

**TITLE:**

The importance of the location of dorsal root ganglion stimulator electrodes within the nerve root exit foramen.

**RUNNING TITLE:**

DRGS electrode location in nerve root foramen

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**CONFLICT OF INTEREST STATEMENT:**

All authors declare that we have read *Neuromodulation: Technology at the Neural Interface's* full Conflict of Interest Policy and have disclosed all declarable relationships as defined therein.

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**ABSTRACT:****1. Objective**

To quantify the relationship between the electrical power requirement to achieve pain relief and the position of the active electrode of dorsal root ganglion stimulators within the spinal nerve root exit foramen.

**2. Materials and methods**

Retrospective analysis of prospectively collected data of 92 consecutive patients undergoing dorsal root ganglion stimulation for chronic pain in a single center. Cervical and sacral cases, and failed trials/explanted DRGS were excluded, so we report on 57 patients with 78 implanted leads.

Anteroposterior and lateral fluoroscopic images of the lead in the exit foramen were examined, and the active electrode positions were put into categories depending on their location relative to fixed anatomical landmarks. The clinical outcome and the power requirements for each of these groups of electrodes were then analyzed.

Overall pain outcome was assessed by numeric pain rating scale score pre-operatively and post-operatively.

**3. Results**

There was no significant relationship between power requirements and mediolateral electrode position, although the lowest average was observed with electrode positions directly below the center of the pedicle.

On lateral x-ray, the lowest power requirements were observed in the electrodes positioned superodorsally or dorsally within the foramen. Importantly, power requirements in this location were consistently low, while the power requirements in other locations were not only higher but also much more variable. Electrodes in the superodorsal position required a median output power almost four times lower than electrodes in other positions ( $p=0.002$ ).

Clinical outcome was not significantly related to power requirement or foraminal position.

**4. Conclusion**

Aiming for a superodorsal electrode position on lateral intraoperative fluoroscopy is desirable, since siting leads in this location reduces the required stimulator output power very substantially and thus will extend battery life. Position within the foramen does not determine clinical outcome, and so the implanter can safely aim for the low power site without detriment to the analgesic efficacy of the system.

**Key words:**

Dorsal root ganglion stimulation; implantable pulse generator; power consumption; chronic pain

## Introduction

Dorsal root ganglion stimulation (DRGS) has emerged in the last seven years as a new treatment option for chronic severe neuropathic pain of various etiologies. It is most often used in situations where the pain is confined to a relatively limited region such as the foot or the groin, although with multiple leads more extensive areas can be covered. A large RCT comparing DRGS against tonic spinal cord stimulation (SCS) showed superior outcomes with DRGS for complex regional pain syndrome (CRPS) in the lower limb (1). Encouraging results have also been seen in several other indications (2, 3).

Aside from efficacy, some of the advantages cited for DRGS compared to conventional tonic SCS are (a) less extraneous paresthesia outside the pain area, (b) the absence of postural shifts in paresthesia because unlike the spinal cord the DRG does not move relative to the electrode with changes in posture, (c) the possibility of paresthesia free operation and (d) the use of much lower stimulus currents because there is no CSF shunt between the electrode and the DRG.

The absence of extraneous paresthesia and of fluctuations in the level of paresthesia are arguably becoming less important with the advent of other paresthesia free stimulation paradigms such as burst and high frequency SCS. However, the low current requirement remains a key advantage, because it translates into greatly increased longevity between battery changes (or in theory between charges if rechargeable, although rechargeable DRGS systems are not yet available).

Battery life in neurostimulators is dependent on how much power they are delivering. For constant current devices delivering rectangular pulses the output power  $OP$  is given by:

$$OP = I^2 \times R \times f \times d$$

where  $I$  is the current amplitude,  $R$  is the impedance,  $f$  is the pulse frequency, and  $d$  is the pulse width. Similar calculations have been performed for deep brain stimulators before (4). Note that this follows the commonly made assumption that the impedance can be approximated as purely resistive.  $OP$  has previously been called ‘total electrical energy delivered’ or ‘TEED’, but it has dimensions of power rather than energy, hence we prefer the term ‘output power’.

Optimal (i.e. the lowest power to achieve desired clinical effect) power requirements would be predicted to occur when there is intimate contact between stimulating electrode and DRG. The DRG is located in the upper part of the exit foramen directly below the pedicle (5), with the motor root ventral to it, and a superodorsal electrode position is therefore typically recommended. The actual impact of electrode position on stimulator output power has not to our knowledge been accurately determined previously. Our goal in this paper is to determine to what degree the output power requirement is under the implanter’s control, i.e. how much the power requirements can be reduced by virtue of precise lead positioning. We will make two simplifying assumptions. Firstly, we will assume that impedance is not under the implanter’s control, i.e. there is not a predictable location in the exit foramen that would produce a lower or higher impedance than elsewhere. Secondly, we will assume that the pulse *frequency* that is needed for optimal pain relief is

unrelated to electrode position. Returning to the above equation, we are therefore left with current amplitude and pulse duration as factors that might be deliberately modifiable by lead positioning. This makes intuitive sense because we are effectively asking what effect electrode position has on the ease of excitation of the ganglion, and stimulation threshold is expressed in terms of these two things. Thus from the point of factors modifiable by the implanter, we can regard  $OP$  as proportional to  $I^2d$ .

In this study we analyse the output power requirements in a series of DRGS cases by foraminal position of the active (cathode) contact. In the subset of cases where patients were treated with a single electrode, and therefore the parameters of that electrode can be correlated with clinical results, we also analyze clinical results versus stimulus current and electrode position, to determine whether the two goals of optimal outcome and long battery life are conflicting or can be achieved simultaneously.

## Methods

### *Mediolateral electrode position*

Anteroposterior (AP) fluoroscopic images of the lead in the exit foramen were analyzed. Using the AP images, the mediolateral position of the cathode in the exit foramen was classified into 5 regions as shown in figure 1: (A) medial to the medial pedicular line, (B) beneath the medial third of the pedicle, (C) beneath the middle third of the pedicle, (D) beneath the lateral third of the pedicle, and (E) lateral to the lateral pedicular line. For example, the active (highlighted) electrode in figure 1 is in AP position C.

### *Rostro caudal and anteroposterior electrode position*

Lateral fluoroscopic images were analyzed. To categorize electrode position the upper part of the exit foramen was divided into three horizontal bands (superior, middle, and inferior) and 3 vertical bands (ventral, middle, and dorsal), yielding a 3x3 grid of 9 possible locations as shown in figure 2. For example, the active (highlighted) electrode in figure 2 is in position 4.

### *Analysis by clinical outcome*

Cases where treatment was with a single lead were analysed to compare clinical outcome with lead position and charge delivery levels. Patients with multiple leads covering contiguous dermatomes were excluded from clinical outcome comparison with current and foraminal location, because the overall clinical outcome could not be attributed to the location of any one of the leads. Responders were defined as patients experiencing  $\geq 50\%$  improvement in pain score.

### *Statistics*

Data were analyzed using a freely available statistical software program, R (6). Where there were sufficient numbers of data points, groups were tested for normality using the Shapiro-Wilk test. All datasets tested were non-normal and were therefore analyzed using the non-parametric Mann Whitney U test or Wilcoxon signed rank test, with the Kruskal-Wallis test being used for datasets with multiple categories.

## **Results**

### *Cases*

We reviewed the imaging of 92 consecutive patients. We excluded all failed trials, one explant due to infection, and one who had a lead migration awaiting revision. We also excluded implants in the cervical or sacral spine where the anatomy is too different to permit meaningful comparison with the thoracolumbar cases that made up the rest of the series. Following these exclusions there were 57 patients included for analysis (31 males and 26 females), with an average age of 43.6 years (range 20.1 – 81.7 years). These patients have been followed up for a median 23.2 months.

Of the 57 patients, 38 patients have a single lead, 18 have 2 leads, and 1 has 4 leads giving a total of 78 DRGS leads for analysis.

With regards to implant level, 5 of the analyzed leads were thoracic: one at each of T8, T9, and T11, and two at T12. The remainder were lumbar: 13 at each of L1 and L2; 9 at L3; 11 at L4, and 27 at L5.

### *Indications for surgery*

These are summarised in table 1. The most common indication in the group studied here was complex regional pain syndrome (24 patients, 43%). Other indications included testicular or groin pain (10 patients), post-traumatic pain in lower limb and back (4 patients), chronic post-operative pain (e.g. after knee surgery, total hip replacement) (5 patients), phantom limb or stump pain (3 patients), and renal pain (2 patients).

### *Effect of mediolateral electrode position*

Mediolateral electrode positions were obtained from anteroposterior radiographs. There were complete data for current, pulse width, active electrode, and an available radiograph for 74 out of the 78 leads.

The median  $I^2d$  for each of the five defined areas is shown in table 2 and fig 3. The lowest median  $I^2d$  is observed in electrode positions directly below the pedicle, however the difference between the groups is not statistically significant ( $p=0.50$ , Kruskal-Wallis test).

### *Rostro caudal and anteroposterior electrode position*

These electrode positions were obtained from lateral radiographs. There were complete data for current, pulse width, active electrode, and an available radiograph for 67 leads.

The active electrode was categorized into regions as in figure 2. The median  $I^2d$  in each of these areas is shown in table 3 and is represented in fig. 4. The lowest median  $I^2d$  was in the superodorsal position 1 and dorsal position 2.

Given that the lowest median  $I^2d$  were obtained in positions 1 and 2, we compared these groups together with the others. The median  $I^2d$  in positions 1 and 2 together was 82.9 mA<sup>2</sup>.μs, and it was 324 mA<sup>2</sup>.μs for the other groups together. This was a highly significant difference ( $p=0.002$ ; Mann Whitney U).

These results imply that a superodorsal or dorsal electrode position within the exit foramen is best for minimizing output power requirements.

### *Pain outcomes*

The mean pre-operative numeric pain rating scale (NRS) score for the entire group was 8.2, and the mean post-operative score was 3.6 ( $p=1.5 \times 10^{-11}$ , Wilcoxon signed rank test). Changes in NRS are shown in figure 5. The mean percentage improvement in pain score was 57% and the responder rate (those with an improvement in pain score of at least 50%) was 63%. There was an improvement in pain score of at least 30% in 84%.

### *Pain outcomes vs. location*

Comparison of the percentage improvement in pain score was carried out for the active electrode position groups. There was no difference between the groups on anteroposterior radiograph electrode position ( $p=0.15$ , Kruskal-Wallis signed rank test) or lateral radiograph electrode position ( $p=0.07$ , Kruskal-Wallis signed rank test, fig 6).

Furthermore, there was no correlation between  $I^2d$  and percentage improvement in pain score across the whole cohort (Pearson's product moment correlation coefficient = -0.027,  $p=0.82$ , fig 7).

### *Pain outcomes by indication (Table 1)*

The highest average percentage improvement in pain scores was observed in patients with groin or testicular pain (86%), post-traumatic pain (69%), and complex regional pain syndrome (57%). The responder rate was also high in the complex regional pain syndrome group (68%) and groin/testicular pain group (80%). The results for the other groups should be interpreted with caution due to the low number of observations.

### *Power requirement by indication*

In order to exclude aetiology of pain as a confounding variable, we examined whether  $Pd$  was dependent on pain aetiology. We divided pain aetiology into 3 categories: CRPS, groin pain, and other causes. As shown in figure 8, there is no significant relationship between pain aetiology and  $Pd$  requirement ( $p=0.95$ , Kruskal-Wallis test).

## **Discussion**

### *Limitations of the study*

With five mediolateral positions and nine locations in the sagittal plane defined for our analysis, we could potentially divide electrode positions into 45 different categories. This is clearly untenable as the number of electrodes in most of the categories would be very small and comparisons would be uninterpretable. We have therefore made the simplifying assumption that position in each of these two ways can be analysed independently.

We have also assumed that the definition of location is applicable to all vertebral levels in the thoracolumbar spine, i.e. that the DRG is in an approximately constant position with respect to the pedicle. This is not exactly true, in particular the DRG at L5 is slightly lateral compared to other levels (4). We have excluded cervical levels because the anatomy is substantially different.

Finally, and for the same reasons, when analysing outcome data, we recognise that the group contains several different indications for treatment but have not subdivided patient groups by aetiology of neuropathic pain. While it is certainly conceivable that different pathologies might result in different excitabilities of ganglion cells, we are presently unaware of experimental evidence that this is the case, and analysis of our data did not show any significant variation of  $Pd$  requirements from pathology to pathology.

### *Output power requirements vs. electrode position and implications for battery life*

Low energy consumption is a key advantage of DRGS. We have shown that there is a large difference in  $Pd$  in different foraminal positions on a lateral radiograph. In the series presented here, the median  $Pd$  in the most optimally positioned (superodorsal) electrodes was approximately a quarter of that of electrodes placed in other positions. This will translate directly into prolonged IPG battery life.

Not all of the power from the battery is delivered to the tissue being stimulated. There is thermal power dissipation in the pulse generator circuitry and in the microcontroller that manages it, and these will contribute to battery depletion. The magnitude of these power 'overheads' and what proportion of overall battery depletion they account for is known only to the manufacturer. The practical upshot is that, for example, a halving of output power cannot be expected to result in a doubling of battery lifespan, because the other power dissipation overheads will remain. The actual increase in longevity will certainly be substantial but can be expected to fall somewhere short of double in this example.



Nevertheless, well positioned electrodes should dramatically extend the mean service life of IPGs with no detriment to efficacy. Every IPG change carries a risk of infection with consequent system and therapy loss, and increased battery life leading to longer intervals between IPG replacement will reduce the patient's exposure to this risk in the long term. As well as the benefits to the patient, reducing the frequency of IPG changes will substantially improve the cost effectiveness of the therapy.

### *Clinical outcome*

Nearly two thirds of patients experienced at least 50% pain relief. Although  $I^2d$  was dependent on lead position on a lateral radiograph, clinical outcome was not dependent on position. This suggests that choosing a lead position with the aim of minimising output power will not compromise clinical outcome.

## **Conclusion**

Lead position in the exit foramen very substantially impacts power requirements in DRGS without affecting clinical outcome. A better position can extend battery life without sacrificing efficacy.

## **Acknowledgement**

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## Tables

Indication	N	Mean pain improvement (%)	Responder rate (%)
Complex regional pain syndrome	24	58	68
Groin/testicular	10	73	80
Post-traumatic	4	68	50
Other post-surgical	5	39	40
Phantom limb/stump	3	50	67
Renal pain	2	60	50
Other	9	51	55

Table 1. Indications for surgery and their outcome

Electrode position	A	B	C	D	E
Median $\bar{P}d$ , mA <sup>2</sup> . $\mu$ s	328	193	167	178	324

Table 2. Median  $\bar{P}d$  in mediolateral electrode locations.

Electrode position	1	2	3	4	5	6	7	8	9
Median $\bar{P}d$ , mA <sup>2</sup> . $\mu$ s	50.0	145	NA	399	389	294	179	213	858

Table 3. Median  $\bar{P}d$  in lateral radiograph electrode locations.

## Figures

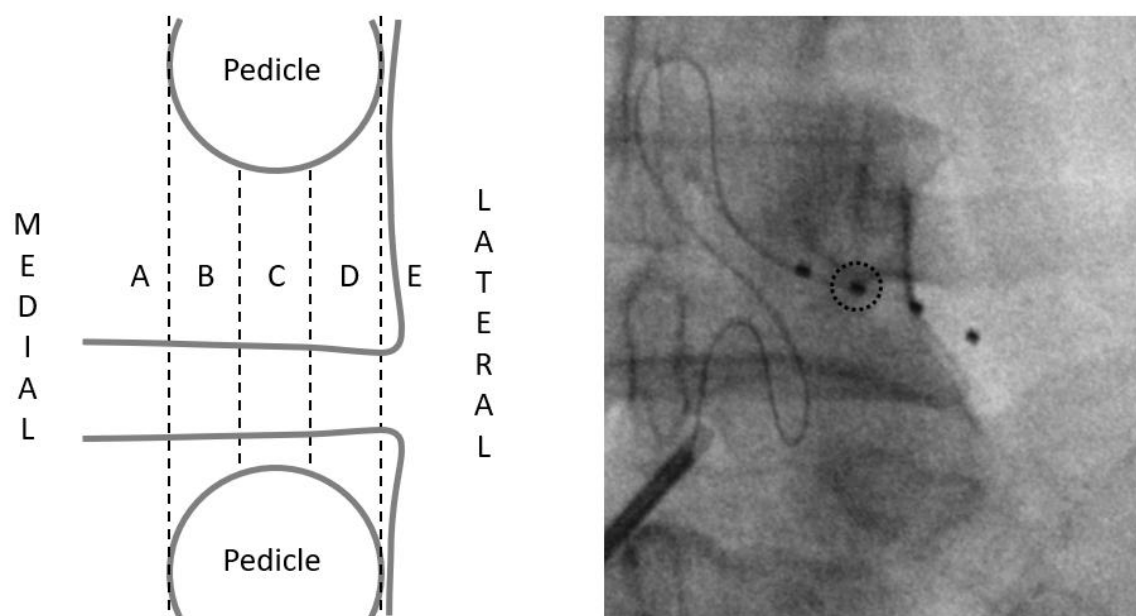


Figure 1. Mediolateral electrode position as defined relative to the pedicle (described in text). The active (highlighted) electrode is in position C.

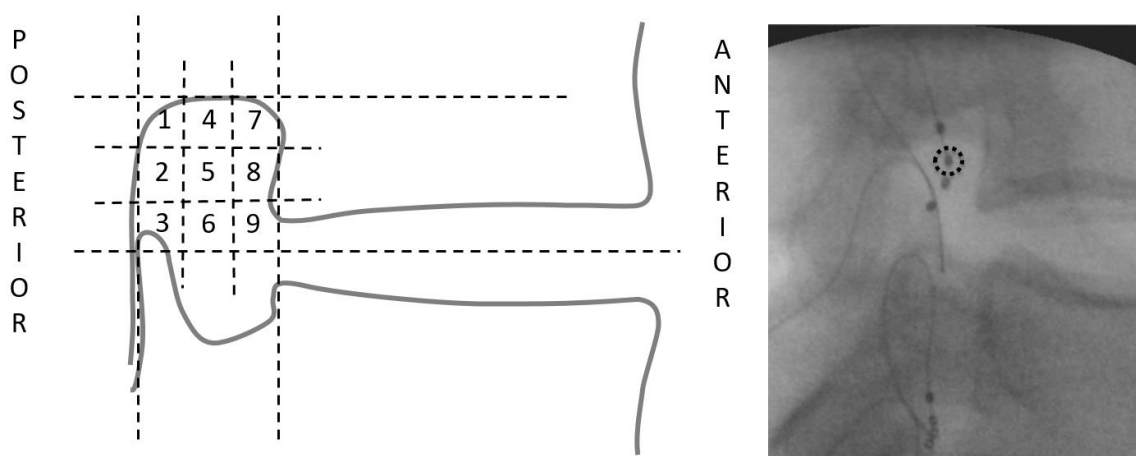


Figure 2. Lateral positions. Boundary definitions: anterior = posterior vertebral line; superior = inferior border of pedicle; posterior = anterior border of posterior elements; inferior = line bisecting disc space. The active (highlighted) electrode is in position 4.

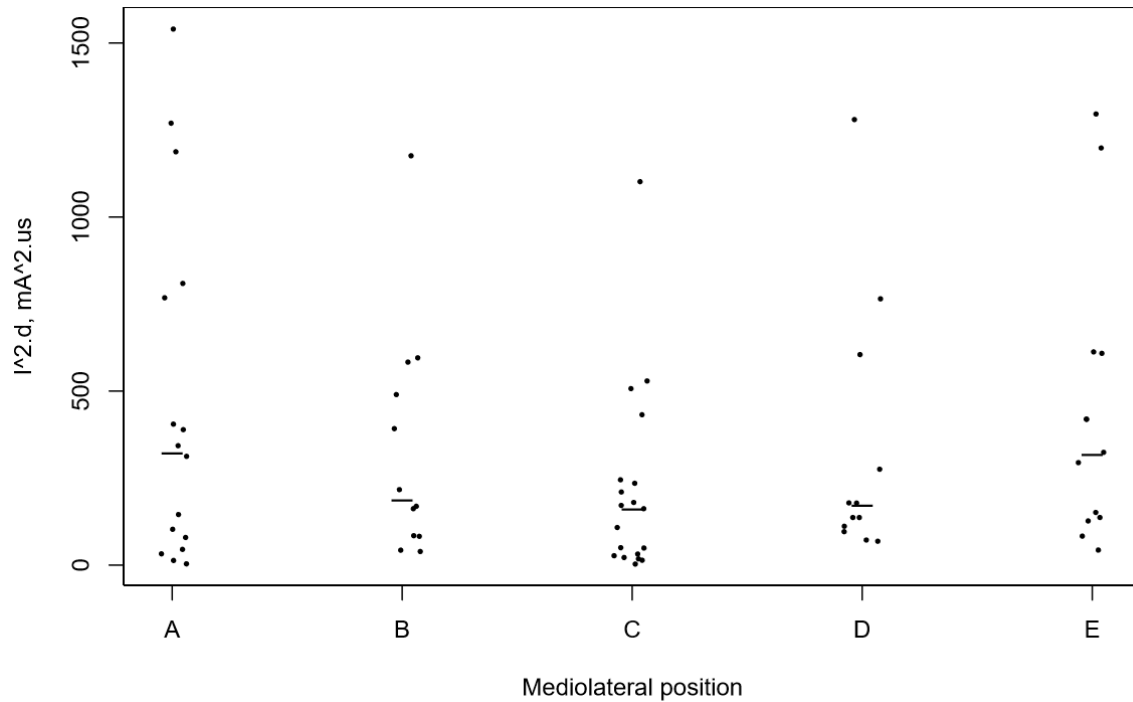


Figure 3.  $I^2d$  requirements in each mediolateral electrode position. The lowest median  $I^2d$  is directly below the middle of the pedicle in position C.

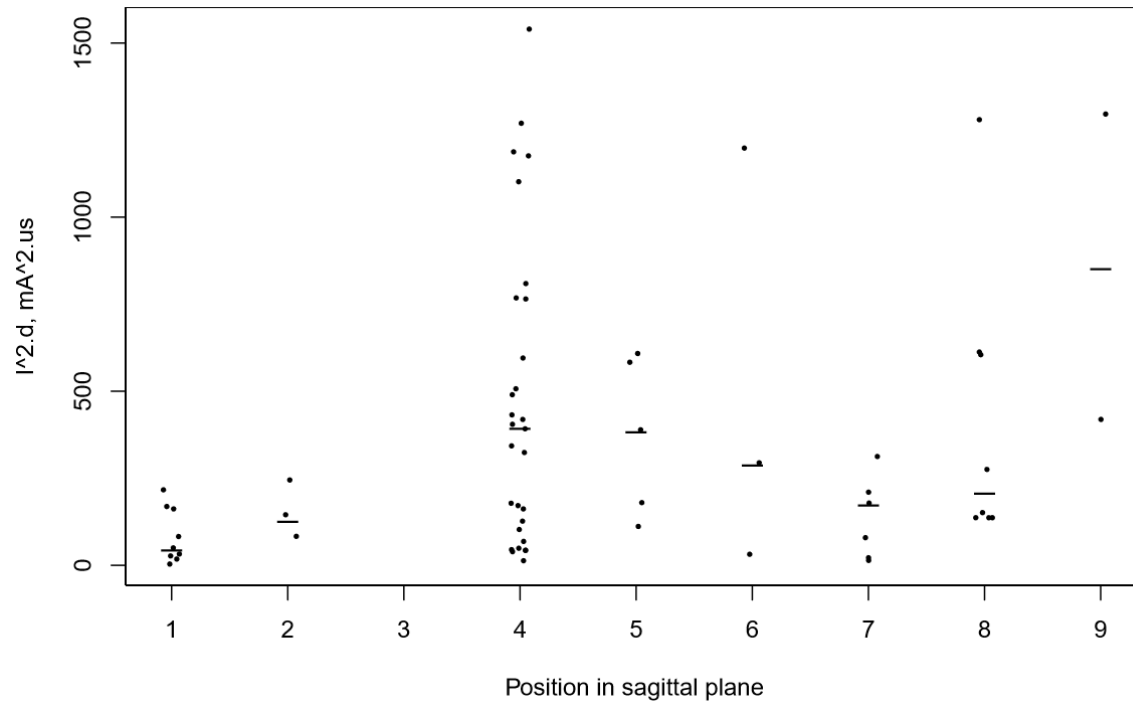


Figure 4.  $I^2d$  requirements in each rostrocaudal and anteroposterior electrode position. The lowest median  $I^2d$  is in the superodorsal corner of the foramen in position 1.

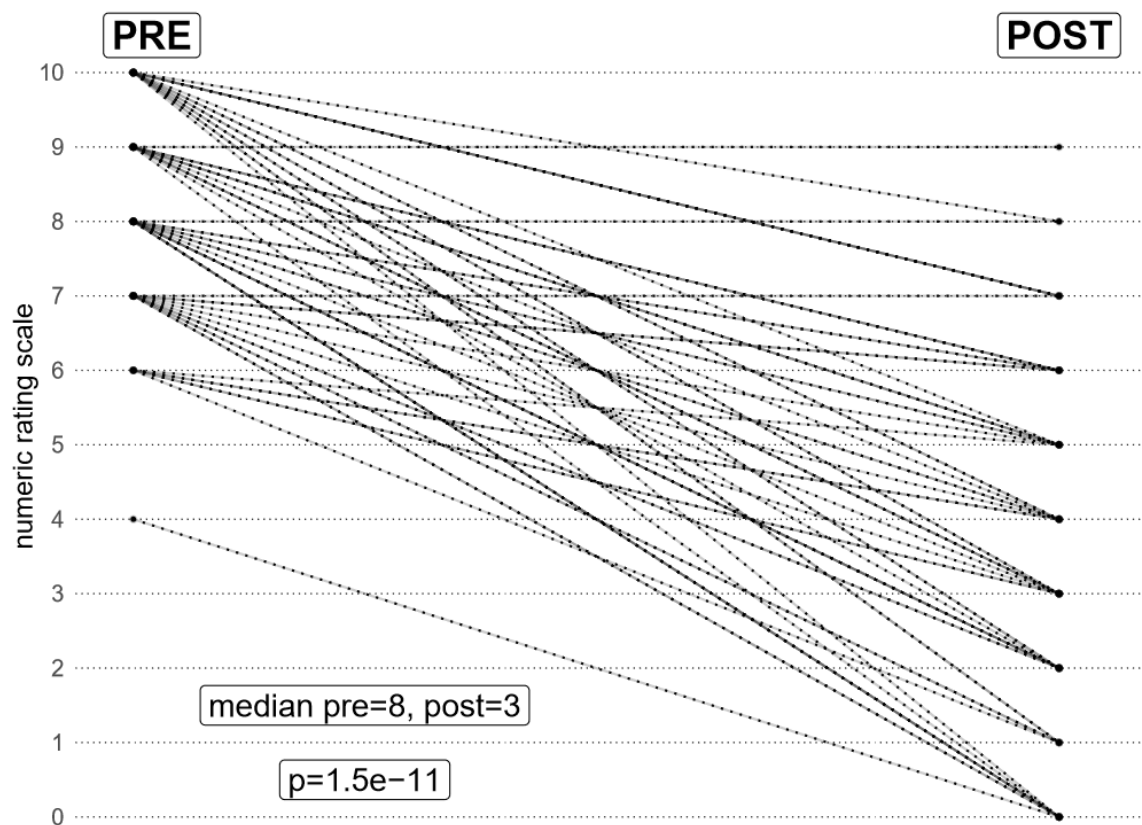


Figure 5. Pain numeric rating scale scores before and after surgery (median pre surgery =8, post-surgery = 3,  $p=1.5 \times 10^{-11}$ , Wilcoxon signed rank test).

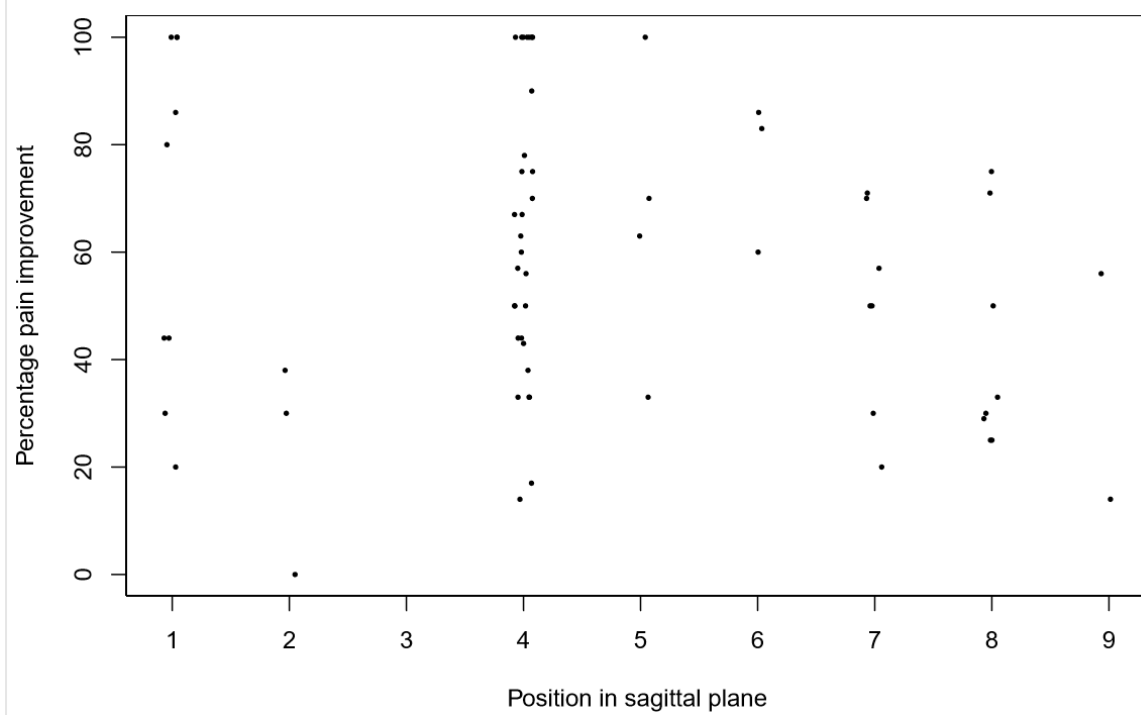


Figure 6. Percentage pain improvement is not significantly different in different sagittal positions

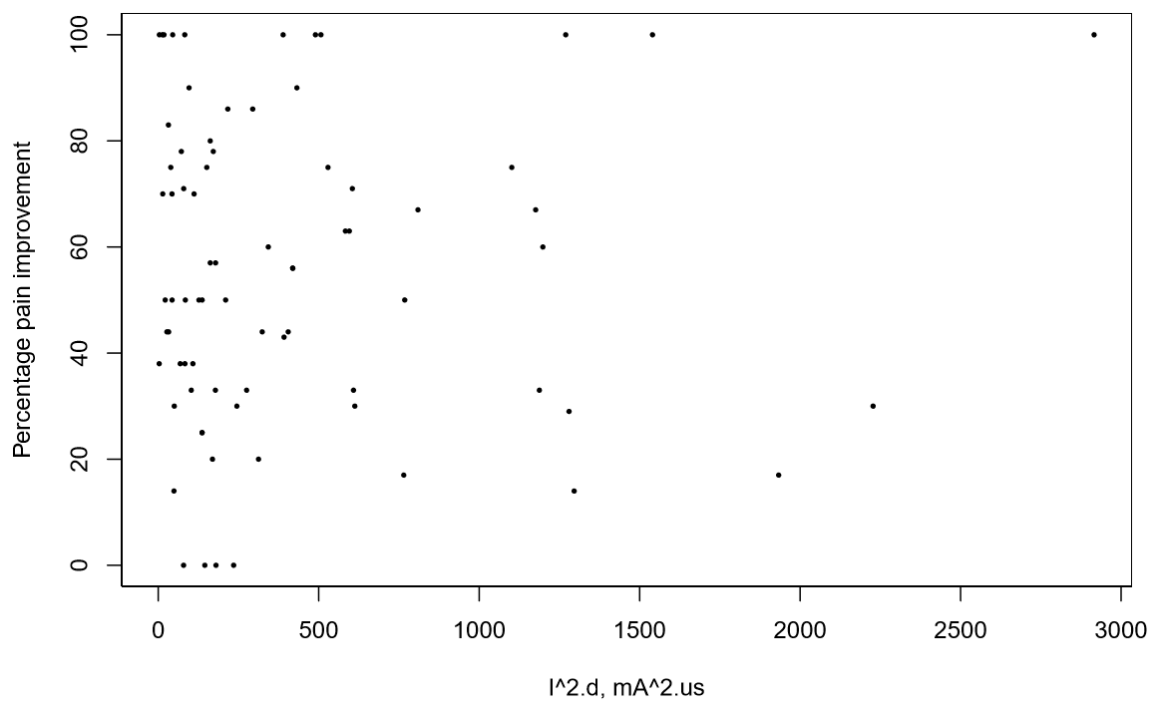


Figure 7.  $I^2d$  and improvement in pain score are not correlated ( $p = 0.8$ )

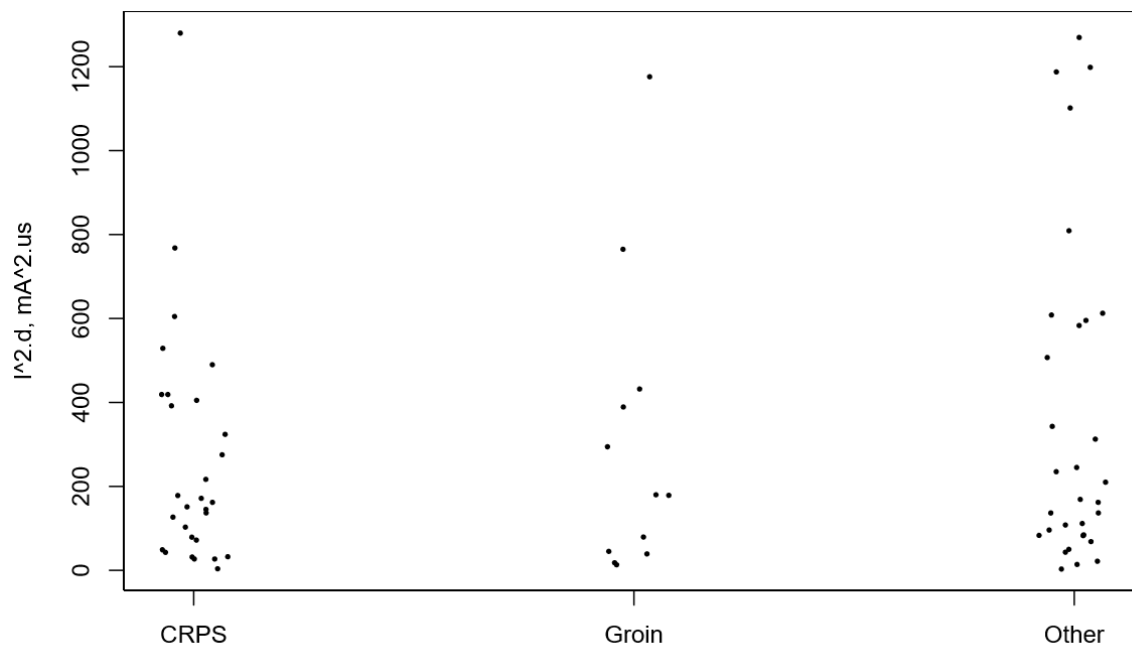


Figure 8.  $I^2d$  is not significantly different for different pathologies