Cumulative Ionising Radiation Exposure in Adolescent Idiopathic Scoliosis Patients Undergoing Posterior Spinal Fusion: A Retrospective Cohort Study Comparing Freehand Versus Patient-Specific Instrumentation

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Abstract

Purpose of the SSC:
To determine the cumulative radiation exposure in patients with adolescent idiopathic scoliosis (AIS) undergoing posterior spinal fusion (PSF) and compare conventional freehand surgery with CT-based patient-specific guide (PSG). Repeated exposure to ionising radiation has been associated with an increased risk of stochastic cancer.

Activities undertaken:
All radiation doses were collected through hospital radiological systems and existing spinal database. CT, radiographic and intra-operative (II) doses were converted to estimated effective dose (mSv). IBM SPSS Statistics was used for statistical analysis.

Observations or results:
A total of 112 patients were included (79 freehand, 33 PSG). Patients treated with PSG received significantly higher cumulative radiation than the freehand group (12.97 vs 5.04 mSv; $p<0.001$). This phenomenon was driven by the pre-operative CT scans required to produce PSG. Otherwise, II and post-operative radiation were comparable between the groups.

Conclusions:
CT based PSG is the main contributor to increased cumulative radiation exposure in AIS patients. Alternative low-dose imaging modalities or imaging protocols may have a role in reducing radiation.

Introduction

Adolescent idiopathic scoliosis (AIS) is the most common form of scoliosis and is defined as a three-dimensional (3D) deformity developing between 10 and 18 years of age. It is estimated that AIS affects 3-4 children per 1000 in United Kingdom. (1) Management of AIS depends on the degree of deformity and ranges from observation and bracing to posterior spinal fusion (PSF) for severe curves. PSF is indicated in less than 1% of AIS cases. (2)

Prior to 2017, Cardiff & Vale University Health Board performed freehand pedicle screw insertion technique with intra-operative imaging (II). More recently, pre-operative computed tomography (CT)-based patient-specific guides (PSG) with II have been introduced to improve pedicle screw placement accuracy.(3)

AIS patients undergo multiple radiological imaging throughout diagnosis, surveillance, intraoperative and post-treatment monitoring, resulting in high cumulative exposure to ionising radiation. The introduction of pre-operative CT scans for PSG has the potential further increase cumulative radiation exposure. This is particularly important in children and adolescents, who are more sensitive to radiation because of their developing tissues and longer life expectancy. (4) Previous epidemiological studies have reported increased risks of malignancy including haematological, breast, thyroid and brain cancers. (5)

Currently, there is no consensus regarding ionising radiation safety levels in scoliosis patients. Despite the increasing use of CT-based PSG for scoliosis surgery, there is limited evidence on their contribution to cumulative radiation throughout the entire treatment pathway. Under the Ionising Radiation (Medical Exposure) Regulations 2017 (IR(ME)R17), all medical exposures must be clinically justified and optimised, ensuring radiation doses are kept as low as reasonably practicable (ALARP).

Aims/objectives

This retrospective cohort study aims to evaluate cumulative ionising radiation exposure in adolescents undergoing PSF.

Objectives:

- To determine the cumulative radiation from diagnosis until 2 years post-operatively.

- To compare the cumulative radiation between patients undergoing PSF with freehand technique and those treated with PSG.
- To identify the stage(s) of treatment pathway contributing the most radiation exposure.
- To determine whether the cumulative radiation approaches thresholds associated with increased stochastic cancer risk.

Patients and Methods

Study design and patient population

A single-centre retrospective cohort study was conducted at UHW. As this study involved retrospective analysis of routinely collected clinical data and did not involve direct patient contact, formal ethical approval was not required.

AIS patients who underwent PSF between January 2017 and June 2024 were identified from existing spinal surgery database. A total of 112 patients met the inclusion criteria of 2 year post-operative follow up. Patients were categorised according to surgical technique: the freehand group (Jig 0; n=79), while the PSF group (Jig 1;n=33) underwent CT-based PSG assisted surgery with II.

Radiation dose collection

Radiation exposure data were collected from 3 sources. Pre- and post-operative CT doses were obtained from spinal database whilst radiographic and II imaging doses were collected manually from Soliton and Philips Vue PACS system respectively. All radiological examinations performed from diagnosis to 2 years post-operatively were included.

Radiation exposure was categorised into the following:

- Pre-operative CT imaging
- Pre-operative whole spine radiograph
- Pre-operative other radiograph
- Intraoperative imaging (II)
- Post-operative CT imaging
- Post-operative radiograph
- Post-operative other radiograph

All data was recorded in a Microsoft Excel.

Effective dose conversion

Radiation doses were converted to estimated effective dose (E) and expressed in millisievert (mSv) to allow comparison across imaging modalities. E estimates total stochastic risk to the whole body by accounting different tissue radiosensitivity in different anatomical regions and was calculated with an equation by the International Commission on Radiological Protection (ICRP Publication 103). (Figure 1). (6)

$$E = \sum_T w_T H_T$$

Figure 1: Effective dose equation established by ICRP Publication 103. Wt is the tissue weighting factor (i.e conversion factor). Ht is the equivalent dose absorbed by organ.

Anatomical region specific conversion factors, derived from published were applied according to medical physics data and radiation protection guidelines (Figure 2). (7)

Imaging modality	Anatomical region	Conversion factor
CT	Whole spine	Multiplication by 0.016[9]
Radiograph	Cervical spine	Multiplication by 0.0031
Radiograph	Whole spine	Multiplication by 0.002
Radiograph	Abdomen	Multiplication by 0.0016
Radiograph	Sacroiliac joint	Multiplication by 0.0078
Radiograph	Chest PA,LAT	Multiplication by 0.0019

Figure 2: Conversion coefficients used to estimate effective radiation dose (mSv) from recorded CT and radiographic dose metrics.

The cumulative E for each patient was calculated by the sum of E from all radiological examinations performed between diagnosis and 2 years post-operatively. (Figure 3)

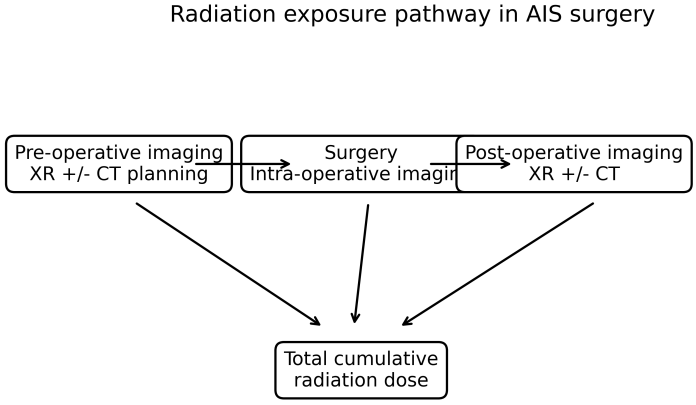

Figure 3: Radiation exposure pathway in AIS surgery, illustrating how total cumulative radiation dose was calculated.

Statistical analysis

Following conversion to mSv, anonymised datasets were analysed by IBM SPSS Statistics. Continuous variables were summarised using mean and standard deviation. Independent-samples t-tests were used to compare radiation exposure between groups. Mean differences with 95% confidence intervals and Cohen's d effect sizes were calculated. Statistical significance was defined as a two-sided p value <0.05.

Results

Patient demographics

In the study, a total of 79 patients are in Jig 0 group and 33 patients in Jig 1 group. However, the number of patients included in each imaging modality varied slightly due to incomplete radiation records. Both groups were predominantly females. The median age at surgery was comparable in both groups (14 years in Jig 0 vs 15 years in Jig 1), with comparable ranges across both cohorts. The median pre-operative cobb angle was 65° (IQR 24; range 35-105°) in Jig 0 and 70° (IQR 30, range 45–110)in Jig 1. (Figure 4) There was no obvious demographic differences between groups.

	Jig 0 (N=79)	Jig 1 (N=33)
Female/ Male	67/12	30/3
Age at surgery, median ± IQR (range)	14 ± 2 (11-17)	15 ± 2 (11-18)
Pre-operative cobb angle, median ± IQR (range)	65±24(35-105)	70±30 (45-110)

Figure 4 illustrates patient demographics, age at surgery and pre-operative cobb angle

Cumulative radiation exposure results

Patients in the Jig 1 group received significantly greater pre-operative CT radiation than the freehand group (8.64±4.89 mSv vs 0.28±1.35mSv; mean difference 8.35 mSv, 95% CI 7.17-9.54;p<0.001). (Figure 5) This represented a very large effect size (Cohen's d= 2.94). Similarly, total pre-operative radiation exposure was also significantly higher in this group (9.92±5.27mSv vs 2.17±1.89mSv; mean difference 7.75 mSv, 95% CI 6.41 to 9.09; p<0.001; Cohen's d 2.38).
The maximum cumulative radiation dose is 33.34 mSv in Jig 1 group compared with 16.17 in Jig 0. No statistically significant difference between groups in pre-operative whole spine radiographic dose (1.55 +/- 0.72 mSv in the jig group vs 1.89 +/- 1.28 mSv in the non-jig group; p=0.156).

Likewise for other pre-operative radiographic exposure, it was similar between the two groups. (0.0005 +/- 0.0025 mSv vs 0.0015 +/- 0.0095 mSv; P=0.532).

II exposure was lower in the Jig 1 group (0.020±0.020 mSv) than in non-jig group (0.037±0.072 mSv), although the difference did not reach statistical significance under the unequal variance model (mean difference -0.017 mSv, 95% CI -0.034 to 0.001; P=0.065). There was no statistically significant difference between post-operative radiation exposure in both groups. (mean difference 0.2 mSv, 95%CI -0.74 to 1.15; p=0.675).

Total cumulative radiation exposure was significantly higher in the Jig 1 group (12.97 +/- 6.07 mSv) than in the Jig 0 group (5.04 +/- 3.11 mSv), with a mean difference of 7.94 mSv (95% CI 6.21 to 9.66; P<0.001).

Figure 6 demonstrates the mean radiation exposure for each imaging modality in both treatment groups with error bars. Figure 7 demonstrates that the increased cumulative radiation in the PSG group was predominantly due to pre-operative CT imaging. In Jig 1 group, pre-operative CT accounted for almost 60% of total cumulative radiation exposure whereas cumulative radiation exposure is mainly driven by pre- and post-operative spine radiographs, each contributing at around 35% (figure 8).

Variable	No jig N	No jig mean +/- SD	Jig N	Jig mean +/- SD	Mean difference (95% CI)	P value
Pre-op CT dose	79	0.28 +/- 1.35	32	8.63 +/- 4.89	8.35 (7.17 to 9.54)	<0.001
Pre-op whole-spine XR dose	79	1.89 +/- 1.28	33	1.55 +/- 0.72	-0.34 (-0.81 to 0.13)	0.156
Pre-op other XR dose	77	0.0015 +/- 0.0095	33	0.0005 +/- 0.0025	-0.0011 (-0.0044 to 0.0023)	0.532
Total pre-op dose	79	2.17 +/- 1.89	33	9.92 +/- 5.27	7.75 (6.41 to 9.09)	<0.001
Post-op CT dose	79	0.70 +/- 1.74	33	0.65 +/- 1.80	-0.05 (-0.77 to 0.67)	0.889
Post-op whole-spine XR dose	79	2.10 +/- 1.21	33	2.37 +/- 1.19	0.27 (-0.23 to 0.76)	0.284
Post-op other XR dose	75	0.03 +/- 0.12	33	0.0089 +/- 0.05	-0.02 (-0.06 to 0.02)	0.372
Total post-op dose	79	2.83 +/- 2.32	33	3.03 +/- 2.24	0.20 (-0.74 to 1.15)	0.675
Intra-operative imaging dose	77	0.04 +/- 0.07	33	0.02 +/- 0.02	-0.02 (-0.03 to 0.0010)	0.065
Total cumulative dose	79	5.04 +/- 3.11	33	12.97 +/- 6.07	7.94 (6.21 to 9.66)	<0.001

Figure 5 summaries the radiation exposure for each imaging modality, together with the number of patients included in each analysis, standard deviations, mean differences and p-values.

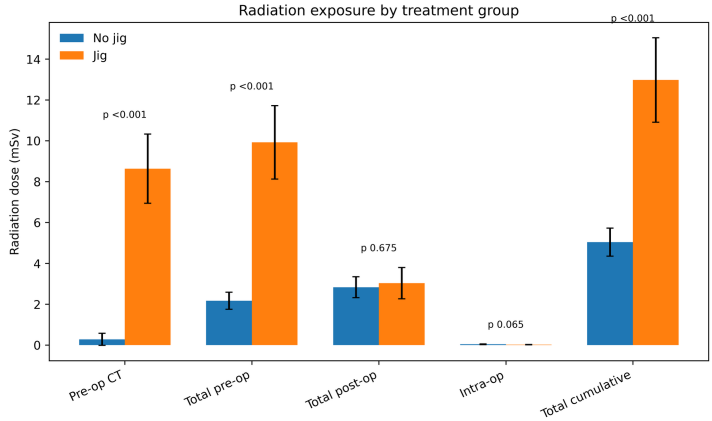

Figure 6: Mean radiation exposure by treatment group. Bars represent mean radiation dose in mSv and error bars represent approximate 95% confidence intervals around the mean.

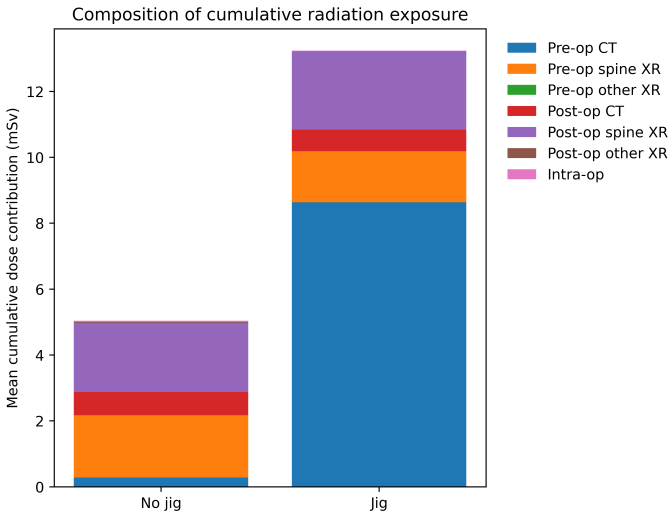

Figure 7 illustrates the composition of cumulative radiation exposure by imaging source.

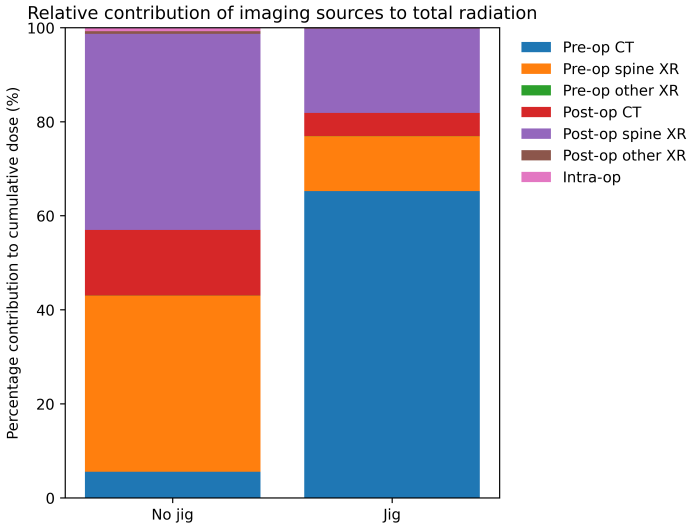

Figure 8 illustrates the percentage contribution of each imaging source to cumulative radiation exposure. The jig group is dominated by pre-operative CT exposure.

Discussion

This study emphasises the introduction of CT-based PSG for PSF is associated with an approximately 2.6-fold increase in cumulative radiation exposure compared with Jig 0 group. The increase was mainly driven by pre-operative CT scan, whilst intra-operative and post-operative radiation exposure remained comparable between groups.

To contextualise these findings, the additional cumulative dose associated with PSG (8.35mSv, $p<0.001$) is equivalent to approximately 3 years of natural background radiation in the UK (2.4mSv/year). (8) In this study, the maximum cumulative dose in Jig 1 is 33.34 mSv, highlighting that some individuals are exposed to relatively high cumulative radiation levels over the course of treatment. The Risk of Pediatric and Adolescent Cancer Associated with Medical Imaging (RIC) Study reported increased relative risks of haematological malignancy at cumulative exposures of 15-20mSv (RR 1.82) and 30-50 mSv (RR 1.97), with risks rising further at higher doses. (9) The predominance of females in this cohort (85%) is relevant given that breast and thyroid tissue are among the most radiosensitive organs in the body. Previous studies have also highlighted concerns over increased breast cancer incidence in female scoliosis patients following repeated imaging. (10) In this study, 10 patients exceeded 15 mSv, with 1 patient exceeding 30 mSv. This subset of patients is at a disproportionately higher risk of stochastic cancer, warranting efforts to find ways to minimise radiation exposure in AIS patients in follow-up.

AIS patients routinely undergo multiple imaging for diagnosis, monitoring of curve progression, operative planning and post-operative follow-up. In 2021, Loughenbury et al. reported the mean cumulative dose of 20. 95 mSv in surgically managed patients, with plain radiographs as the dominant radiation contributor. (11) Our findings reinforces this evidence by demonstrating that, within the surgically managed AIS patients, the driver of increased cumulative radiation is not due to frequent follow-up imaging, it is from pre-operative CT for PSG.

The higher pre-operative CT dose observed in the PSG group is expected and reflects imaging requirement necessary to manufacture accurate PSG. Studies have demonstrated that it improved pedicle screw accuracy and reduces incidence of neurovascular injuries, particularly in patients with more severe curve or complex anatomy. (12) It is important to interpret the additional radiation exposure observed within the context of recognised surgical benefits, and not on its own.

Although the difference in II doses was not statistically significant, it was marginally reduced in Jig 1. This could be explained by the reduction of repeated II confirmation of screw placement with the usage of PSG. This shows how PSG shifts radiation exposure from the operating theatres to the planning phase.(13)

For total post-operative radiation exposure, there was no statistically significant difference between treatment groups. This indicates that PSG does not influence the frequency of follow-up imaging.

The findings reinforce the importance of IR(ME)R17 principle that every medical exposure must be justified and radiation doses kept ALARP. Strategies such as low dose CT and EOS imaging techniques may help to reduce radiation exposure without compromising guide accuracy. In particular, EOS delivers up to 85% less radiation compared to traditional radiographs and it provides continuous image of the entire spine. (14)

Future studies should incorporate clinical outcomes alongside radiation exposure to better evaluate the overall value of CT-based PSG. Cost effectiveness analyses and use of lower- dose imaging modalities may help reduce radiation exposure whilst preserving PSG surgical advantages.

Limitations

This study has several limitations. This was a retrospective single-centre study, which may not be applicable in different institutions using different imaging guidelines or surgical techniques. Additionally, several radiographic examinations had incomplete dose documentation, which resulted in slight underestimation of cumulative radiation exposure.

E was estimated using published conversion coefficients rather than using Monte Carlo Radiation Transport Simulation, which represents the gold standard for patient-specific organ radiation absorption.

Conclusion

To conclude, the introduction of CT-based PSG significantly increased cumulative radiation exposure in AIS patients. The increase is primarily from pre-operative CT imaging, whilst II and post-operative radiation exposure are comparable between techniques.

Low-dose CT technologies, EOS imaging and optimised imaging pathways may minimise radiation exposure whilst preserving surgical benefits of PSG.

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