Analysis of Current Density in the Carpal Tunnel Region During an Electrical Accident by way of the Finite Element Method

M.S. Morse[1], J.S. Berg[2], R.L.TenWolde[1]
[1]Department of Electrical Engineering, University of San Diego, San Diego, CA, USA
[2] Naval Medical Center, San Diego, CA , USA

Abstract— **Carpal Tunnel Syndrome (CTS) has been diagnosed in as many as 10% of the hand-involved electrical contacts studied by the authors. Typically a CTS diagnosis is indicative of median nerve compression. Such would not be consistent with the known apparatus of electrical injury. Using the finite element method, current density has been evaluated in the carpal tunnel region during an electrical contact. The results indicate that while the majority of current does not transverse the nerve tissue, the current density is significantly elevated in the nerves as they traverse the carpal tunnel region. In certain circumstances, the localized current elevation could cause nerve damage which would masquerade as CTS when diagnostically tested.**

Keywords—**Carpal tunnel, electric shock, electrical injury**

I. INTRODUCTION

Symptoms following a low amperage electric shock are diverse and often unpredictable [1,2,3,4,5,6,7,8,9]. For electrical contacts of less than 1000V a study of 108 subjects demonstrated that external tissue burning was absent in 43% of the cases [10]. Where burning does occur, it typically occurs at entry or exit points where current density is usually highest as is also tissue resistance.

The traditional theory is that tissue damage from electrical contact depends mainly on three factors: 1) the pathway and resistance of the tissues traversed by the current, 2) the heat generated by the current and, 3) the duration of the electrical contact [3]. An additional theory suggests that the electric field associated with the current may act on the cell membranes causing cellular atrophy. The greatest injury from an electric field would be anticipated to occur in nerve and muscle cells. [11]

Carpal tunnel syndrome (CTS) post-electric injury has been reported in case studies done on individuals receiving electric shocks even when minimal observable tissue damage was noted directly following the electrical incident. [4,6] In evaluating 10 hand-to-hand electric shock cases with minimal gross tissue damage, three cases showed diagnostic indications of Carpal Tunnel Syndrome. In those three cases, the results of the release surgery proved less than adequate.[4] More recent work by the authors suggests that in hand-involved electric shock injuries manifesting diffuse, long-term symptomatology, CTS may be present six months post-contact in as many as 10% of the cases reviewed. This number was over seven times the population baseline demonstrating statistical significance. (Based on a study of 136 electric shock victims.)

It has been reported that for a 3mm diameter peripheral nerve (in cats), a current of 40 ma applied for a duration of 5 seconds is sufficient to cause lasting disorders in function and structure [8]. Further, a rudimentary voltage-divider analysis of neural current density in the carpal tunnel region has suggested that localized nerve damage could result from even a brief duration shock with hand-entry current of approximately 1 [12].

The hypothesis tested herein is that the current density or charge exposure to the median nerve in the region of the carpal tunnel can exceed the threshold required to cause neural damage even when the source current is not high enough to cause more obvious tissue damage (such as entry and exit burns.) The damage is presumed to be localized to the carpal tunnel due to the reduction in conductive tissue in the region of the wrist. Localized nerve damage would then diagnostically mimic CTS.

II. METHODS

Cross sectional color images of the human arm were obtained from the Visual Human Project. The images underwent extensive preprocessing prior to being applied to FEMlab (version 2.3) Finite Element Method (FEM) software for the purpose of determining current distribution in an electrical contact.

Preprocessing:

The data from the Visual Human Project contained images in .raw format. Using Adobe Photoshop software, each image was converted to .psd format, all of the background and non-arm-tissue were removed and all slices of the arm were aligned using the lower right corner as the reference. The final images utilized 16 bit color and were trimmed to 720 x 720 pixels and saved in both .BMP and .JPG format. (Fig. 1) A maximum likelihood pattern recognition algorithm was developed to recognize six different tissue types from the color of the tissues in each image. Unfortunately, the classifier was only accurate for gross tissues. Fine tissues such as nerves had to be classified manually. (Fig 2.) Once classification was complete, the 720 by 720 image was reduced to an 80 by 80 numerical matrix with each number representing one of the tissue types.

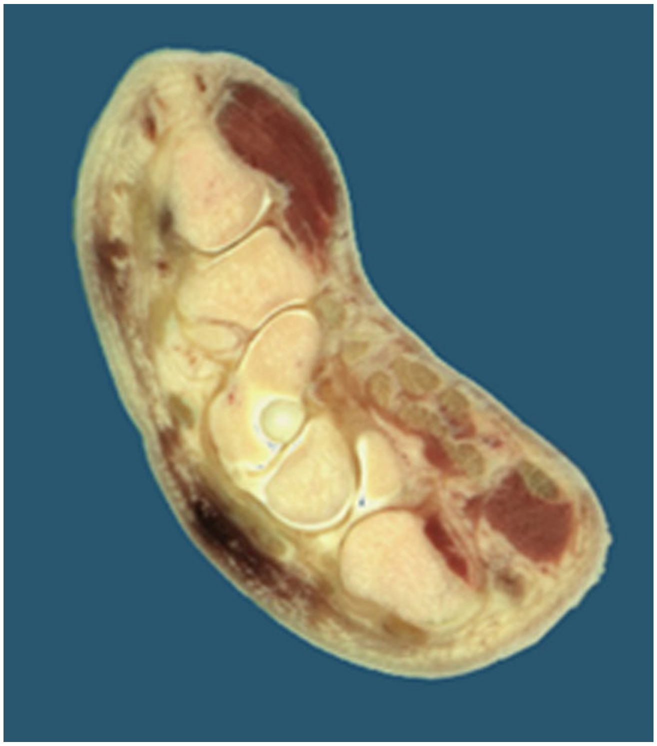

Fig. 1. Carpal tunnel region without background.

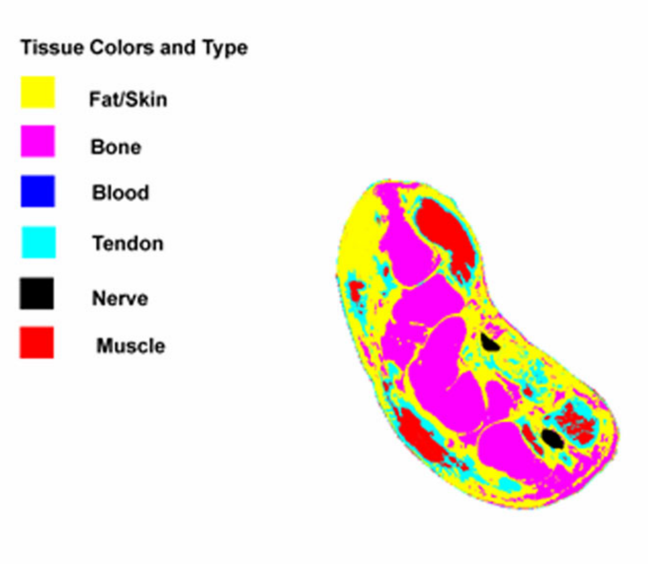

Fig 2. Carpal tunnel region characterized by tissue type.

Finite Element Method:

Once all classification was complete, the tissue-type matrix was analyzed using the finite element method. Each element of the tissue type was then characterized by its parametric electrical resistivity. Table 1 contains values of resistivity (ρ) for tissues of the human body. Other than liquids such as blood and urine, nerves have the lowest electrical resistivity [13,14,15].

Table I
Parametric Resistivity of Tissues

MATERIAL	RESISTIVITY
Blood	1.6
Nerve	2.5
Skeletal Muscle	7.0
Bone	160.0
Fat/Skin	27.0

The two dimensional tissue restivity matrix was then extruded into a three dimensional tissue slice of thickness 1 millimeter. It was anticipated that by processing multiple images in this manner, finite element cubes of homogenous tissue of 1 mm in length and 1 pixel x 1 pixel in cross-sectional area could ultimately come together to describe the whole arm.

Initial application of the FEMlab software was made to individual extruded cross-sections.   The goal being to compare the results of cross-sections taken along the length of the arm to a cross-section taken at the carpal tunnel. Each cross section would be subjected to a current flow that would be theoretically similar to the current flow from a presumed electrical contact.   The point of application of the current was from a point that was established distant from the cross-section through a homogenous medium approximating generic soft tissue. (NOTE: Various approaches were tried before this set-up was deemed to be a valid estimate of an actual contact.)

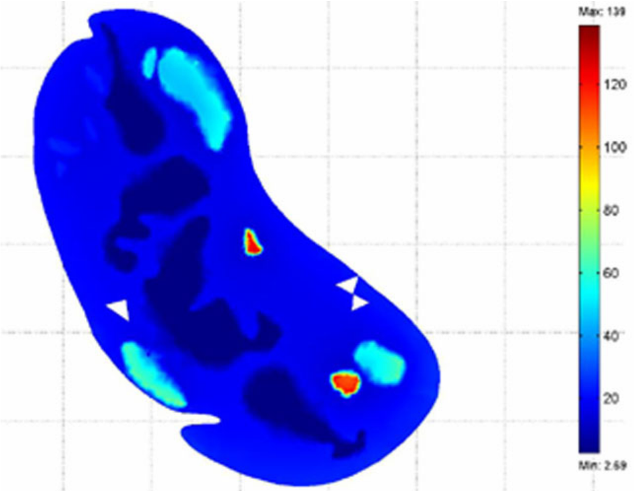

Fig. 3. Results of FEM analysis on data taken from fig. 1 indicating relative current density.

III. RESULTS

Fig. 3 shows the results of the FEM analysis for the cross-section of the carpal tunnel region from fig 1.. The lowest current density is found within the bones and is approximately zero on the relative scale shown. Current density in fat, skin and tendon appears to be somewhat uniform and is shown at a value of approximately 20 on the relative scale. Current density in muscle is approximately 35 to 40 on the relative scale. The current density observed in the nerve tissue is approximately 120 on the relative scale.

V. DISCUSSION

Not surprisingly, these results indicate that the tissue with the lowest current density exposure would be hard tissue (bone), shown in darkest blue in fig. 3. The soft tissue (other than the nerves), shown in mid-blue on fig. 3 demonstrate a somewhat diffuse exposure to current. Muscle demonstrates a slightly higher current density exposure (light blue on fig. 3). Integration across all of the soft tissue shown in mid-blue and the muscle shown in light blue demonstrates that almost all of the current is distributed among the soft tissues other than the nerves. The nerves although carrying only a very small total amount of current represent focal points with current density spiking to between three and six times that of the other soft tissues. The result is that the nerves would undergo more rapid heating and would also be more apt to suffer damage from the higher levels of current to which they are exposed.

VI. CONCLUSIONS

In sum, the FEM analysis of the tissue matrix indicates that dramatically higher current densities are observed in the nerve tissue of the carpal tunnel region than in other surrounding tissues. Given the susceptibility of nerve to electrical injury coupled with the dramatically high current density, it is very likely that electrical injury to nerve will far precede injury to other tissues in the carpal tunnel region. It is further very likely that this injury would mimic CTS during diagnostic testing.

VII. REFERENCES

[1] Bongard, O and B. Fagrell, "Delayed Arterial Thrombosis following an Apparently Trivial Low-Voltage Electric Injury," *VASA*, vol.18, pp. 162-166, Feb.1989.

[2] Farrell, Donald F., M.D. and Arnold Starr, M.D., "Delayed Neurological Sequelae of Electrical Injuries," *Neurology,"* vol 18, pp 601-606, June 1968.

[3] Irvine, J.,"Electric Shock and Associated Injuries," *The Practitioner*, vol. 233, pp. 1454-1457, Nov. 8, 1989.

[4] Morse, M.S. and D.K. Weiss, "An Evaluation Protocol for Electric Shock Injury Supported by Minimal Diagnostic Evidence," presented at IEEE-EMBS 15th Ann. Conf., San Diego, CA, Nov. 1993.

[5] Panse, Frederick, "Electrical Trauma," *Handbook of Clinical Neurology - Injuries of the Brain and Skull, part I,* vol 23, pp 683-729.

[6] Rosenberg, D.B.,"Neurologic Sequelae of Minor Electric Burns," *Arch. Phys. Med. Rehabil.* vol 70, pp. 914-915, Dec. 1989.

[7] Solem, Lynn, M.D., R.P. Fischer, M.D. and R.G. Strate, M.D., "The Natural History of Electrical Injury," *The Journal of Trauma,* vol. 7, no 7, pp 487 - 492, 1977.

[8] Somogyi, E. and C.G. Tedeschi, "Section 4. Injury by Electrical Force, " *Forensic Medicine, A Study in Trauma*, vol 1, p 660.

[9] Skoog, Toord, M.D., "Electrical Injuries," *The Journal of Trauma,* vol 10, no 16, pp 816-830, 1970.

[10] Wright, RK, J.H. Davis, “The investigation of Electrical Deaths: a report of 220 Fatalities*” J. Forensic Sci.*, Vol 25 pg. 514, 1980.

[11] Lee, R.C. and M.S. Kolodney, "Electrical Injury Mechanisms: Electrical Breakdown of Cell Membranes," *Plastic and Reconstructive Surgery*, vol 80, no 6, pp 672 -679, Nov., 1987.

[12] Morse, M.S., " A Study of Carpal Tunnel Injury Following Electrical Trauma" presented at *22nd IEEE-EMBS Conf.*, Chicago, CA, Jul. 2000.

[13] Baker, L., "Principles of the Impedance Technique," *IEEE Eng. in Medicine and Bio*., pp. 11-13, March 1989.

[14] Geddes, L.A. and L.E. Baker, "The Specific Resistance of Biological Material -- A Compendium of Data For the Biomedical Engineer adn Physiologist," *Med. and Biol. Eng.,* vol 5, pp 271-293, 1967.

[15] Hammam, M.S., "A Range of Body Impedance Values for Low Voltage, Low Source Impedance systems of 60 Hz, " *IEEE Trans. Power Apparatus and Systems*, vol. PAS-102, No. 5, pp. 1097-1105, May 1983.