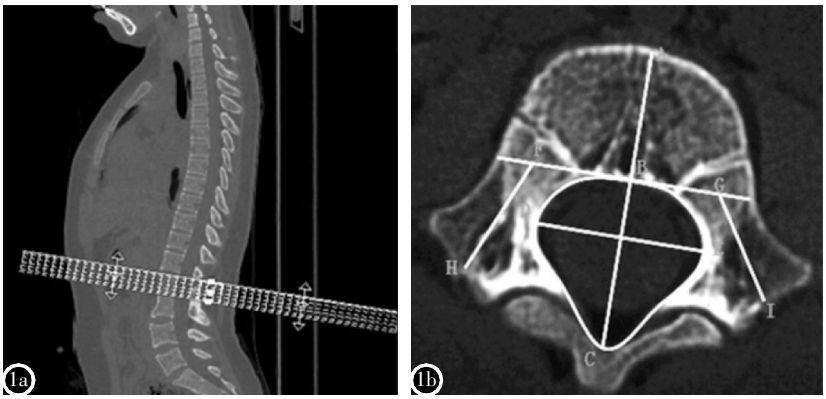

图 1 **a** CT 矢状位上调整是轴位图像与椎体上终板平行 **b** CT 轴位上显示各个参数测量方法:AB 为椎体前后径(VAP),BC 之间的距离为椎管前后径(CAP),DE 之间的距离为椎管横径(CLAT),GI 和 FH 分别为左右椎弓根长度 (PL),BECD 围成的空腔为椎管面积(AREA)

Figure 1 **a** Axial image was adjusted to be parallel to the upper endplate **b** The line between A and B was the anteroposterior diameter of the vertebral body(VAP). The line between B and C was the anteroposterior diameter of the spinal canal(CAP). DE was the transverse diameter of the spinal canal(CLAT). FH and GI were the right and left pedicle length(PL). The wall of the spinal canal defined the area of the spinal canal(AREA)

组中，固定椎椎体前后径的生长值明显低于非固定椎(P<0.05)，而固定椎椎管前后径的生长值明显高于非固定椎(P<0.05)。在腰椎组，非固定椎椎管形状可见明显的由圆形至三叶草形的形变，但固定椎组此形变不明显(图 3)。

3 讨论

椎弓根螺钉系统由于其强大的三维矫形效果而在脊柱矫形手术中得到广泛应用[4-6]。在婴幼儿患者中应用椎弓根螺钉亦有报道。Ruf 等[19]报道在 1~2 岁幼儿中应用椎弓根螺钉是安全可靠的。Li[20]和 Meuller 等[9]也认为椎弓根螺钉系统可在婴幼儿患者中安全应用。虽然上述研究已证实了椎弓根螺钉系统的安全性及有效性，但由于螺钉置入可能对椎体重要的生长发育结构——中央神经骺板(neurocentral synchondrosis, NCS)造成损害，所

表 3 固定椎和非固定椎生长值和生长百分比比较

Table 3 Comparison of growth value and percentage between NIV And IV

	生长值(mm) Growth value		*P*值	生长百分比(%) Growth percentage		*P*值 *P* value
	NIV	IV		NIV	IV	
PLL(mm)	2.0±2.4	2.4±1.5	0.404	10.2±10.3	13.2±8.6	0.2
PLR(mm)	2.1±2.2	2.4±2.0	0.644	10.6±9.1	12.5±10.1	0.432
VAP(mm)	6.1±3.0	3.8±2.5	0.001	28.1±11.0	20.5±12.1	0.009
CAP(mm)	1.1±1.3	2.2±1.7	0.008	6.0±6.0	11.2±7.1	0.003
CLAT(mm)	2.6±1.5	3.7±2.3	0.026	12.2±7.1	16.6±9.7	0.046
AREA(mm^2)	39.2±26.3	72.8±48.5	0.002	13.4±8.1	21.3±11.6	0.003

注：NIV，非固定椎；IV，固定椎；PLL，左侧椎弓根长度；PLR，右侧椎弓根长度；VAP，椎体前后径；CAP，椎管前后径；CLAT，椎管横径；AREA，椎管面积

Note: NIV, non-instrumented vertebrae; IV, instrumented vertebrae; PLL, left of pedicle length; PLR, right of pedicle length; VAP, A-P diameter of vertebral body; CAP, A-P diameter of the spinal canal; CLAT, transverse diameter of the spinal canal; AREA, area of the spinal canal

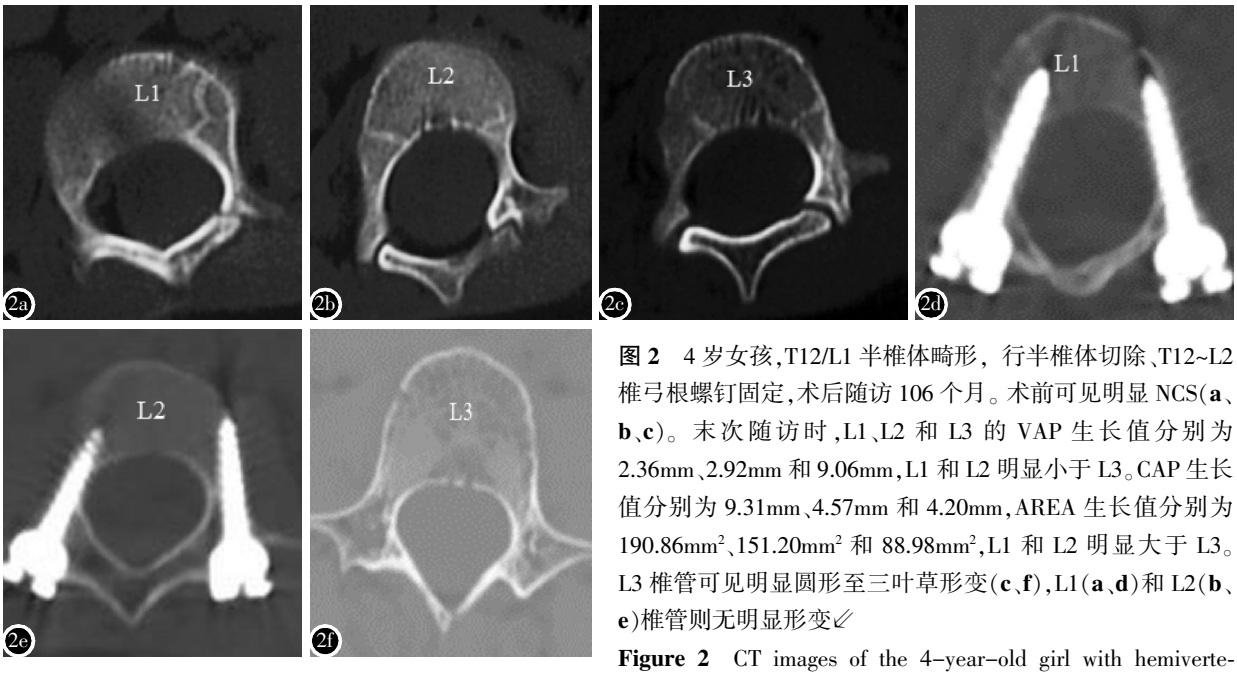

图 2 4 岁女孩，T12/L1 半椎体畸形，行半椎体切除、T12~L2 椎弓根螺钉固定，术后随访 106 个月。术前可见明显 NCS(**a**、**b**、**c**)。末次随访时，L1、L2 和 L3 的 VAP 生长值分别为 2.36mm、2.92mm 和 9.06mm，L1 和 L2 明显小于 L3。CAP 生长值分别为 9.31mm、4.57mm 和 4.20mm，AREA 生长值分别为 190.86mm^2、151.20mm^2 和 88.98mm^2，L1 和 L2 明显大于 L3。L3 椎管可见明显圆形至三叶草形变(**c**、**f**)，L1(**a**、**d**)和 L2(**b**、**e**)椎管则无明显形变

Figure 2 CT images of the 4-year-old girl with hemivertebra located at T12/L1. Hemivertebra resection and instrumentation from T12-L2 were performed. The follow-up was 106 months. NCS could be noted before surgery(**a**, **b**, **c**). At the final follow-up, growth value of VAP was 2.36mm, 2.92mm and 9.06mm in L1, L2 and L3, respectively. Growth value of CAP was 9.31mm, 4.57mm and 4.20mm in L1, L2 and L3. Growth value of AREA was 190.86mm^2, 151.20mm^2 and 88.98mm^2 in L1, L2 and L3. The shape-change phenomenon could be noted in L3(**c**, **f**) but not so obvious in L1(**a**, **d**) and L2(**b**, **e**)

以很多医生仍担心它是否会对椎体的生长发育产生影响。

Nicoladoni等[21]首次提出了 NCS 的概念，NCS 成对的存在于椎体和椎弓根的连接处。Zhang 等[12]应用 MRI 对婴幼儿患者的中央神经骺板进行形态学分析，发现腰椎中央神经骺板的闭合始于 3 岁，在 8~10 岁时完全闭合；胸椎中央神经骺板的闭合始于 5 岁，完全闭合年龄晚于腰椎。Yamazaki 等[13]发现胸椎中央神经骺板最迟在 16 岁才完全闭合。本研究纳入病例的平均手术年龄为 3.4(2~5)岁，小于中央神经骺板完全闭合年龄，平均随访时间为 7.2(5~11)年，末次随访时大部分患者

表 4 胸椎固定椎与非固定椎生长值比较

Table 4 Comparison of growth between NIV and IV in thoracic vertebrae

	术前 Preoperative		末次随访 Final follow-up		生长值 Growth value		*P*值 *P* value
	NIV	IV	NIV	IV	NIV	IV	
PLL(mm)	15.9±1.2	16.7±2.0	18.4±2.8	18.8±2.5	2.4±2.9	2.3±1.5	0.463
PLR(mm)	16.7±1.0	17.1±1.7	19.3±2.5	19.7±2.0	2.8±2.6	2.6±2.1	0.391
VAP(mm)	15.0±2.1	14.3±2.0	19.5±3.8	17.4±3.8	5.4±2.3	3.6±2.1	0.018
CAP(mm)	15.9±1.1	16.3±1.5	17.9±1.8	17.7±1.7	1.3±1.3	1.6±1.1	0.244
CLAT(mm)	16.8±1.7	17.2±2.4	19.2±2.5	20.3±3.1	2.8±1.4	3.3±1.7	0.383
AREA(mm^2)	213.2±24.2	229.4±43.3	252.8±45.0	280.4±63.3	43.2±24.6	56.3±36.2	0.232

表 5 腰椎固定椎与非固定椎生长值比较

Table 5 Comparison of growth between NIV and IV in lumber vertebrae

参数	术前 Preoperative		末次随访 Final follow-up		生长值 Growth value		
	NIV	IV	NIV	IV	NIV	IV	*P*值 *P* value
PLL(mm)	15.7±2.8	16.2±2.8	16.8±3.1	18.1±2.7	1.3±1.1	2.5±1.5	0.04
PLR(mm)	16.1±3.1	17.1±3.4	16.7±3.3	18.2±3.0	1.1±0.8	2.1±1.8	0.02
VAP(mm)	17.8±2.0	16.7±3.2	24.2±4.3	19.3±3.1	7.2±3.7	4.0±2.8	0.007
CAP(mm)	18.0±1.6	17.4±2.3	18.9±2.7	20.1±3.1	1.0±1.2	2.8±2.0	0.019
CLAT(mm)	22.6±2.5	20.6±3.6	24.8±2.4	23.8±3.2	2.2±1.6	4.1±2.7	0.025
AREA(mm^2)	316.4±43.4	298.7±78.5	348.8±64.5	378.6±99.1	32.7±28.9	88.5±54.0	0.003

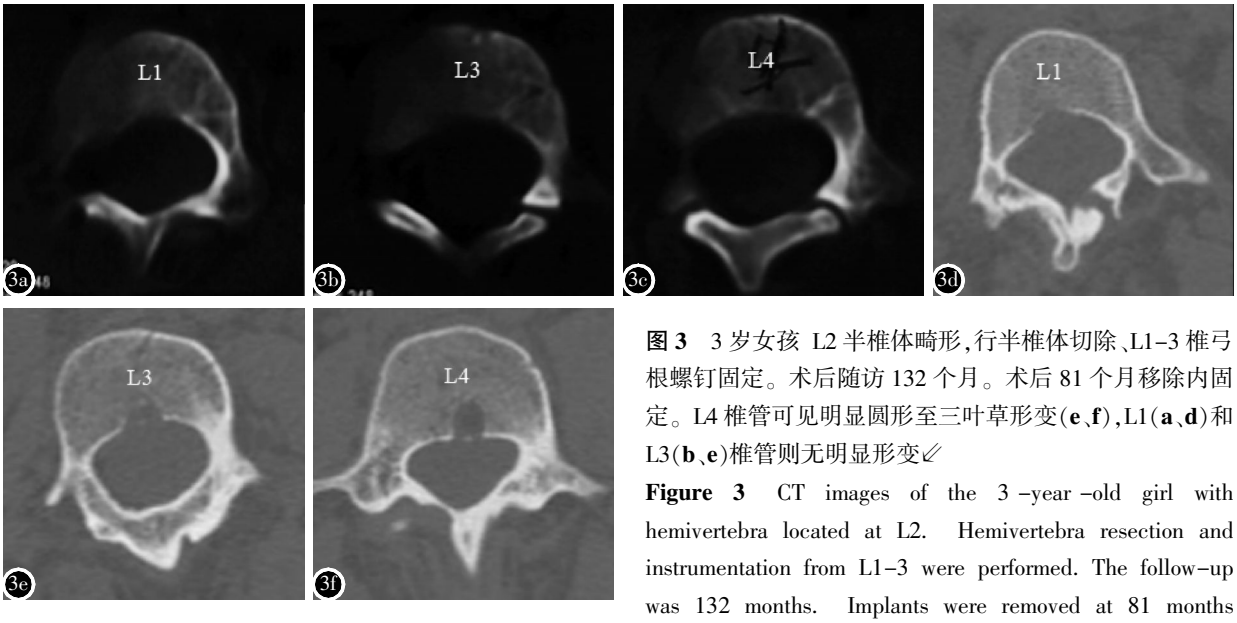

图 3 3 岁女孩 L2 半椎体畸形，行半椎体切除、L1-3 椎弓根螺钉固定。术后随访 132 个月。术后 81 个月移除内固定。L4 椎管可见明显圆形至三叶草形变(**e**、**f**)，L1(**a**、**d**)和 L3(**b**、**e**)椎管则无明显形变

Figure 3 CT images of the 3-year-old girl with hemivertebra located at L2. Hemivertebra resection and instrumentation from L1-3 were performed. The follow-up was 132 months. Implants were removed at 81 months after surgery. The shape-change phenomenon was apparent in L4(**c**, **f**) but not so obvious in L1(**a**, **d**) and L3(**b**, **e**)

的中央神经骺板基本完全闭合。

有学者认为,在椎体发育中,中央神经骺板的完整性至关重要。因此,椎弓根螺钉置入可能损伤中央神经骺板的完整性,进而对脊柱的生长造成负面影响。许多动物实验研究已经证实了这个假说。Beguiristain 等[22]对两月大的猪进行了选择性中央神经骺板固定术,随后猪出现了凸向手术侧的脊柱侧凸。Cil 等[23]对 3 组未发育成熟的猪(4~6 周)进行相同的实验,作为比较,其中一组仅行椎弓根螺钉置入,另一组行椎弓根螺钉置入联合加压,结果发现在术侧均出现了椎弓根长度短缩和椎管的变窄。Wang 等[24]对 16 只狗进行了类似的动物实验研究,术后用 CT 对椎管进行形态学分析。他们指出,椎弓根螺钉置入对幼犬的椎管生长发育有显著影响,还可能导致医源性脊柱狭窄。Zhang 等[15,25]发现,在未成熟的猪中应用椎弓根螺钉系统可能导致脊柱侧凸和术侧椎体、椎管的发育迟缓,随后在另一侧施行相同手术则能逆转这种结构性脊柱侧凸。这些研究表明,损害中央神经骺板可能导致椎弓根和椎管的发育迟缓。以上动物实验均已证实椎弓根螺钉系统在未发育成熟动物脊柱的应用可能会给椎体和椎管的生长发育造成负面影响。

然而部分临床研究表明,在婴幼儿患者中应用椎弓根螺钉系统并不会影响脊柱生长发育。Ruf 等[19]对 3 例共置入 8 颗椎弓根螺钉的患儿进行了 5 年以上的随访研究,分别在术后第 5、6、8 年进行 MRI 检查,未见明显椎管狭窄,但并没有在 MRI 上进行任何数据测量。后来他们又使用 CT 或 MR 对随访 10 年患者的椎体进行测量,发现,与非固定椎体相比,固定椎体的椎管前后径和椎管面积略有增加(105.7%和 106.7%)[27],但未进行统计学分析。Olgun 等[28]研究了 16 例接受椎弓根螺钉固定的患儿,平均手术年龄为 34 个月,术前和随访时均进行 CT 或 MRI 检查。他们发现固定组和非固定组的脊柱生长无显著差异。但平均随访时间仅 30.6 个月。Chang 等[7]认为,与 6 岁后施行手术相比,6 岁前施行椎弓根螺钉置入对椎体和椎管生长发育并没有造成不良影响。Kahraman 等[26]在 4 个节段(UIV、LIV、UAV、LAV)对术前和随访时椎体参数进行比较,发现各个椎体生长发育情况类似。

本研究结果发现,椎弓根螺钉置入可能减缓椎体的生长,加快椎管的生长。其机理可能是椎弓根螺钉破坏了 NCS 的完整性,进而导致骨质构成的椎体的生长发育减缓。但由骨质围成的空腔,即椎管的生长发育的增快则可能继发于椎体增长速度的减缓。综上,椎弓根螺钉系统可能减慢了椎体的生长,却间接地促进椎管的生长。

我们把胸椎和腰椎进行亚组分析后,在腰椎组发现了类似的结论。Porter 等[29]发现腰椎椎管形状会随着年龄增长从圆形变成三叶草形。本研究中,腰椎非固定组出现了这种椎管形状演变。但在腰椎固定组中,这种现象并不明显。椎弓根螺钉的置入可能通过减缓椎体的生长来减缓椎体后壁的后移,进而延缓或者阻断了椎管从圆形至三叶草的形变。

综上所述,椎弓根螺钉系统可能减缓椎体的生长发育,间接地促进椎管的生长发育,可能减缓或阻止腰椎椎管的形变。但是这种负面影响很小,在末次随访时,置入椎弓根螺钉的椎体较术前均有明显的生长发育,且无医源性椎管狭窄出现。所以在≤5 岁的婴幼儿应用椎弓根螺钉系统对椎体生长发育并无严重影响。

4 参考文献

1. Boucher HH. A method of spinal fusion[J]. J Bone Joint Surg Br, 1959, 41-B(2): 248-259.
2. Roy-Camille R, Saillant G, Mazel C. Internal fixation of the lumbar spine with pedicle screw plating[J]. Clin Orthop Relat Res, 1986, 203: 7-17.
3. Roy-Camille R, Saillant G, Mazel C. Plating of thoracic, thoracolumbar, and lumbar injuries with pedicle screw plates[J]. Orthop Clin North Am, 1986, 17(1): 147-159.
4. Fu G, Kawakami N, Goto M, et al. Comparison of vertebral rotation corrected by different techniques and anchors in surgical treatment of adolescent thoracic idiopathic scoliosis[J]. J Spinal Disord Tech, 2009, 22(3): 182-189.
5. Rose PS, Lenke LG, Bridwell KH, et al. Pedicle screw instrumentation for adult idiopathic scoliosis: an improvement over hook/hybrid fixation[J]. Spine(Phila Pa 1976), 2009, 34(8): 852-858.
6. Kuklo TR, Potter BK, Lenke LG, et al. Surgical revision rates of hooks versus hybrid versus screws versus combined anteroposterior spinal fusion for adolescent idiopathic scoliosis [J]. Spine(Phila Pa 1976), 2007, 32(20): 2258-2264.
7. Chang DG, Suk SI, Kim JH, et al. Surgical outcomes by age at the time of surgery in the treatment of congenital scoliosis in children under age 10 years [J]. Spine J, 2015, 15 (8): 1783-1795.

8. Chang DG, Kim JH, Ha KY, et al. Posterior hemivertebra resection and short segment fusion with pedicle screw fixation for congenital scoliosis in children younger than 10 years: greater than 7-year follow-up[J]. Spine(Phila Pa 1976), 2015, 40(8): E484-491.
9. Mueller TL, Miller NH, Baulesh DM, et al. The safety of spinal pedicle screws in children ages 1 to 12 [J]. Spine J, 2013, 13(8): 894-901.
10. Harimaya K, Lenke LG, Son-Hing JP, et al. Safety and accuracy of pedicle screws and constructs placed in infantile and juvenile patients[J]. Spine(Phila Pa 1976), 2011, 36(20): 1645-1651.
11. Vital JM, Beguiristain JL, Algara C, et al. The neurocentral vertebral cartilage: anatomy, physiology and physiopathology [J]. Surg Radiol Anat, 1989, 11(4): 323-328.
12. Zhang H, Sucato DJ, Nurenberg P, et al. Morphometric analysis of neurocentral synchondrosis using magnetic resonance imaging in the normal skeletally immature spine [J]. Spine(Phila Pa 1976), 2010, 35(1): 76-82.
13. Yamazaki A, Mason DE, Caro PA. Age of closure of the neurocentral cartilage in the thoracic spine [J]. J Pediatr Orthop, 1998, 18(2): 168-172.
14. Maat GJ, Matricali B, van Persijn VME. Postnatal development and structure of the neurocentral junction: its relevance for spinal surgery[J]. Spine(Phila Pa 1976), 1996, 21(6): 661-666.
15. Zhang H, Sucato DJ. Unilateral pedicle screw epiphysiodesis of the neurocentral synchondrosis. Production of idiopathic-like scoliosis in an immature animal model[J]. J Bone Joint Surg Am, 2008, 90(11): 2460-2469.
16. Fekete TF, Kleinstück FS, Mannion AF, et al. Prospective study of the effect of pedicle screw placement on development of the immature vertebra in an in vivo porcine model[J]. Eur Spine J, 2011, 20(11): 1892-1898.
17. Zhou X, Zhang H, Sucato DJ, et al. Effect of dual screws across the vertebral neurocentral synchondrosis on spinal canal development in an immature spine: a porcine model[J]. J Bone Joint Surg Am, 2014, 96(17): e146.
18. Zindrick MR, Knight GW, Sartori MJ, et al. Pedicle morphology of the immature thoracolumbar spine[J]. Spine(Phila Pa 1976), 2000, 25(21): 2726-2735.
19. Ruf M, Harms J. Pedicle screws in 1- and 2-year-old children: technique, complications, and effect on further growth [J]. Spine(Phila Pa 1976), 2002, 27(21): E460-466.
20. Li J, Lü GH, Wang B, et al. Pedicle screw implantation in the thoracic and lumbar spine of 1-4-year-old children: evaluating the safety and accuracy by a computer tomography follow-up[J]. J Spinal Disord Tech, 2013, 26(2): E46-52.
21. CN. Anatomie und Mechanismus der Skoliose [M]. Berlin, Germany: Urban & Schwarzenberg, 1909.
22. Beguiristain JL, De Salis J, Oriaifo A, et al. Experimental scoliosis by epiphysiodesis in pigs[J]. Int Orthop, 1980, 3(4): 317-321.
23. Cil A, Yazici M, Daglioglu K, et al. The effect of pedicle screw placement with or without application of compression across the neurocentral cartilage on the morphology of the spinal canal and pedicle in immature pigs[J]. Spine(Phila Pa 1976), 2005, 30(11): 1287-1293.
24. Wang L, Luo ZJ, Luo LJ, et al. The effect of pedicle screw insertion through the neurocentral cartilage on the growth of immature canine vertebra[J]. Orthop Surg, 2009, 1(2): 137-143.
25. Zhang H, Sucato DJ. Neurocentral synchondrosis screws to create and correct experimental deformity: a pilot study [J]. Clin Orthop Relat Res, 2011, 469: 1383-1390.
26. Kahraman S, Karadereler S, Cobanoglu M, et al. Does pedicle screw fixation under age 5 cause spinal canal narrowing? A CT study with minimum 5 years follow-up[J]. Eur Spine J, 2016, 25(6): 1665-1673.
27. Ruf M HJ. Development of the spinal canal after transpedicular instrumentation in one and two year old children [C]. SRS 45th Annual Meeting. Kyoto, Japan, 2010.
28. Olgun ZD, Demirkiran G, Ayvaz M, et al. The effect of pedicle screw insertion at a young age on pedicle and canal development[J]. Spine(Phila Pa 1976), 2012, 37(20): 1778-1784.
29. Porter RW, Pavitt D. The vertebral canal: I. Nutrition and development, an archaeological study [J]. Spine (Phila Pa 1976), 1987, 12(9): 901-906.

(收稿日期:2018-09-16 修回日期:2018-11-08)
(英文编审 郑国权/贾丹彤)
(本文编辑 彭向峰)