Chinese Journal of Physiology 46(3): 137-141, 2003

Short Communication

Electrical Conduction through Nerve and DNA

H. Abdelmelek[1,3], A. El-May Ben Hamouda[1], M. Ben Salem[2], JM. Pequignot[3] and M. Sakly[1]

[1]*Laboratoire de Physiologie Animale, Faculté des Sciences de Bizerte 7021 Jarzouna, Tunisia*
[2]*Laboratoire de Physique des Matériaux, Faculté des Sciences de Bizerte 7021 Jarzouna, Tunisia*
[3]*Laboratoire de Physiologie des Régulations Energétiques, Cellulaires et Moléculaires UMR 5578 CNRS, Villeurbanne, France*

Abstract

The aim of the present study was to analyse electric resistivity at different ambient temperatures between 300 to 20K in the frog sciatic nerve and salmon sperm DNA. When the electrical contacts were leaned just into the sciatic nerve, an increase of the sciatic nerve resistivity was observed for 240 K < T < 300 K and a rise of electrical conductivity was apparent below 240 K. This dependence is generally associated with a semiconductor behaviour. Once the sciatic nerve temperature was driven below 250K, the resistivity abruptly decreased and then at temperatures lower than 234 K, it remained constant and close to one tenth of its ambient temperature value. By contrast, when the electrical contacts were leaned into Salmon sperm DNA, the resistivity remained constant between 300K to 20K, showing a high electrical stability at low temperature. Thus, we report the existence of a new form of electric conductivity in the sciatic nerve at low ambient temperature, which in turn has many electric similarities with inorganic or organic superconductors, whereas temperature failed to alter DNA electrical properties until 20K.

Key Words: electric conductivity, sciatic nerve, DNA, cold, superconductor

Introduction

The evolution of the nervous system has been an important factor in the adaptation of animals to their environment (4). It might therefore be expected that natural selection on nerve or neurone conduction could have caused several structural changes (4). Electrical activity is of major importance in the function of nerve cells, playing a fundamental role in the transmission of signals and in the processing of information in the nervous system. The temperature affects the conduction velocity, both locally at the recording site and generally along the nerve. Locally the electric potential amplitude increases as the temperature in the recording site decreases by one degree (9). The conduction velocity is also dependent on the axonal diameter, the presence of myelin and the properties of the membrane (15). Recent data reported that the conduction velocity remained constant (between 283-285 K and 293 K) in squid giant axons (13), while another study in ducklings demonstrates a modulation effect of cold on the serotonergic and dopaminergic systems (3). In addition, sciatic nerves isolated from frogs frozen at 265.5 K were refractory to electrical stimulation, whereas those obtained from frogs surviving exposure to 270.5 K or 268 K generally exhibited normal characteristics of compound action potentials (5). Moreover, indirect evidence suggests that electron tunnelling may occur across junctions between micro-regions in living systems (5). I t was proposed that in living systems electric behaviour could be understood in terms of “superconductivity” (2, 5). Superconductivity is the ability of certain materials to conduct electric current with zero resistance. The name given to the phenomenon was due to the very high electrical conductivity below the critical temperature Tc. Interestingly, Evidence for electrical conductivity in nerve and deoxyribonucleic acid (DNA) molecules has been inconclusive until now. Until recently it was not certain whether DNA molecules conduct or insulate at low temperatures.

Corresponding author: Hafedh Abdelmelek, D.V.M., Ph.D., Faculté des Sciences de Bizerte 7021 Jarzouna, Tunisia. Fax: (216) 72 446 080, Tel: (216) 72 446 080, E-mail: Hafedh.Abdelmelek@fsb.rnu.tn
Received: March 6, 2003; Revised: June 6, 2003; Accepted: June 18, 2003.

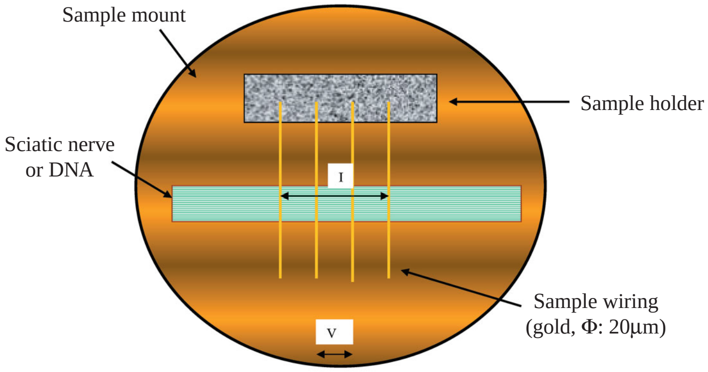

Fig. 1. Illustration of the Four-point Probe technique.

Kasumov et al. (10) have shown that DNA can conduct current under certain conditions. In these experiments, DNA molecules were placed between rhenium and carbon electrodes 0.5 mK apart, and the temperature was lowered to the value at which both electrodes became superconducting (10). It was found that at temperatures above 1 K the resistance of one DNA molecule is about 100 Kohm (10). Cooling DNA to below 1 K, however, gives rise to the so-called "proximity induced" superconductivity effect, due to the flow of holes and electrons from the electrodes, and the resistance of DNA falls off dramatically (10). The physical mechanism responsible for this phenomenon is not yet known.

Consequently, the present study performed an experimental approach to determine the temperature dependence of resistance in the frog sciatic nerve and Salmon sperm DNA.

Materials and Methods

Sample Preparation

Sciatic nerve samples (n=6) were obtained by decapitation of frogs (*Rana esculenta*) with light anaesthesia (Halothane 2.5% in air). Sciatic nerves were conserved in Ringer-buffer during 1 to 5 min. The proximal segments of the sciatic nerves (1cm) were harvested in order to study resistivity. For the present experiments we used a lyophilised salmon sperm DNA (Sigma, France). The electrical resistivity variations of the sciatic nerve or DNA with varying temperature were investigated by employing the four-probe technique. The temperature variation was achieved using a Helium exchange gas filled cryostat. Temperature was measured using a calibrated Si-diode sensor with an accuracy of 0.1 K and was varied from 300 K to 20 K. The two external wires (the distance between the 'current' wires: 8 mm) were used as current leads and the other two as the voltage leads (the distance between the 'current' wires: 2 mm) to record potential differences. We used a variable current with very low frequency (36Hz). The four electrical contacts were made using gold wires that were leaned into the nerve or DNA. The two external wires were used as current leads and the other two as the voltage leads to record potential differences. The value of the current used for the resistivity measurements was 20 µA (1, 2).

Four–point Probe

The Four–point Probe technique is the most common method of determining the critical temperature (Tc) of a superconductor (Fig. 1). Tc^{onset} is temperature at which resistivity starts decreasing. Wires are attached to a material. Through two of these points a voltage is applied and, if the material is conductive, a current will flow. Then, if any resistance exists in the material, a voltage will appear across the other two points in accordance with Ohm's law. When the material enters a superconductor state, its resistance drops to zero and no voltage appears across the second set of points.

Animals were cared for under the Tunisian code of practice for the Care and Use of Animals for Scientific Purposes. The experimental protocols were approved by the Faculty Ethics Committee (Faculte des Sciences de Bizerte, Tunisia).

Statistical Analysis

The term "p" is related to statistical analysis. In frog, the temperature –induced changes of resistivity were analyzed using the one-way ANOVA for repeated measures; observed differences between groups were tested by Student's-*t* test. Statistical significance was recognized at $P<0.05$.

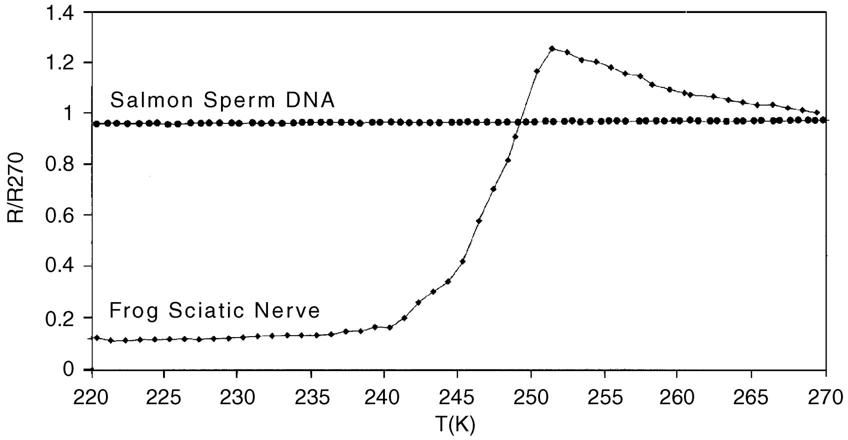

Fig. 2. Resistance of the frog sciatic nerve and salmon sperm DNA as a function of temperature An external recording with the gold paste. The resistance decreases with decreasing temperature in nerve but it remains constant in DNA. Salmon sperm DNA(●) vs frog sciatic nerve (♦).

Results

The measurement of resistance at 270 K, R_{270} (0.950 ± 0.002 Ω vs 0.826 ± 0.001 Ω, $P<0.05$) in sciatic nerves were higher (+13%) than DNA resistance (R_{270}).

When the electrical wires were leaned on the sciatic nerve, the nerve resistivity increased with temperature and reached a maximum relative value close to 1.3 at a temperature of about 250 K (see Fig. 2). Such dependence could be associated with a semiconducting behaviour in the normal state of materials. The nerve resistivity decreases abruptly at temperatures lower than 250 K, stabilising at a low relative value close to 0.1. In the present case, the R-T curve at 250 K showed a marked fall of resistivity without reaching the zero point. When the electrical wires were leaned on the Salmon sperm DNA, the DNA resistivity remained constant with temperature (see Fig. 2). According to our data, we have a significant difference between the R/R_{270} behavior with temperature of nerve and DNA.

Discussion

The present study shows that low temperatures induce a striking decrease of resistivity in the frog sciatic nerve with a width transition of about $\Delta T=10K$. By contrast, the temperature failed to alter the Salmon sperm DNA resistivity.

Recent data have shown that organic elements, such as tetracene and pentacene, present a normal state semiconducting behaviour (11). Moreover, sciatic nerves harvested from frogs frozen at 265.5 K were refractory to electrical stimulation (5). The fastest conducting nerve fibres appear to behave like wires and have their own insulating sheaths (15). Our main interest lies in the properties of large-scale nerve networks at low temperature, and which are responsible for such nervous system functions in frog. The present study on the sciatic nerve revealed a temperature dependency of the electric resistivity. When the electrical wires are just leaned on the sciatic nerve, the nerve resitivity increases with temperature. Such dependence is generally associated with a semi-conducting behavior. Semiconductor is a substance, usually a solid chemical element or compound that can conduct electricity under some conditions but not others, making it a good medium for the control of electrical current. Its conductance varies depending on the current or voltage applied to a control electrode ($dR/dT<0$). According to our findings, in frog the marked decrease of resistivity at low ambient temperature (250 K) can be mediated by a mechanism, which has many similarities with organic superconductors (14). Thus, the decrease or increase of temperature has a proportional effect on the sciatic nerve resistivity. Furthermore, our data suggests the existence of a new electrical conductivity mechanism. Knowledge of changes in frog sciatic nerve conductivity under cold environment is still limited. Nerve fibres conduct nerve impulses very quickly because the myelin sheath has gaps, which allows the nerve impulse to jump from gap to gap and travel faster (15). The temperature transition (Tc) in the sciatic nerves of frog remains constant and reproducible at 250 K. The present data reveal many similarities of the sciatic nerve with superconductors. If we assume the existence of “High-T superconductivity” behaviour of the nerve, there is increasing evidence to attribute this “superconductivity” to myelin sheaths. Moreover, numerous studies are dealing with the relationship between structure of the living matter and physical properties as superconductors (1, 2, 6, 10). The mechanism of superconductivity and the saltation over the myelin sheathed portions of the nerves showed many similarities. Myelinic nerves conduct impulses very quickly because the myelin sheath has gaps, which allows the nerve impulse to jump from gap to gap and travel faster. Interestingly, in superconductor materials we found Josephson junction. Josephson Junctions are thin layer of insulating material sandwiched between two superconducting layers. Electrons "Tunnel" through this non-superconducting region in what is known as the Josephson effects. Here a superconducting current flows even in the absence of an external voltage. Moreover, the gradient shift of superconductor-like behavior in the nervous system from frog to rabbit is correlated with the degree of myelinisation (1). DNA plays a pivotal role in biology as the carrier of genetic information in all living species. Recently, however, physicists and chemists have become increasingly interested in the electronic properties of DNA. According to some, DNA is a molecular wire that can conduct charge carriers with virtually no resistance (10). Others, however, find that DNA behaves as an insulator. Experiments are now starting to provide the first clues about the mechanisms that underlie charge transport in DNA. The field has recently been revived with the advent of measurements on single DNA molecules, in particular Megan *et al*. (12). Megan *et al.* (12) measured the fluorescence produced by an excited molecule and found that it no longer emitted light when attached to a DNA molecule. However, the situation among physicists who are measuring electronic transport through DNA molecules over larger distances is much less clear. The idea that electron transfer is enhanced in DNA appears quite reasonable. Indeed, the possibilities for testing electron transport in DNA are great because the molecule adopts many different structures. The first direct electrical measurements on small bundles of DNA were made by Fink and Schonenberger (7). They developed a special high-vacuum low-energy electron microscope that could image thin free-standing bundles of DNA stretched across a hole in a membrane (8). They could also measure the conductance (the inverse of resistance) by touching the DNA bundles with an additional metal tip. The surprising result was that DNA bundles almost 1 µm in length appear to behave like an ohmic conductor. This was quite unexpected because in the simplest picture one expects that DNA will be a semiconductor with a large energy gap between the valence and conduction bands, in other words DNA is expected to be an insulator (8). Interestingly, Kasumov *et al.* (10) reported that DNA supports a "proximity-induced" supercurrent when cooled below 1 K, the temperature at which rhenium becomes a superconductor. In the present study temperature failed to alter DNA resistivity. We did not find that DNA showed low-gap semiconducting behaviour until 20K, which contrasts with measurements by others. So, where does the field currently stand on the issue of the conduction properties of DNA? It is clear that claims range from everything from well-insulating behaviour to the support of superconducting currents through DNA has been reported. Our team has shown that nerve has special electrical properties and can work as a tiny electrical wire. Until 20K, electrical properties of DNA remained constant. This recent result on nerve and DNA opens up a possible route to new applications in the comprehension of biological systems and showed clearly the electrical stability of DNA compared to the nerve.

In summary, we have described, for the first time to the best of our knowledge, that the frog sciatic nerve resistivity can be markedly decreased by temperature but not salmon sperm DNA resistivity. The mechanism underlying the decrease of resistivity with temperature in nerve remains to be investigated.

Acknowledgments

This work was supported by grants from the Tunisian Ministry of High Education.

References

1. Abdelmelek, H., M'Chirgui A., Ben Salem M. and M, Sakly. Impact of evolution on the electrical properties of sciatic nerves: Superconductivity-like. *Phys. Chem. News*, 2003, (*in press*).
2. Abdelmelek, H., Amara S., M'Chirgui, A., Ben Salem, M and Sakly, M. Effects of acute exposure to magnetic field on sciatic nerve electrical properties: Biosuperconductivity. *Biomag* 2002: 1109-1115, 2002.
3. Abdelmelek, H., Cottet-Emard, JM., Pequignot, JM and Barre, H. Changes with age in spinal cord monoaminergic system responses to cold acclimatization. *J. Neural. Transm*. 107: 1175-1185, 2000.
4. Barton, R.A. and Harvey, P.H. Mosaic evolution of brain structure in mammals. *Nature* 405: 1055-1058, 2000.
5. Costanzo, E., Allenspach, A.L., and Lee, R.E.J.R. Electrophysiolgical and ultrastructural correlates of cryoinjury in sciatic nerve of the freeze-tolerant wood frog, Rana sylvatica. *J. Comp. Physiol. [B]* 169: 351-359, 2000.
6. Del Giudice, E., Doglia, S., Milani, M., Smith, C.W. and Vitiello, G. Biological sensitivity to weak magnetic field due to biological superconductive josephson junctions. *Physiol. Chem. and Phys.* 5: 786-791, 1973.
7. Fink, H.W. and Schönenberger, C. Electrical conduction through DNA molecules. *Nature* 398: 407-410, 1999.
8. Fink, H.W. DNA and conducting electrons. *Cell. Mol. Life Sci.* 58: 1-3, 2001.
9. Hopf, H.C. and Maurer, K. Temperature dependence of the electrical and mechanical responses of the adductor pollicis muscle in humans. *Muscle Nerve* 13: 259-262, 1990.
10. Kasumov, A.Y., Kociak, M., Guéron, S., Revlet, B., Volkov, V.T., Klinov, D.V. and Bouchiat, H. Proximity-induced superconductivity in DNA. *Science* 291: 280-282, 2001.

11. Katz, H.E., Lovinger, A.J., Johnson, J., Kloc, C., Siegrist, T., Li, W., Lin, Y.Y. and Dodabalapur, A. A soluble and air-stable organic semiconductor with high electron mobility. *Nature* 404: 478-480, 2000.
12. Megan, E., Nunez, E. and Barton, J.K. Probing DNA charge transport with metallointercalators. *Curr. Opin. Chem. Biol.* 4: 199-206, 2000.
13. Rosenthal, J.J. and Bezanilla, F. Seasonal variation in conduction velocity of action potentials in squid giant axons. *Biol. Bull.* 199: 135-143, 2000.
14. Schön, J.H., Kloc, Ch and Batlogg, B. Superconductivity in molecular crystals induced by charge injection. *Nature* 406: 702-704, 2000.
15. Stålberg, E. and Erdem, H. Nerve conductive studies. *Norol. Bil. D.* 17, issue 2, 2000.