Effects of Spatial Configuration of Electrodes on Patterns of Peripheral Nerve Activation and Noise Shielding

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Abstract

Multi-electrode cuff electrodes is an important component in an implanted functional neural stimulation system. We constructed finite element models to investigate the effects of changing the spatial configuration of electrodes in a cuff electrode system on the noise shielding and activation pattern. The results could facilitate designing of cuff electrodes. For noise resistance, a 2D model with an external noise source was constructed. For activation pattern, two 3D models, a unifascicular and a multifascicular model, were constructed. Three types of electrode configurations, transverse, longitudinal and cross, on both types of 3D models were simulated. Model parameters were changed systematically and simulations were performed. For noise resistance in sensing applications, increasing the cuff length reduced the interference of external noise. For stimulation with three types of electrode arrangement, i.e., transverse, longitudinal and cross, we found cross arrangement was the best one having the advantages of both convex activated region and lower threshold current.

***Keywords*:** Neural prosthesis, Microelectrode, Electroneurography

Introduction

Neural prosthesis, a new and growing development in rehabilitation engineering, samples neural signals for monitoring muscle status and implements motor control through electrical stimulation [1]. The advantages include less electrical current for stimulation (as compared with intramuscular and epimesial electrodes) and better sensing ability. On the other hand, the extra costs include larger risk of nerve injury, and more effort to design and manufacture the prosthetic system.

In order to manufacture a cuff electrode, designing with the aid of model simulation was indispensable. The modeling of peripheral nerve stimulation was a relatively recent development. Vetlink [2] compared the power of selective stimulation in three types, i.e., intrafascicular, intraneural and extraneural, electrodes in both unifascicular and multi-fascicular nerve configurations. The authors concluded that the former two types of electrodes had better selective power and the difference was more prominent in the multi-fascicular configuration. Cavanaugh et al. [3] showed that, for cuff electrode systems, the interfascicular type had better power of selective stimulation over the extrafascicular type. Even though the above studies indicated that intrafascicular electrodes were better, we adopted extrafascicular electrode configuration and developed a multi-microelectrode cuff system [4]. The extrafascicular electrode was relatively non-invasive, thus causing less harm to the nerve fibers and easy to implement. Chintalacharuvu et al. [5], using finite element analyses in a 3D anisotropic model of an unifascicular nerve, demonstrated that extrafascicular cuff electrode with narrow-spaced tripolar arrangement could produce smaller stimulation area (i.e., had steeper potential gradient) near the nerve surface and had better controllability over the stimulation area. Deurloo et al. [6] studied the stimulation selectivity of different extrafascicular electrode configurations and found that the transverse configuration was the only one that produced convex activation area, though the threshold current was higher. Choi et al. [7] provided quantitative measures for evaluating different configurations of cuff electrodes on the stimulation selectivity. Their simulations predicted that cuff electrodes that could flatten the nerve had better stimulation selectively than those kept the nerve circular. There were even less studies on the noise resistance in the literature. Longer cuffs had better noise resistance and signal sensing ability than the shorter ones [8]. Yet, in practical applications, shorter cuffs had the advantages of easy implementation and less tissue injury. Rahal et al. [9] showed that the shorter cuff electrodes were relatively immune to the

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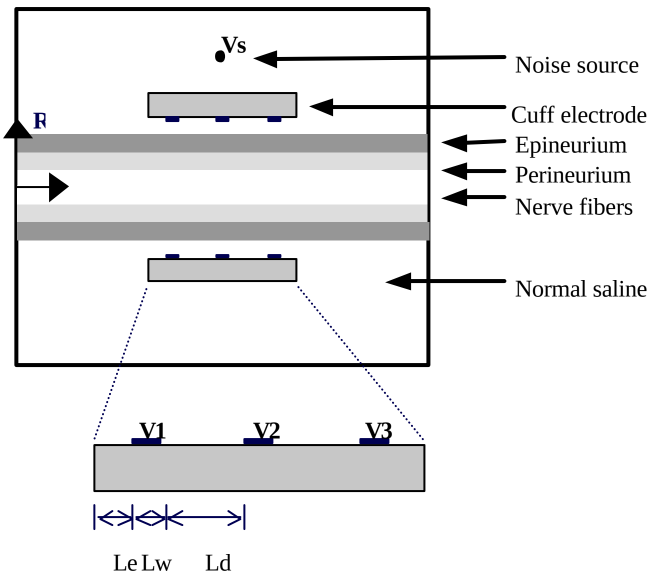

Figure 1. Schematic drawing of model A. Vs, V1, V2 and V3 were electrical potentials at the noise source, right, center and left electrodes, respectively. R and L indicated the radial and longitudinal directions, respectively.

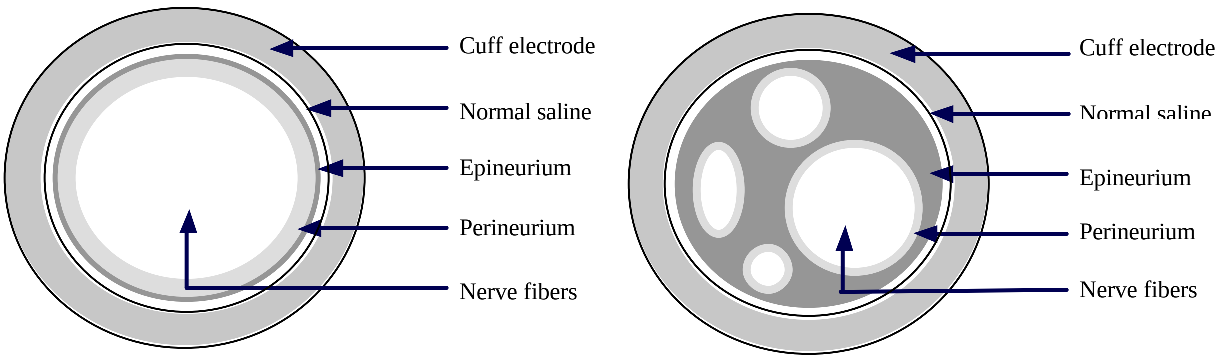

Figure 2. Schematic drawing of models B and C.

interference of external electromyography (EMG), if the end electrodes were placed a few millimeters away from the ends of the cuff. Peres-Orive et al. [10], as a counterpart of stimulation cuff electrodes, concluded that cuff electrodes that could flatten the nerve had better sensing selectively than those kept the nerve circular.

The goals of this study are two folds. First is to analyze the length of cuff electrode on the resistance of external noises and second is to investigate the spatial electrode arrangement on the efficiency and shape of activation. The results of current study can facilitate the design of next generation of cuff electrodes.

Methods

Model Description

Three models were constructed for analyses. Model A (Figure 1) was designed to investigate the effect of cuff electrode length on external noise resistance. The nerve was simplified as a three-layered (epineurium, perineurium and endoneurium) concentric cylinder. The cuff electrode, wrapping around the nerve, was modeled according to the microelectrode system that we manufactured and contained three electrodes [4]. The surrounding environment was assumed to be the homogeneous normal saline. The noise, generated by an assumptive EMG point source, was placed at 1 mm from the midpoint of the outer surface of cuff. The strength of the EMG source was set to be 2 mA to produce a potential around 1 mV, which was a typical magnitude for measured EMG. Since the model was symmetric in the axial direction, 2D model, showing one longitudinal section, was adopted. Tripolar electrode configuration with two end electrodes as the reference and the center electrode as the sensing electrode was implemented. Models B and C were designed to investigate the effect of spatial arrange of electrodes on the stimulation efficiency. Model B (Figure 2) was a 3D version of model A, with more electrodes on the cuff. Model C was a more realistic model, derived from a real nerve image and incorporated

Table 1. Electrical properties of materials in the models.

	Element type*	Radial Impedance Unit:Ω·m	Axial Impedance Unit:Ω	Reference
Normal Saline	PLANE67 SOLID5	0.5	0.5	[7]
Silicone Rubber	PLANE67 SOLID5	$1x10^{10}$	$1x10^{10}$	[11]
Epineurium	PLANE67 SOLID5	12.11	12.11	[11]
Perineurium	PLANE67 SOLID5	478	478	[11]
Nerve Fiber	PLANE67 SOLID5	12.5	2	[6]

* Element type names were defined in reference for software ANSYS.

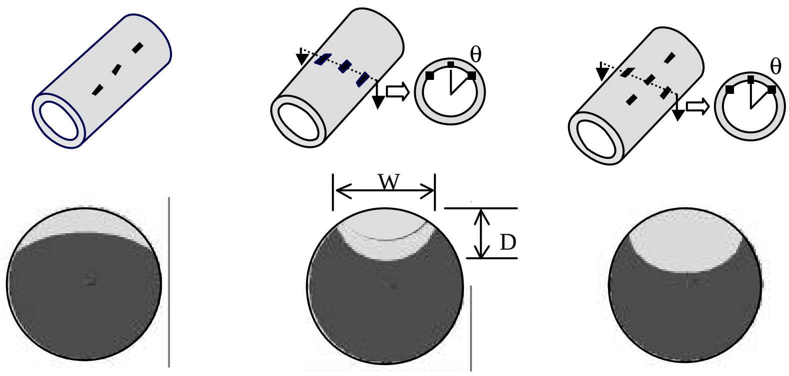

Figure 3. Upper row: electrode arrangements for models B and C: transverse, longitudinal and cross. Lower row: representative shape of activated region (lighter area) for the corresponding electrode arrangement. W and D are the width and depth of the activated region, respectively.

four fascicles of different sizes. The detailed dimensions of components were listed in Appendix. The values for the necessary parameters were adopted from the literature and listed in Table 1.

Finite Element Analyses

Software package ANSYS (www.ansys.com) was used for analyses. In all three models, the electrical potential at the margin of the model, i.e., the outer limit of normal saline, was set as zero. In simulation with the model A, noise source strength was kept constant and the cuff length was systematically changed and simulation was performed. Quadriangular element was used as the building elements. In models B and C, three types of electrode configuration (Figure 3), i.e., longitudinal arrangement, transverse arrangement and cross arrangement, were simulated systematically and sequentially. The size of electrode was 700 x 700μm^2. In model A and in LA, the distance between the electrodes was 7.5 mm. In the transverse arrangement, the distance between electrodes was measured by the angle spanned at the center (θ). Hexahedron was used as the building element of both models B and C. In simulation with the models B and C, current applied through longitudinal leads (I_L) or/and through transverse leads (I_T) were changed independently and systematically to evaluate the changes in activated area.

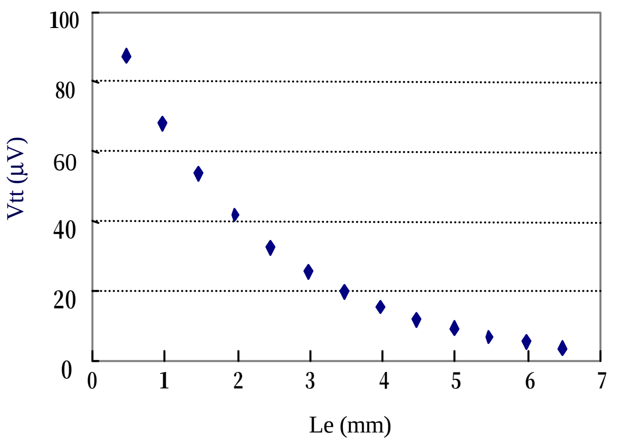

Figure 4. Relationship between the cuff length and the sensed noise amplitude.

We assumed the resting membrane potential of nerve fibers was homogenous and set as –70 mV and the threshold of generating action potential was set as -35 mV.

Function Parameters

The activated region was defined as the area that the field potential exceeded –35 mV. Two parameters (W and D) representing the width and depth of the activated region was

Table 2. The effect of element size on simulation results

Model	Mesh size no.	Node number	Element numbers	V1 Unit:mV		V2 Unit:mV	
A	1	6,141	5,984	0.1198		0.1038	
	2	14,039	13,800	0.1201		0.1041	
	3	22,557	22,236	0.1209		0.1048	
				Vmax		Vc	
B	4	14,085	13,376	-38.17		-34.81	
	5	33,327	31,992	-37.38		-34.12	
	6	59,843	57,728	-37.08		-33.81	
				Va	Vb	Vc	Vd
C	7	62,402	59640	-26.01	-17.86	-17.20	-16.44
	8	98,930	95,424	-25.56	-17.61	-16.85	-16.11
	9	136,914	132,216	-25.38	-17.46	-16.73	-15.98
	10	109,888	99,580	-25.56	-17.62	-16.85	-16.11

V1 and V2 were shown in Figure 1.

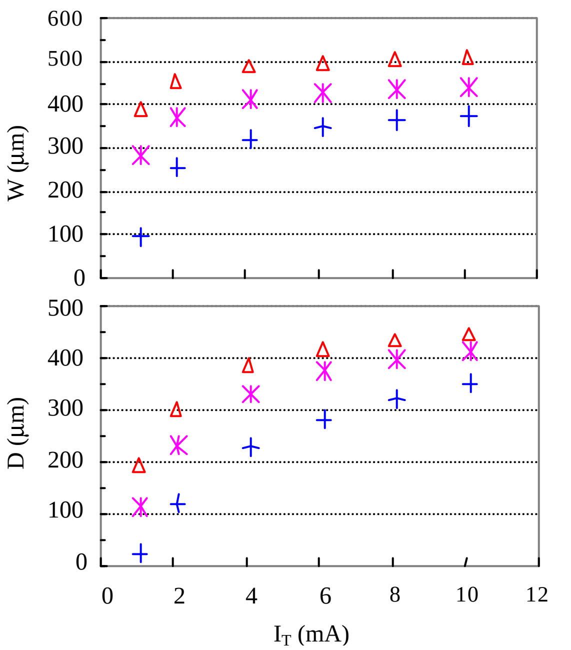

Figure 5. Relationship between the current strength and the width and depth of activated region (W and D) defined in Figure 3, respectively, with transverse arrangement in model B. θ was 30 degrees in the triangled line, 45 degrees in the starred line and 60 degrees in the crossed line. I_T: current strength in transverse direction.

used to evaluate the efficiency and activated shape of stimulation. The goal of electrode arrangement was to maximize D/W ratio and minimize the input current strength to reach the threshold of generating action potential.

Results

Validation of convergence of Finite Element Analyses

Before the main simulations, we did mesh with different element sizes to test the consistency of the simulation results. Table 2 showed that the simulation results remained almost constant for when the element numbers equal or larger than 13,800 for model A, 31992 for model B and 95,424 for model C. Mesh size numbers 2, 5 and 8 were used in the following simulations for models A, B and C, respectively.

Length of cuff electrode on noise resistance

Because the distance between electrodes and size of electrodes were kept constant throughout this part of simulation, changing the total length of cuff electrode was equivalent to changing the distance of the end electrode to the margin of the cuff (Le). Figure 4 showed the relationship between the noise magnitude and Le for a representative condition, i.e., a point EMG source in the midline just outside the cuff electrode. As Le increased, the noise magnitude decreased accordingly. The decrease was faster initially and became more gradual later. Since the typical peak-to-peak background noise for electroneurography was about 5-10 μV, the current results indicated that Le had to be larger than 6 mm to reduce the EMG effect to the background noise level.

Electrode configuration on stimulation efficiency

The lower row of Figure 3 showed the typical shapes of activated regions by stimulation with three types of electrode arrangement. Longitudinal arrangement had larger W/D ratio and the activated region was concave; transverse arrangement had smallest W/D ratio and the activated region was convex; and cross arrangement had intermediate W/D ratio depending on the I_T/I_L ratio and the activated region was also convex.

Figures 5 and 6 were the results of simulation with model B. Figure 5 showed the results of increasing I_T in the transverse arrangement. Both W and D increased initially and saturated as the whole nerve bundle was activated. Increasing I_T in another two electrode arrangements also had similar trend (results not shown). Increasing θ did not change the trend, though W saturated more quickly (due to improved stimulation efficiency).

Figure 6 showed the results of changing I_T/I_L ratio in the cross arrangement. As expected, increasing I_T/I_L would

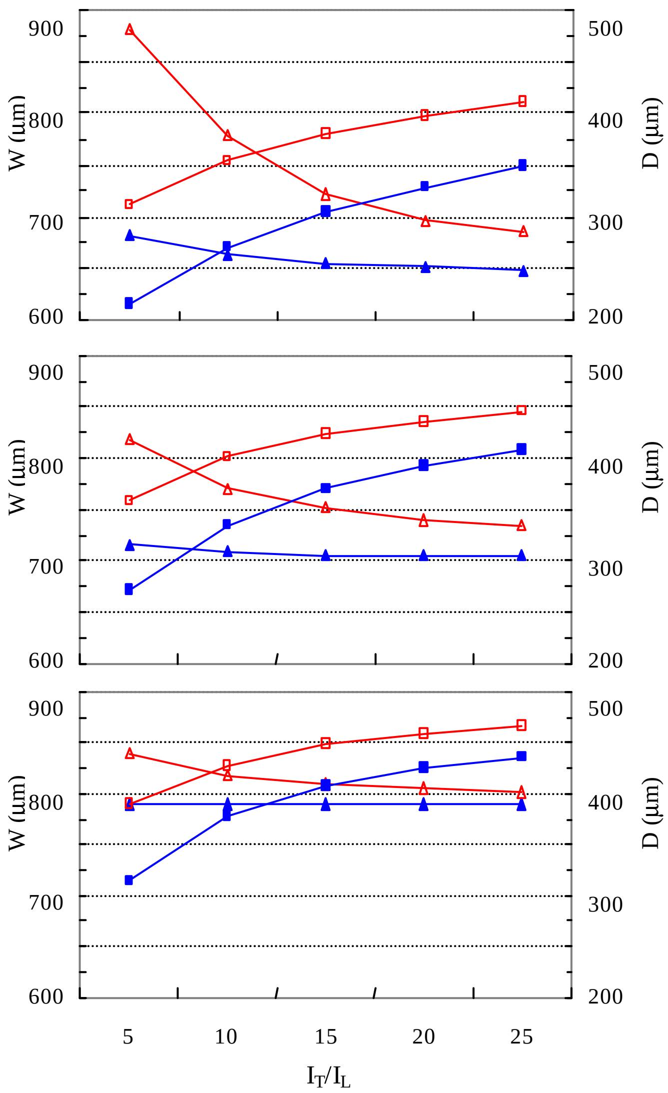

Figure 6. Relationship between the current strength ratio (transverse/ longitudinal) and W and D, respectively, with cross arrangement in model B. Empty-triangled line: W with source strength of 15.2 µA and filled-triangled line: W with source strength of 15.6 µA. Empty-quadriangled line: D with source strength of 15.2 µA and filled-quadriangled line: D with source strength of 15.6 µA. I_T and I_L: current strengths in transverse and longitudinal direction, respectively.

decrease W and increase D, thus, decreasing W/D ratio. The effect was more prominent when the overall current strength was larger, as shown with empty rectangle and triangle lines. Increasing θ decreased this effect, though the efficiency (the activated area) increased as in the case of the transverse arrangement.

Figure 7 showed the results of simulation with model C. The cross-configured and fixed total-dimension electrodes were placed by try and error around the nerve trunk. It demonstrated that, with appropriate selection of stimulation parameters and locations of electrodes, each nerve bundle could be activated independently.

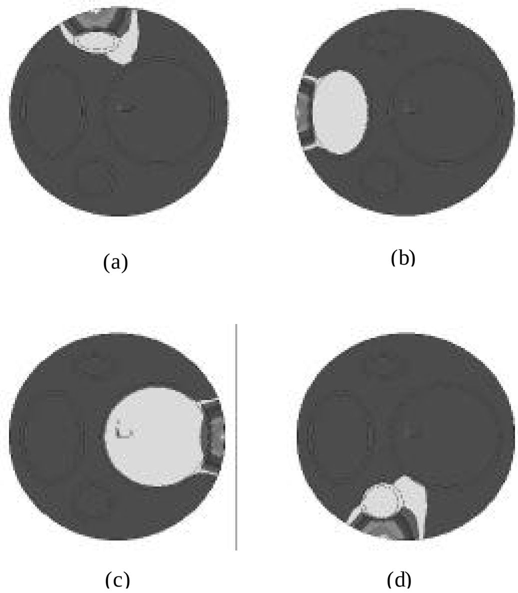

Figure 7. Selective activation of fascicle with cross arrangement in model C. The lighter area was the activated region. In each subplot, one single fascicle was activated.

Discussion

Noise resistance

The results of current study quantified the view of Rahal et al. [9] that if the end electrodes were placed a few millimeters away from the ends of the cuff, the noise amplitude would decrease. Though this method could reduce the external noise level, it increased the cuff length if the electrode distance was kept constant. The available area for electrode placement was also reduced. More effort would be necessary to investigate the influence of noise sources away from the midline of the cuff electrode.

Comparison of different electrode arrangements

Increasing I_T increased the overall activated area, yet kept the trend of W/D ratio and general shape of activated region relatively constant (results not shown). In other words, the trend of W/D ratio and shape of activated region was independent of current strength. The results of transverse and longitudinal arrangements in the current study were compatible with the conclusion of Deurloo et al. [6]. While the longitudinal arrangement had concave activated region but the current threshold was lower, the transverse arrangement had convex activated region but the current threshold was higher. In this study, we found that cross arrangement also had convex activated region and the current threshold was much lower than the value in transverse arrangement. As an example, for an activated area of 625 x 350 μm^2 (W x D), current threshold for the transverse and cross arrangements were 10 mA and 395.2 µA, respectively. In other words, cross arrangement had convex activated area as in transverse arrangement and had low threshold current as in longitudinal arrangement.

Differential activation of intrafascicular region

Theoretically, it was possible to create potential gradient within a fascicle so that only part of the fascicle was activated. The simulation results also supported this notion. Yet, we noted that the potential gradient was small inside a fascicle, so that a subtle change of stimulation strength near the threshold would change dramatically the activated area within a fascicle. This result implied that it would be difficult, if not impossible, to control the size of activated area practically. Conversely, the potential gradient was larger across the perifascicular layer, making the activation of a fascicle like all or none phenomenon. In our simulation, typically, the potential difference was less than 5 mV within a fascicle and around 50 mV across the perineurial layer.

Implication for Neural prostheses

Cross arrangement had the advantages of both transverse and longitudinal arrangements. The cost was the increased number of electrodes. As the micro-fabrication technology advances, making multiple electrodes in desired configurations is relatively easy. We expect the cross arrangement could improve the controllability of electrical stimulation without substantially increasing the current input.

Conclusions

We constructed finite element models to investigate the effect of changing the spatial configuration of electrodes in a cuff electrode system on the noise resistance and activation pattern. For noise resistance in sensing applications, increasing the cuff length reduced the interference of external noise. For stimulation with three types of electrode arrangement, i.e., transverse, longitudinal and cross, we found cross arrangement was the best one having the advantages of both convex activated region and lower threshold current.

Acknowledgement

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Appendix

1. Dimension of components in model A

	Thickness or Diameter (μm)	Longitudinal length (mm)
Nerve Bundle	1000	50
Perineurium	50	
Epineurium	150	
Cuff Electrode	300	18 ~ 30
Normal Saline	filling all the empty space in 56 x50 mm^2 area	

2. Dimension of components in model B

	Thickness or Diameter (μm)	Longitudinal length (mm)
Nerve Bundle	1000	50
Perineurium	50	
Epineurium	150	
Cuff Electrode	300	30
Normal Saline	filling all the empty space in 56 x56 x 50 mm^3 volume	

3. Dimension of components in model C

		Thickness or Diameter (μm)	Longitudinal length (mm)
Nerve bundle	F1	440 x 220	50
	F2	1030 x 750	
	F3	1200 x 1200	
	F4	400 x 400	
Perineurium		50	
Epineurium		2500	
Cuff Electrode		300	30
Normal Saline		filling all the empty space in 56 x56 x 50 mm^3 volume	

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