Title:

Electrode movement prevention – an animal model

Short title:

A new electrode fixation protocol

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Electrode movement prevention – an animal model

Abstract

Introduction

Electrode migration is the most common complication of spinal cord stimulation (SCS). The problem of longitudinal migration has already been solved, but lateral migration remains the most common current complication. The present article describes new electrodes fixation opportunities for the reduction of lateral migration in SCS.

Material and Methods

The pig was chosen as an animal model to illustrate a new protocol of electrode fixation for the control of lateral and longitudinal migration. The displacement of the electrode was measured using two different optical methods: the digital image stereo-correlation and the digital image processing methods.

Results

Fixation with two anchors has always considerably reduced electrode displacement and when fixation is done with two anchors and a loop then lateral migration is reduced by 62.5% and longitudinal migration is reduced by 94.1%. It was shown that the results are significantly different at the α=0.001significance level.

Conclusion

Based on a statistical evaluation it is possible to state that the differences between experimental results obtained for three different protocols of lead fixation are statistically significant and we can recommend the new fixation method for common practice.

Key words spinal cord stimulation, electrode movement prevention, pig model

Introduction

Neuromodulation is the process in which several classes of neurotransmitters in the nervous system regulate diverse populations of neurons, but neuromodulation in neurosurgery is the process in which artificial devices alter the function of the nervous system. One of the neuromodulation methods for the treatment of chronic pain is spinal cord stimulation (SCS). Electrode migration is the most common complication of SCS and is more frequent with percutaneous electrodes than with paddle-type ones. Electrode migration may be compensated by stimulator reprogramming, but if this fails, surgical repositioning is mandatory (Bendersky and Yampolsky, 2014).The most common complication that requires a revision surgery in 23% of patients is electrode displacement (Andersen, 1997). Wire migration is hard-ware complications. SCS is associated with several complications. Hardware-related complications are common in 38% of cases and this includes wire migration in 22.6% (Makhail et al., 2011). In the present article a new electrodes fixation is described–to reduce wire migration complications. Two anchor fixation options and three different types of lead fixation are discussed in this work.

Material and Methods

One pig (Landrace, 53kg) was used for all experiments. Prior to the study, the animal was housed in an accredited conventional University animal facility with natural daylight, free access to water, feed twice daily by a mixture recommended for young swine. Ambient conditions (temperature, air) were regulated according to relevant recommendations. Animals were kept in groups of up to four. The pig was anaesthetised using a standard general anaesthesia procedure. After 24 h of fasting, anesthesia was induced by midazolam (0.3 mg/kg IM) followed by ketamine hydrochloride (15 to 20 mg/kg IM). Anesthesia was continued with initial propofol and morphine boluses, (2 mg/kg IV and 0.1 to 0.2 mg/kg IV, respectively) and

animals were orotracheally intubated. Continuous IV infusion of propofol (8 to 10 mg/kg/h) combined with morphine (0.1 to 0.2 mg/kg/h) IV were used to maintain anesthesia, the depth of which was regularly assessed by photoreaction and corneal reflex. Anesthesia was provided during the whole study. Mechanical ventilation was maintained throughout the study in volume control regime set to Vt 8 ml/kg, PEEP 5 cm H_2O, FiO_2 0.25, I:E 1:2, rate adjusted to keep pCO_2 5.0-5,5 kPa (34-41 mm Hg). Stimulating electrodes were inserted through the fascia and the muscle (musculus longissimus dorsi) up to the cutaneous surface to simulate the passage of an electrode in the real environment. The electrode passed through the fascia and the muscle and the slave followed at a distance of 10 cm.The lead was fixed in the incision before entry into the spine by one of the methods listed above. Fixation was carried out to the fascia in all cases. The second end of the lead was tunnelled from the side of the pig and fastened to a rope. The rope passing over a pulley was loaded with a weight of 1 kg, causing the movement of the wire. The rope was loaded gradually over the course of 15 seconds. Porcine respiratory movements were eliminated (arteficial ventilation) during the measurement. The displacement of the electrode was measured and evaluated by two different optical methods (Sun et al., 2002):

- Digital image stereo-correlation method
- Digital image processing method

Digital image stereo-correlation method

Measurement and evaluation were carried out by a ISTRA4Dantec Dynamics optical correlation device which allows non-contact measurement of the three-dimensional displacements of points on the surface of a body. One white target with random pattern of black dots was attached to the electrode and the second one on the skin of the pig (Fig. 4).The targets moved slowly during the loading of the wire. The images of the moving targets were recorded simultaneously by two cameras with a sampling frequency of 17 frames per second (Fig. 5). The recorded images were then processed with the ISTRA4 software and the 3D coordinates (x, y and z) of the target points were determined. The three components of displacement Δx, Δy and Δz were calculated as the difference of coordinates between the actual and the reference images. The example of total displacement evaluation is illustrated in Fig. 6.The electrode with its target lies freely on the dorsal part of the pig and therefore the movement of the target is a general spatial motion. The total displacement d of the end of the electrodes is described by the equation

$$d = \sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2}.$$

Measurement of electrode displacement by means of digital image processing (DIP)

The measurement was focused on precise determination of the displacement of the electrode in the longitudinal direction of the spine. A small glass tube with an internal diameter of 3 mm was fixed with sutures onto the dorsal skin of the pig parallel to the spine. The pseudo-stimulation wire was passed through the epidural space, up to the body surface of the pig and inserted into the tube; Fig. 7.Two targets were glued onto the surface of the tube with a distance of 100 mm between them ensuring a fixed benchmark permanent photographic image. The electrode could move freely in the tube axis direction while its movement in the transverse direction was limited by the tube wall. The wire was loaded in the same way as previously described. In each experimental session, two digital images of the electrode position were recorded with a resolution of 4608 x 3456 pixels.The first image was recorded before any load application (starting position) and the second one was recorded in steady state at the end of loading.

The pixel coordinates of both targets and the labelled end of the electrode were determined in each image with the Matlab Image Processing Toolbox. The coordinates correspond to places with the maximum correlation coefficient between matrix *A* containing the grayscale intensities of rectangular area around the targets or around the electrode end and matrix B of the same size picked from every image using detailed scanning. The correlation coefficient *r* is defined by

$$r = \frac{\sum_m \sum_n \left(A_{mn} - \bar{A}\right)\left(B_{mn} - \bar{B}\right)}{\sqrt{\left(\sum_m \sum_n \left(A_{mn} - \bar{A}\right)^2\right)\left(\sum_m \sum_n \left(B_{mn} - \bar{B}\right)^2\right)}},$$

Where $\bar{A}$ and $\bar{B}$ are the means of values in matrices *A* and *B*. The distance of the targets in pixel units in every image was used for conversion between pixels and millimetres. The targets distance was 100 mm, or about 2811 pixels, respectively, and therefore the measurement accuracy of the position of the electrode is higher than 0.1 mm.

Results

Digital image stereo-correlation method

Three different ways of wire anchoring were chosen for comparison of the electrode movement. The influence of the different ways of anchoring the wire is illustrated on Graf. 1 where the total displacement *d* during the loading are displayed. The electrode displacement depends markedly on the anchoring lead, namely the number of anchors and the type of lead anchoring. It is evident that fixation of the lead by two anchors with a loop between them significantly reduces the total displacement of the electrode, i.e. the lateral migration of the electrode was reduced by 62.5%

Measurement of electrode displacement by means of digital image processing (DIP)

The position of the electrode end was determined in each image and its displacement of the electrode was calculated as the difference between its positions before and after loading. The results of the three sets of measurements are presented in Graf. 2 and in Table 1.It is evident that the method of wire anchoring is critical in avoiding displacement of the electrode due to sudden patient movement (longitudinal migration).

Exploratory data analysis (EDA) was conducted within statistical analysis of the results and the parametricity was verified by the Shapiro-Wilk test. Subsequently analysis of variance (ANOVA) was used to assess the significance of the difference between electrode displacements measured for the three types of fixation. It was shown that the results are significantly different at the α=0.001significance level.

Discussion

Military University Hospital is a large neuromodulation centre in Czech Republic. The major part of neuromodulation therapy in Czech Republic is performed there. We have many years of experience. The first neuro-stimulation of SCS in Czech Republic was performed at our department in 1973 (Beneš et al., 1973).A new type of electrode fixation was used with two anchors and a loop in our department over the last two years. We have had no complications with electrode migration since we started using the new fixation method. This is why we wanted to demonstrate the importance of the new fixation method in laboratory conditions.

The most common type of neuromodulation is the stimulation of SCS. In the world litterature the terms neuromodulation and neuro-stimulation are often confused or published for the same concept (Rokyta and Fricova, 2012).

The main indication for neuro-stimulation is failed back surgery syndrome (FBSS). In more than 85% of cases, neurostimulation is performed in patients with FBSS (Masopust, 2014). One of the causes of FBSS is epidural fibrosis (EF) (Braverman et al., 2011; Coskun et al., 2000). Although neuromodulation remains the most widely used method for treatment of refractory pain at FBSS, there is no evidence of the greater effectiveness of SCS versus alternative treatments (Turner et al., 2010). Neuromodulation may still be beneficial for carefully classified patients. (Waszak et al., 2017)

Our patients who are indicated for neuro-modulation have MRI-proven EF in more than 90% of cases (Masopust et al., 2014). EF behaves as a reparative inflammation with characteristic symptoms and clinical course (pain) (Masopust et al., 2007). FBSS is a major cause of chronic neuropathic pain. FBSS affects more than 40% of patients who undergo spinal surgery for low back pain (Lad et al., 2014).The relationship between EF and FBSS has been widely discussed in the algesiological literature. Especially, the role of EF in the development of FBSS is discussed, as is its prevention and treatment. Clinically significant EF is described in the literature as between 5% and 33% (Frish et al., 1996, Cinottis et al., 1998). If the patient is predisposed to EF, we assume that the moving activity of the electrodes is low for scarring of electrodes. But it is true that EF does not affect electrode fixation due to a long period of scarring and electrode migration was the most common complication for our patients.

SCS is associated with many complications. Hardware-related complications are common in 38% of cases (Makhail et al., 2011). These complications included electrode displacement in 22.6% of cases (Makhail et al., 2011). Electrode migration is the most common complication of SCS. An electrode shift occurs more often for percutaneous electrodes than for paddle type ones (Bendersky and Yampolsky, 2014).

We can sometime solve the electrode movement by neuro-stimulation reprogramming-but this solution is not always possible and surgical repositioning is necessary in 23% of cases (Andersen, 1997).

A special case is deep brain stimulation, where there is the possibility of fixation to the bone (Contarino et al., 2013).

Other complications are very rare. These complications include epidural hematoma and a dura injury with cerebrospinal fluid leakage (Eldrige et al., 2006; Franzini et al., 2005). The rarest complication is epidural abscess (Rauchwerger et al., 2008). We can influence these

complications and minimize them with the correct insertion angle and a smooth introduction. “Midline anchoring” is used (Mironer et al., 2004).

But why is the migration of wires so frequently a complication? Many types of anchors were manufactured when neuromodulation therapy became the standard medical method. Now we can use a firmer anchoring system in practise. The result is a stronger connection between electrode and anchor. But today we know that fixation between the anchor and electrode is not the cause of electrode movement. Unfortunately there exists the problem of the biological response of tissues. The tissues are different for each individual. Collagen is the most abundant structural protein to be found in the extracellular matrix. These proteins have mechanical and supportive functions in a wide range of connective tissues (Sun et al., 2002).
The elasticity of a tissue is determined by the type of collagen monomer and its occurrence. And it is precisely the elasticity of the tissue that is the first cause of the instability and electrode shift. The second cause of instability is a fixation at one point between an anchor and a fascia. The fixation is done on both sides of the anchor. The anchor with three silicone wings was made and recommended as a prevention of anchor movement (Kumar et al., 2007). More point fixations cannot help us with our problem of the movement of an electrode because fixations are done between an electrode and a fascia near each other. The displacement can be reduced by fixing the anchor to the deep fascia firmly and supplemented by using of silicone glue and by placing the pulse generator on an abdominal wall instead of the gluteal region (Kumar et al., 2007). However although these recommendations are beneficial, they cannot change the number of complications resulting from physical laws. When the bar is fixed in one place, then no number of fixations can prevent the bar from moving in a circle. If we want to impede the movement of the rod, we have to make two fixations in two places sufficiently far apart. We can only use these methods if the bar is rigid. When the rod is flexible then the fixation points cannot be placed into one plane, otherwise the rod bends between fixations and we are not able to impede movement of the distal end. This conclusion should be validated in an animal model. We need evidence for the hypothesis that the displacement of the electrode depends markedly on the anchoring wire, namely the number of anchors and the manner of the anchoring wire. And for that we did three models. The first model was with one anchor, the second model was with two anchors close to each other and the last and third was a model with two anchors with a loop between them (Petrikova et al., 2017).

Two types of electrode migration are possible. The first type is lateral migration and the further type is longitudinal migration. A change in electrode position on a dura surface without the

possibility of reprogramming is created by lateral migration. Longitudinal migration is important in order to avoid a progressive ejection of electrodes. Longitudinal migration was resolved as early as 2006 (Renard and North, 2006). Lateral migration remains the most common complication today. An animal model was used to demonstrate the importance of our new model of fixation for lateral migration.

On the animal model, the electrode was implanted through the same tissue as in humans, this means through the skin, subcutaneous fat, fascia and muscle. The rope trajectory was the same as in our patients, it means at right angles to the electrodes because in this way the rotational movement of the body is simulated. The respiratory movements of our porcine were eliminated during the measurement. That was needed if we wished to attain maximum reality. An animal model was anaesthetised using standard general anaesthesia means.

It was evident from our measurements that electrode fixation by two anchors with a loop between them significantly reduces the total displacement of the electrode i.e. lateral migration. Our measurement was made by the digital image stereo-correlation method. Lateral migration of the electrode was reduced by 62.5%

Using digital image processing, it is evident that the method of anchoring wire is critical in order to avoid the displacement of the electrode due to sudden patient movement. Lateral migration of the electrode was reduced by 94.1% It was shown that results are significantly different at the a=0.001significance level.

Results which were obtained by both measuring methods demonstrate the difference between the tested types of anchoring wires. Fastening with two anchors significantly reduced the displacement of the electrodes. The electrode almost does not move when fixation is performed with two anchors and a loop. The average shift was less than 1mm.

Based on a statistical evaluation it is possible to state that the differences between the experimental results obtained for three different types of cable fixation are statistically significant.

Conclusion

Results obtained by both measuring methods demonstrate the difference between the tested types of anchoring wires.

Fixation with two anchors has always considerably reduced electrode displacement and when fixation is performed with two anchors and a loop then lateral migration is reduced by 62.5% and longitudinal migration is reduced by 94.1%

Based on statistical evaluation it is possible to state that the differences between experimental results obtained for three different types of cable fixation are statistically significant and we can recommend the new fixation method for common practice.

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Pictures:

Figure 1. Electrode fixed by one anchor

Figure 2. Electrode fixed by two anchors

Figure 3. Electrode fixed by two anchors with a loop

Figure 4. Target with random pattern of black dots

Figure 5. Digital image stereo-correlation system with two cameras

Figure 6. Example of total displacement evaluation.

Figure 7. Experimental setting of the electrode displacement (DIP)

Graf 1. Total displacement of the end ofelectrode.

Graf 2. Displacement of electrode for different anchoring wires

Table 1. Displacement of electrode for different anchoring wires

Fig 1

Fig 2

Fig 3

Fig 4

Fig 5

Fig 6

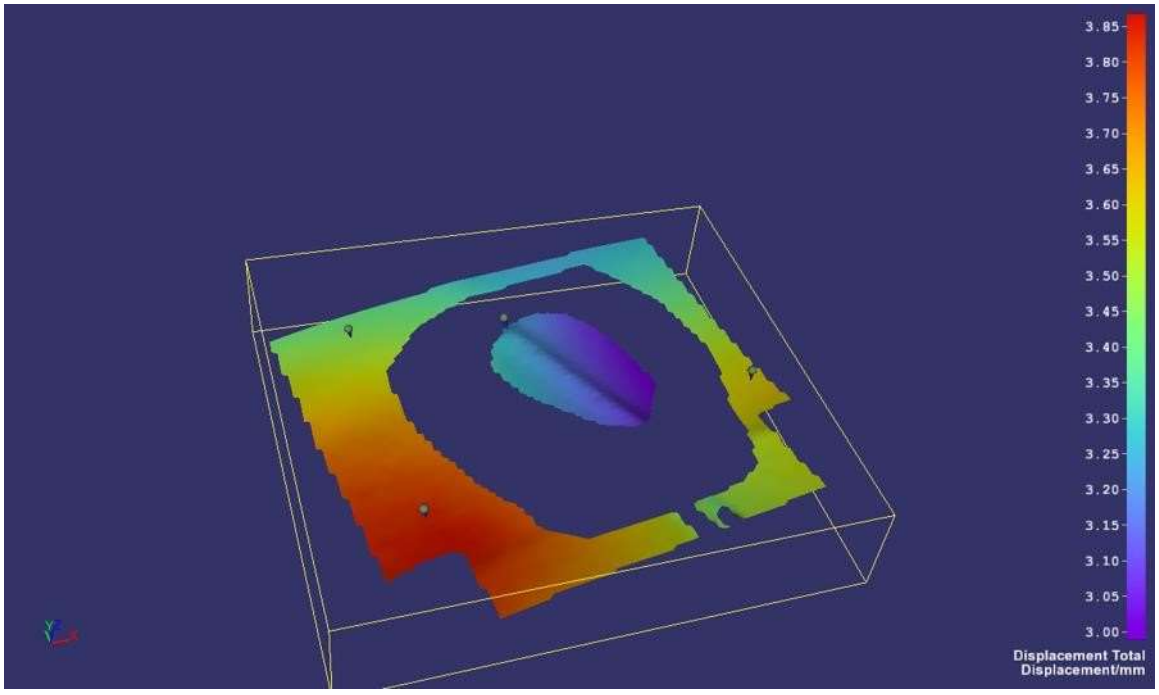
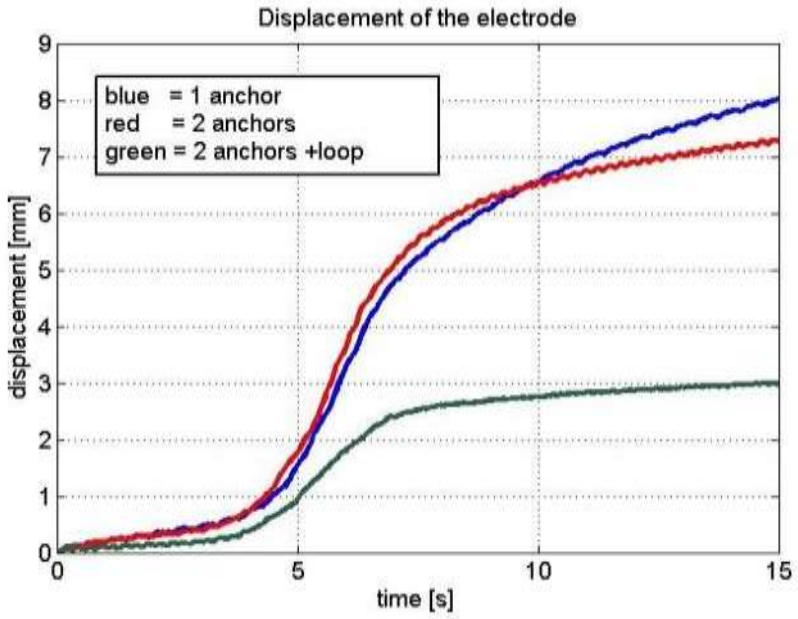
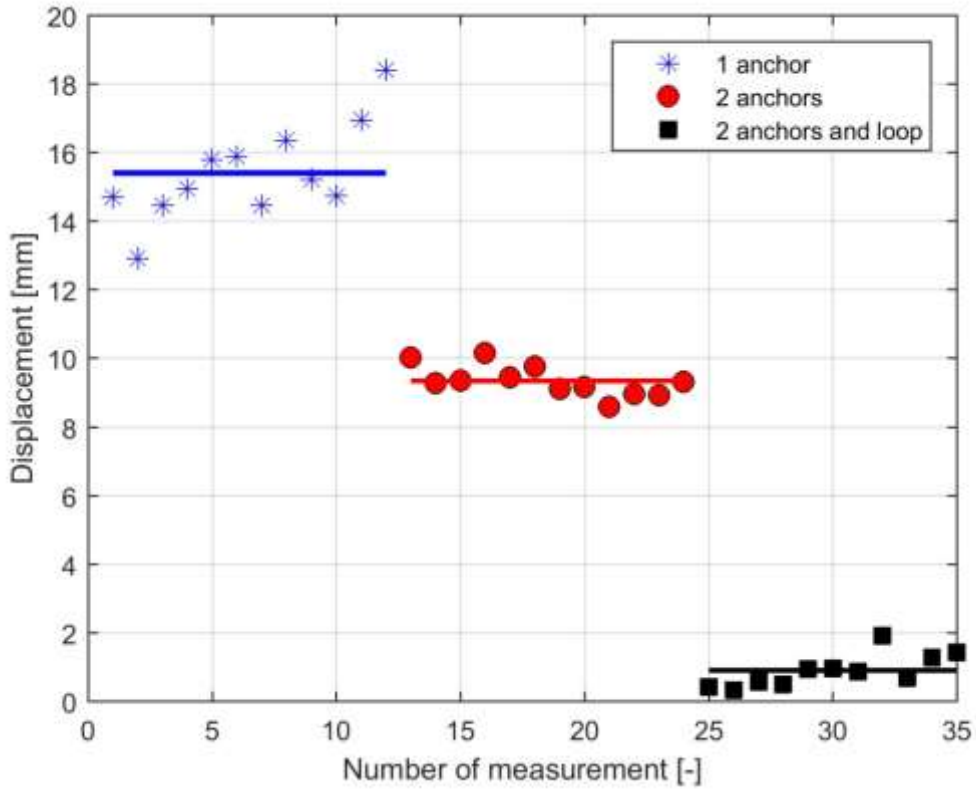

3.85
3.80
3.75
3.70
3.65
3.60
3.55
3.50
3.45
3.40
3.35
3.30
3.25
3.20
3.15
3.10
3.05
3.00
Displacement Total
Displacement/mm

Fig 7

Graf 1


Displacement of the electrode
blue = 1 anchor
red = 2 anchors
green = 2 anchors +loop
displacement [mm]
time [s]
0
1
2
3
4
5
6
7
8
9
0
5
10
15

Graf 2



Tab 1

Way of anchoring wire	1 anchor	2 anchors	2 anchors and loop
Number of measurements	12	12	11
Average displacement [mm]	15,41	9,35	0,92
Standard deviation [mm]	1,41	0,46	0,48