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EMG vs. Thermography in Severe Carpal Tunnel Syndrome

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1. Introduction

Carpal tunnel syndrome (CTS) is one of the most common compressive neuropathies in the upper extremities (Bland, 2007) and a frequent cause of pain, paresthesias and impaired hand function. A syndrome is, by definition, a collection of signs and symptoms. Its clinical symptoms depend on duration and degree of the compression of the median nerve (MN). At first the sensory nerve fibres are affected, but as the compression persists, large calibre myelinated nerve fibres (sensory and motor) undergo damage as well. Clinical symptoms and signs alone are not sufficient to confirm the diagnosis and surgical release, electrodiagnostic methods are needed for this purpose (Rosenbaum & Ochoa, 2002).

Within the last decades, CTS reached epidemic proportions in many occupations and industries. It represents a large expense because of absence from work and wage compensation due to temporary incapacity for work. For this reason numerous researches, not only in the field of medicine, are looking for a non-invasive diagnostic method for determining those loads in workplaces that facilitate the development of CTS (Ammer, 1999, 2003; R.T. Herrick & S.K. Herrick, 1987; Schartelmüller & Ammer, 1996; Tchou et al., 1992).

Intelligent systems have turned out to be useful and successful aids in medicine for determining, classifying, sample searching, data analysis, and new knowledge discovery (Haas & Burnham, 2008). But thermography, on the contrary, did not receive due attention (American Academy of Neurology, 1990) in the area of determining entrapment neuropathies, despite its advantages (completely safe, passive investigation, without contact, painless and can be easily repeated with low costs of use) (Hackett, 1976).

1.1 Thermography

Thermography is a procedure for remote determination of temperature of objects, based on the detection of infrared radiation that the observed objects emit. As the name itself implies, thermographic or infrared cameras detect electromagnetic radiation below the frequency of red light. The range of wave lengths of infrared radiation includes lengths ranging from 700 nm to 1 mm, while thermographic cameras operate within an even narrower spectre, ranging from approx. 900 nm and 14 μm. As all objects emit infrared radiation, thermographic camera can determine an object's temperature on the basis of object's energy flux density. In this manner it can create a thermal image of observed objects (Fig. 1), where warmer objects usually appear in a warmer and lighter colour (light red to white) and colder objects appear in a colder and darker colour (blue to black) (Gaussorgues, 1994).
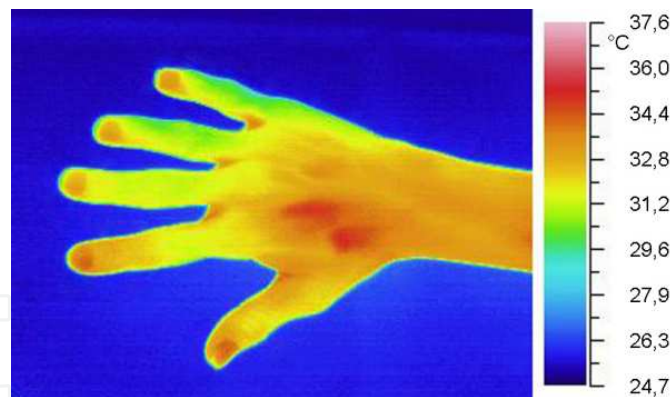
Fig. 1. Thermographic image of a patient's hand.

The possibility of detection of warmer objects on a colder background resulted in the development of thermography primarily for military and surveillance purposes, but with the decrease in prices of (initially very expensive) cameras, thermography established its position in numerous other areas too, such as industry, medicine, meteorology, and archaeology (Ring, 1995b).

Thermography, as we know it today, started to develop as late as the second half of the 20th century. Before this, remote temperature measurement was not possible, so surface measurements performed with various thermometers were used. The invention of the first thermometer is ascribed to the Venetian scientist Santorio Santorio, who improved Galileo's thermoscope in the beginning of the 17th century and equipped it with a scale, whereby enabling reading of ambient temperature. The precision of this thermometer was poor, because it was filled with air, and the effect of air pressure on the thermometer was not taken into account. The following improvement occurred in the mid 17th century – the use of alcohol in a closed bottle somewhat improved precision. The first mercury thermometer was made in 1714 by Gabriel Fahrenheit, who also takes credit for the first standardized temperature scale. He used the recently discovered freezing point and boiling point as reference values, and divided the intermediate interval to 180 degrees. He also added additional 32 degrees for values below the freezing point and set the lowest temperature 0, because this was the lowest temperature, which he achieved in his laboratory with a mixture of ice, water, and salt. In 1742, a Swedish scientist Anders Celsius developed his own scale by dividing the interval between the boiling point and the freezing point to 100 degrees. Interestingly enough, 0° was used to mark the boiling point, and 100° for the freezing point. The following year, Jean Pierre Cristin reversed the Celsius's scale and called it the hundred-degree scale. This name was in use until 1948, when it was renamed into the Celsius scale by international agreement. In 1848, a Scot William Thomson, later known as Lord Kelvin, proposed an absolute temperature scale with absolute zero at the lowest theoretical temperature the body can have -273.15°C. The standard unit for temperature is named after him – Kelvin (K).

At the end of the 16th century, a Neapolitan Giambattista della Porta was the first to notice the consequences of thermal radiation. In working on experiments with the concave glass he established that warmth or coldness can also reflect from glass, after placing candle flame and snowball in front of the glass. Almost two decades later, in 1790, a Swiss physicist, Pierre Prevost, introduced a theory, according to which all bodies, both warm and cold, thermally radiate, and that the quantity of radiation depends on body temperature. Only a few years later, a British astronomer of German descent, William Herschel, while diverting

sunrays by means of prism discovered radiation beyond a still visible, red part of the light spectrum (Ring, 1987). With the thermometer he detected higher temperature beyond the red part of the spectrum and predicted that there is invisible light.

Herschel published his results in 1800, and named the invisible radiation "heat rays". The name infrared radiation was established as late as the second half of the 19th century. This was followed by the period of new developments in the area of thermodynamics. Firstly, in 1859, Gustav Kirchhoff introduced his law of thermal radiation, followed by Stefan (1879, by means of experiments) and Boltzmann (1884, with theoretical derivation) with the black body radiation law. In 1893, Wilhelm Wien introduced his relation between the wave length of the strongest radiation of black body and its temperature, which lead to Planck's black-body radiation law published in 1901. These laws represent physical background, which serves as the basis for the functioning of thermographic cameras.

One of the first steps in the development of the measurement of thermal radiation was the discovery of thermoelectric effect or the Seebeck's effect, named after his inventor, Thomas Johann Seebeck, Estonian physicist of German origin. In 1821 he discovered that voltage exists between two ends of metal rods, when these ends are at different temperatures. This resulted in the discovery of thermocouple. For measuring the created voltage he had to connect a metal rod to a conductor, which resulted in voltage opposite to the initial one. By using a different metal he was able to take advantage of the difference in both voltages, since it depends on the material used. He measured the created voltage and with it, indirectly, the temperature difference. Increase in temperature difference also increased the measured voltage, and this enabled him to calibrate the thermocouple and use it as a thermometer. Italian physicists Leopoldo Nobili and Macedonio Melloni increased the precision of temperature measurement by connecting several thermocouples. But in 1878, Samuel Pierpont Langley, an American astronomer, took a step further, as he invented a bolometer.

Langley used two platinum strips, covered with soot, as the ends of the Wheatstone bridge or the electrical resistance meter, equipped with a sensitive galvanometer and battery. One of the strips was exposed to infrared radiation, which caused the strip to warm up. This altered its resistance, which he was able to measure with his circuit. Thus he created the first temperature sensor, which exploits predictable variations of platinum resistance as the result of temperature variations. In the 20th century, the discovery of new combinations of materials lead to increasingly more precise and smaller bolometers, which in the mid 1980s resulted in the invention of the microbolometer – fields of temperature sensors made of silicon or vanadium oxide or amorphous silicon (Fig. 2). It was invented by the American corporation Honeywell for the US Department of Defense. After 1992 the technology became available to the wider public and is now used as the detection field in thermographic cameras of numerous producers (Cuthbertson, 1995).

Thermographic camera is an infrared camera, which generates a thermal image on the basis of measured values of infrared radiation of observed objects. Unlike a thermovision camera, which is used for watching in dark or under poor visibility conditions, a thermographic camera also determines actual values of surface temperatures of observed objects. The activity of thermographic camera can basically be compared to the activity of an ordinary digital videocamera, whereby the role of CCD sensors is assumed by the field of thermal IR sensors (microbolometers or semi-conductors with a narrow passage). By taking into account emissivity, distance, ambient temperature, and other factors, the camera calculates temperatures, which are detected by individual sensors, and generates thermal image on the

basis of these temperatures. For the display of individual temperatures it uses a non-linear palette of so-called "non-primary colours", ranging from white for the highest temperature through red and yellow shades for higher temperatures to blue for lower, and black for the lowest temperatures (Fig. 1). The resolution of a thermal image rarely exceeds 320x240 pixels and is determined by the number of IR sensors (Fig. 2).
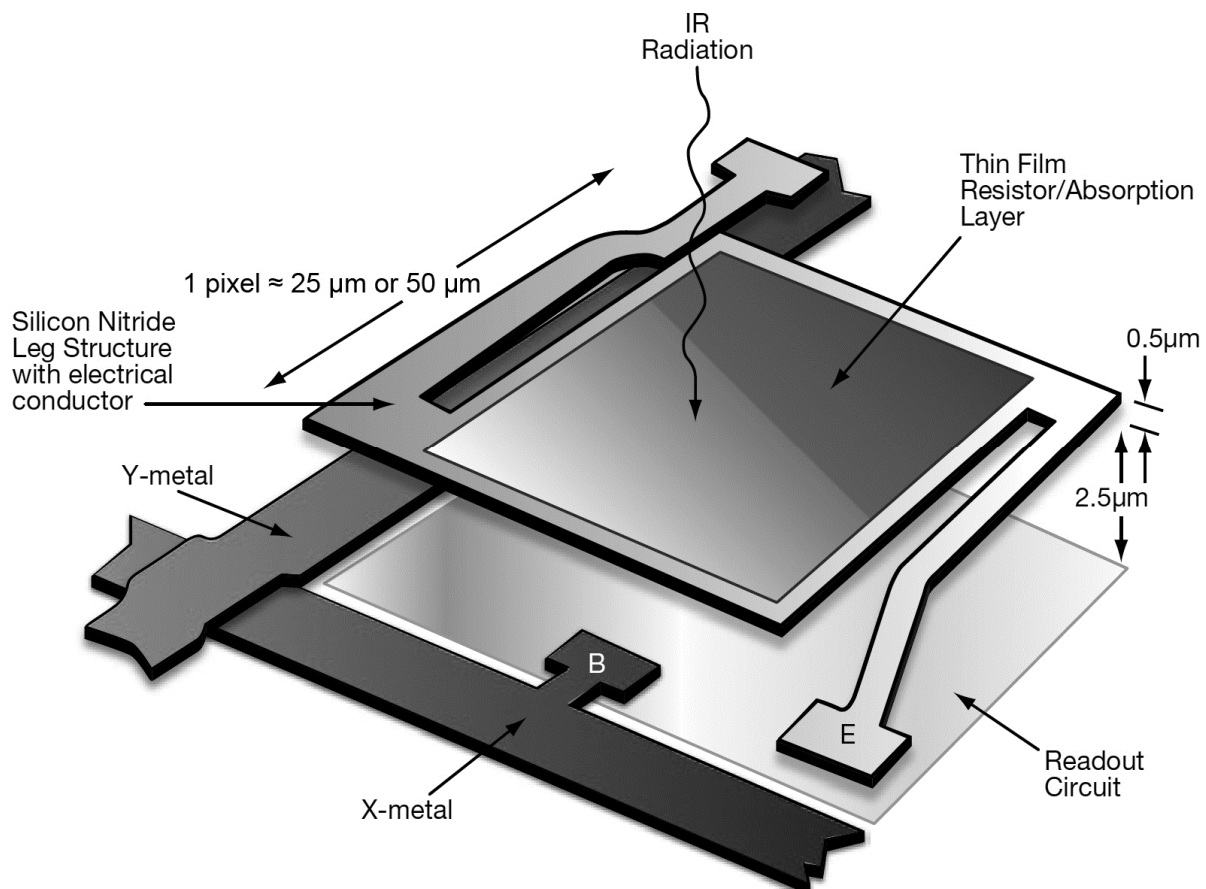

Fig. 2. The basis structure of a microbolometer (uncooled IR camera pixel).

Despite the initial development solely for military purposes, today thermographic cameras are used in different areas. Thermography is an excellent method of examination, also useful in the field of medicine for its safety (passive, no touch examination), lack of pain and invasiveness, easy reproducibility and low running costs (Hackett, 1976). Despite its advantages TG is not useful for routine diagnosis of CTS, since unmyelinated fibres remain intact until late in the severe nerve entrapment (American Academy of Neurology, 1990). Many patients with EMG diagnosed CTS have normal thermographic studies; however TG may show abnormalities in median nerve distribution in severe cases of CTS (Rosenbaum & Ochoa, 2002). To ensure reliability of TG pattern recognition we introduced a novel approach to thermal image analysis by using an artificial neural network (ANN).

1.2 Artificial neural networks

Data mining techniques provide a variety of different approaches for data analysis. ANNs are one of them (Larose, 2005). They are increasingly used in problem domains involving classification and are capable of finding shared features in a set of seemingly unrelated data.

An ANN is an abstract computational model of the human brain. Similar to the brain, an ANN is composed of artificial neurons and interconnections. When we view such a network as a graph, neurons can be represented as nodes and interconnections as edges (Fig. 3). There are many known variations of ANNs, differing in their topology, orientation of connections and approaches to learning (Kasabov, 1996). Probably the most established are "feed-forward backpropagation" neural networks (a.k.a. multilayer perceptrons). Due to its efficiency and relatively simple training process this type of ANN was chosen for our classification (diagnosis of CTS, based on collected data).
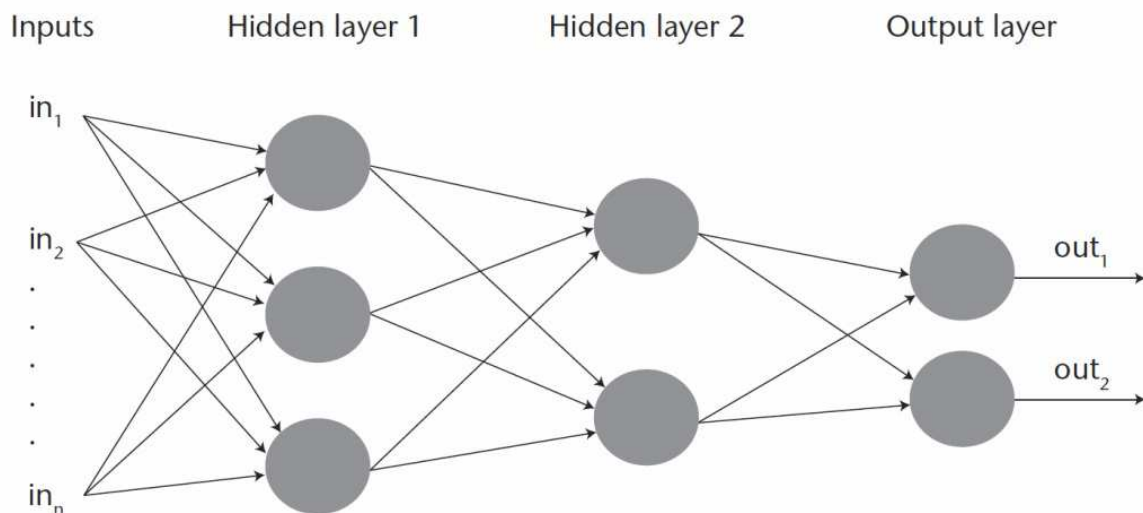

Fig. 3. Example of an ANN (multilayer perceptron).

A multilayer perceptron consists of layers of neurons, more specifically an input layer, an output layer and at least one hidden middle layer. Neurons on the same layer are not connected; all interconnections are directed from the input layer towards the output layer. The input layer is represented by normalized numerical values or inputs, passed on to the neurons on the 1st hidden layer. These neurons generate their own numerical outputs and pass them on to the next layer. This process continues until the last (output) layer and resembles the transmission of impulses inside the brain. Each connection in a network is weighted. The weights are internal parameters of an ANN and simulate the biological synaptic strengths in a natural neuron (McCulloch & Pitts, 1943).

An artificial neuron generates its output through an activation function (Fig. 4) which accepts as its input the sum of weighted outputs from neurons on the previous layer and an externally applied bias, denoted by b_k (1). The bias has the effect of increasing or lowering the net input of the activation function, depending on whether it is positive or negative. Weights and biases directly affect the importance of individual connections.

$$net_k = x_1 w_{k1} + x_2 w_{k2} + \cdots + x_m w_{km} + b_k \qquad (1)$$

Different activation functions are commonly used. We chose the log-sigmoid function (2).

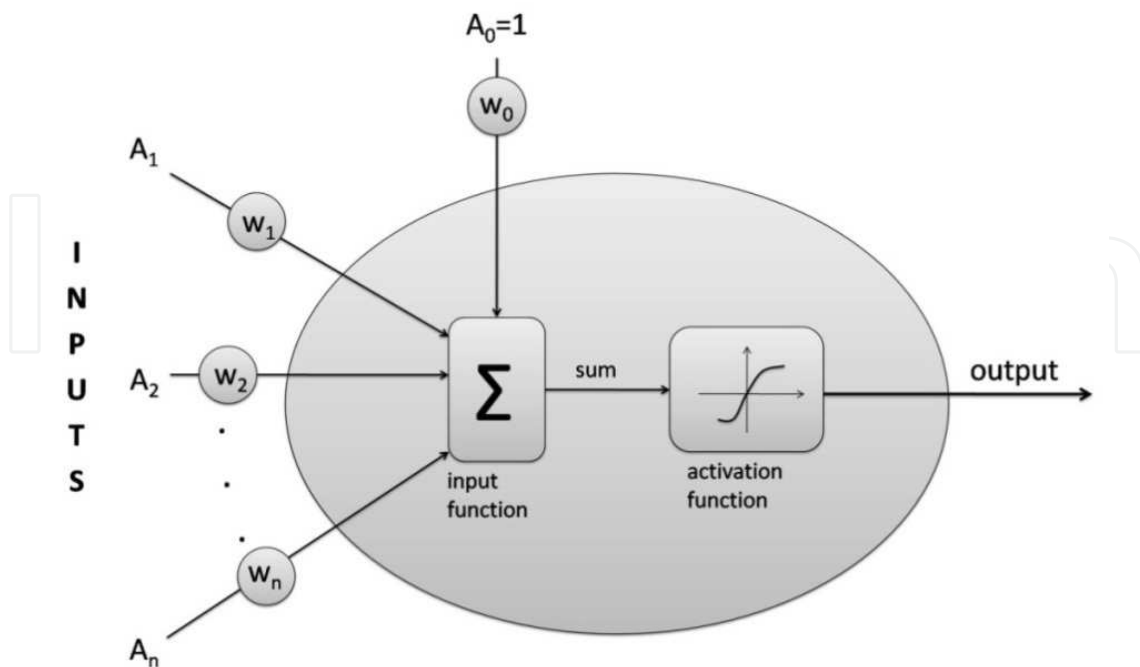$$f(net_k) = \frac{1}{1 + e^{-net}} \qquad (2)$$

Fig. 4. Model of an artificial neuron.

The output of a multilayer perceptron consists of numerical values, generated by the last (output) layer. It is usually mapped into a binary value, identifying the class of the object, represented by its numerical descriptors at the input level. In order to successfully classify input objects an ANN must go through a thorough process of supervised learning. It consists of applying a large number of training examples to the inputs of an ANN and adjusting the parameters (weights) according to a highly popular algorithm known as the "error back-propagation algorithm".

First, numerical descriptors of an object from the training set are applied to the inputs of the ANN. The network classifies the object by calculating the output values. The output is compared to the desired (correct) result and an error value is calculated. If this error exceeds the defined threshold value, the sequence of corrective adjustments to the weights is started. Adjustments are done from the output towards the input layer as the error signal travels backwards. After the corrections are done, the network generates a smaller error when classifying the same object, thus improves itself through learning. A more detailed description of the error back-propagation algorithm is beyond the scope of this chapter and is well documented in literature (Rojas, 1996). More knowledgeable readers might find it interesting that weight adjustments were done under *generalized delta rule* which included a *momentum* constant, increasing the rate of learning while avoiding the danger of instability (Kantardzic, 2003).

In theory, if the training set is large and diverse enough, an ANN can accumulate enough knowledge to reliably classify unknown objects.

To test the reliability of an ANN the data to be classified is usually divided into two sets. The first set consists of cases used for the learning process through which an ANN adapts itself and the second set consists of cases, previously unknown to trained ANN. These cases are then classified and the results are compared to actual class values.

2. Background

There have been several studies published that have used thermography as a diagnostic tool for determining various entrapment neuropathies (Ammer, 1999, 2003; R.T. Herrick & S.K. Herrick, 1987; Schartelmüller & Ammer, 1996; Tchou et al., 1992). There is a generally accepted opinion that thermography is not appropriate for routine diagnostics of CTS and other entrapment neuropathies, as they predominantly affect thick myelinated fibres, while thermography (indirectly through the arrangement of temperature changes) enables only an assessment of the functional status of thin, mostly unmyelinated, nociceptor and sympathetic, vasomotor nerve fibres (Rosenbaum & Ochoa, 2002). However, since MN contains motor, sensory and sympathetic fibres, we can justifiably expect involvement of the autonomous nervous system and consequently thermoregulation of hand, when entrapment occurs. A quick, precise, dynamic, very sensitive, and non-invasive surface detection of temperature changes of the skin is within the domain of thermography (Jones & Plassmann, 2002).

3. Methods

Monitoring the dynamics of thermographic changes in CTS aided by artificial intelligence, represented the basic research challenge. We asked ourselves if the artificial intelligence system can identify the typical CTS pattern from the thermogram of a hand, and, if so, at what stage of entrapment. Much like in other entrapment neuropathies, the myelinated fibres are the ones that are primarily affected, but chronic or extremely severe acute entrapment also captures thin sympathetic (autonomous) nerve fibres (Benaroch, 2007). However, it is necessary to point out that the latter have the capacity of improving much faster (Marotte, 1974).

In 1976, for the purposes of thermographic diagnostics in the area of entrapment neuropathies, researchers developed the provocative cold stress test (Ring, 1995a). In this test the patient's hands wrapped in thin plastic gloves are submerged in cold water (in different researchers temperature varies from 1°C to no more than 20°C) for 1 minute. After a 10 to 15-minute adaptation to the room temperature the temperature changes of the hand are determined using an IR camera. Thermographic images are taken before and after the stress test, in specific time intervals. During this process the patient should not touch anything.

According to a theory, provocation excites sympathetic autonomous nerve fibres of the hand and induces vasoconstriction. Quantitative thermography (measurement of hand temperature after a specific time interval) is used for estimating the response of the autonomous nervous system. It is expressed as vasodilation or reactive hyperthermia, which consequently normalizes hand temperature. A healthy person develops reactive hyperthermia relatively early (within 10 minutes) and equally on all fingers. But in CTS, by using thermography, we discovered different temperature changes. Neurophysiologic basis of the procedure is the measurement of the response of the sympathetic nervous system. Autonomous nerve fibres, which innervate the skin, run together with sensory fibres of peripheral nerves and also have the same arrangement within an individual nerve (Kline & Hudson, 1990). The autonomous, vegetative, nervous system of the hand controls sweat secretion and vasomotorics. The latter is responsible for the control of skin circulation required for maintaining body temperature. In vasodilation body temperature is diverted from the body and, vice versa, in vasoconstriction the temperature is retained. The initial response of the body to the provocation cold stress test is vasoconstriction.

We believe that the provocation stress test is more useful for research purposes. In our previous clinical practice the method did not stand the test. We often tried with different water temperatures. We have used ice cold water, in line with the published standard and protocol for clinical thermography (International Academy of Clinical Thermology, 2002), as well as warmer water, up to 20°C, which is recommended by Ring (Ring, 1995a). The latter claims that in the case of cold water the regeneration period is (too) long, while the Guidelines advise against water that is warmer than ice cold, as otherwise sympaticus stimulation would not be sufficient. The basic deficiencies of the test we have come across in clinical use are: it is too time consuming, unpractical (requires putting on and taking off thin plastic gloves with as little contact as possible), "old-fashioned" (the majority of patients thought it was too banal holding hands in a vessel with usually cold water, and for this reason they were not very cooperative), and unpleasant (people with impaired autonomous nervous system experience holding hands in cold water as pain). Numerous volunteers have declared that they would rather undergo EMG investigation again than the provocation cold stress test. Clear and simple instructions not to touch the wall or bottom of the vessel have frequently been breached. Constant supervision was required for a very simple test. Obviously, other clinicians have also come across similar problems, because we found no literature sources on published clinical (just research) studies using the provocation stress test on a sufficiently large population, which would provide enough data for a reliable statistical analysis. For the reasons described above our attention has been directed to finding a method that would enable us to abandon the stress test.

In currently published studies, thermographic images were analysed by means of commercial computer programmes and manual definition of fields of interest (Ammer, 1999, 2003; R.T. Herrick & S.K. Herrick, 1987; Schartelmüller & Ammer, 1996; Medical Imaging Research Group, University of Glamorgan, 2004). The analysis of thermographic images is a demanding and time-consuming task, because the precision in determining the fields of interest of images is the decisive factor for a proper diagnosis. We often require measurements with a precision of 0.1°K.

For this purpose we have developed software tool, which provided us with an exact analysis of thermographic images and automated the CTS diagnosis procedure, while eliminating the need for the preliminary provocation cold stress test (Fig. 5).

We have used the well-known advantages of machine learning by using data mining (Kantardzic, 2002). We have developed a neural network, which is capable of diagnosing CTS on the basis of very discrete temperature differences that are invisible to the eye on a thermographic image.

Patients were selected from a pool of clinically suspect CTS patients referred by general practitioners and various specialists to our department. The exclusion criteria for participation was: previous operation for CTS, negative electrodiagnostic test for CTS, abnormal hand anatomy (amputations, injuries, other anomalies) preventing the acquisition of standard images of hands. Volunteers who did not exhibit symptoms of CTS and were subsequently diagnosed by electromyography as not having the syndrome were used to acquire images of healthy hands (dorsal and palmar views).

For our pilot study 112 images were examined: 23 patients (15 females, eight males; mean age 51.4 years, range 26-71 years) were used to acquire 60 images depicting 30 hands (dorsal and palmar views) at different stages of CTS; 13 volunteers (eight females, five males; mean age: 48.3 years, range 28-66 years) who did not exhibit symptoms of CTS and who were

subsequently diagnosed by EMG as not suffering from the syndrome were used to acquire 52 images of healthy hands (dorsal and palmar views of 26 hands).
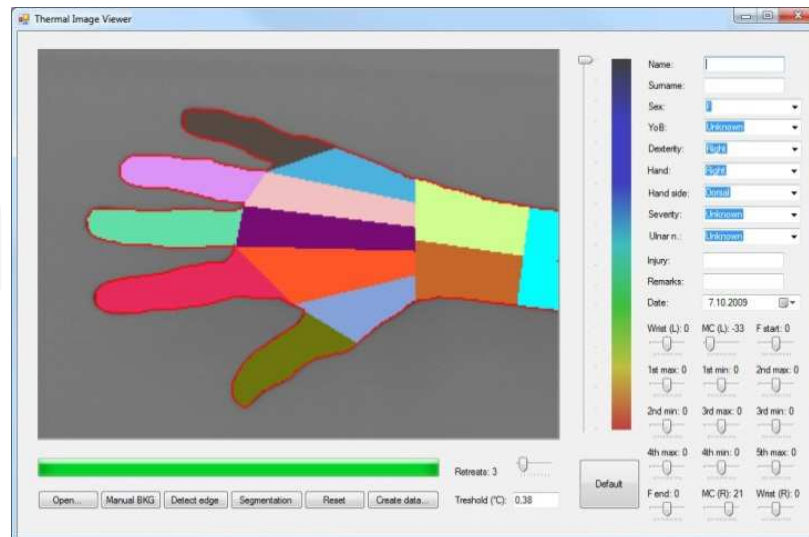

Fig. 5. Computer software for identification of mean temperatures of individual hand segments.

The results of a pilot study were very promising. In the majority of performed measurements classification exceeded the 77% effectiveness (Table 1).

The most important segments turned out to be fingers, especially the index finger and the little finger (which also coincides with the anatomic distal innervation area for the median or ulnar nerve (ulnaris). The results also coincided with a similar study carried out by Schartelmüller and Amer in relation to the thoracic syndrome pathology by means of manual analysis of thermograms (Schartelmüller & Ammer, 1996). Successful classification of our neural network was supported by the fact that whenever we excluded the majority of fields of interest of MN (thumb, index finger, and middle finger), the efficiency was not better, only accidental.

Included segments	Success rate (%)
All dorsal segments (reference case)	80.6
All segments	74.3
All palmar segments	65.6
All dorsal but thumb	81.8
All dorsal but index finger	77.3
All dorsal but middle finger	81.8
All dorsal but ring finger	79.2
All dorsal but little finger	75.2
All dorsal but index and little finger	70.8
All dorsal but thumb, index and middle finger	64.5
All dorsal without wrist segments	82.5
All dorsal without metacarpal segments	78.4

Table 1. Pilot study CTS classification success rates (each success rate percentage is the mean of five repeat runs on 22 randomly selected hands).

The findings of our pilot study spoke in favour of the applicability of the intelligent system for discerning CTS from thermovision images. In a smaller number of study and test cases (n = 112) the efficiency of classification exceeded our expectations. We were aware of the fact that a small set of elements can lead to misleadingly good (or bad) results. Therefore, for a realistic evaluation of efficiency of classification we have collected a significantly larger data base. In total we acquired 502 images of 251 hands (dorsal and palmar side of each hand). 71 patients (52 females and 19 males with mean age 56.8 years, range 23 – 90 years) contributed 274 images of 137 hands (in 5 patients only one hand met the inclusion criteria) and 57 volunteers (35 females, 22 males; mean age 47.6 years, range 25 – 74 years) contributed 228 images of 114 healthy hands.

3.1 Statistical analysis

All statistical analyses were performed using the R Project for Statistical Computing, a software language and environment for statistical computing, available as free software under the terms of GNU General Public License. Where appropriate, data are presented as mean ± SD or as percentages. Comparisons between patient and volunteer groups regarding segment temperatures were analysed by non-parametric Mann-Whitney-Wilcoxon test since it is used to compare two independent groups of sampled data and unlike the parametric t-test, makes no assumptions about the distribution of the data (e.g., normality). A p-value < 0.05 was considered to be statistically significant.

4. Study results

The prevailing opinion in literature states that for determining CTS by using thermography dorsal segments of the hand are more important than the palmar ones (R.T. Herrick & S.K. Herrick, 1987). Even more so, we have confirmed that palmar segments are not useful for detecting CTS by means of IR thermography (Fig. 6).

The finding was a surprise to us, because we have initially expected palmar changes, considering the distal innervation sample of MN. Our explanation is that obvious temperature differences on the dorsal or palmar side are the result of hand complexity. They originate both from anatomical and physiological and functional features of the hand. In anatomical terms, the skin on the hand is thinner and contains essentially more sweat glands (>450/cm²) than on the dorsal side (Tortora & Derrickson, 2008). In physiological terms, the emotional stress is initially reflected by palm sweating (next to feet and armpits). In the majority of basic hand functions (grasping, leaning, carrying) the palmar side of palms and fingers is burdened. Everything we have described above has an important influence on local temperature changes even in a healthy person, which is in our opinion a sufficient reason why the palmar side of hands is not the most appropriate for a credible analysis of thermograms in CTS cases.

One of our further objectives, after having expanded our data base, was the attempt of classifying CTS with thermography, while considering neurophysiological levels of MN entrapment. For this purpose we have developed a neural network, which is capable of classifying data into four classes (no entrapment, mild, moderate, severe). However, the results of this classification were even weaker. We have also tried using other methods of machine learning (Podgorelec et al., 2002), but they did not produce favourable results either, so we abandoned the idea. On the basis of statistical data processing (Table 2), which has shown significant difference among healthy patients and the severe level of CTS entrapment, we have decided to use only the latter for classification.
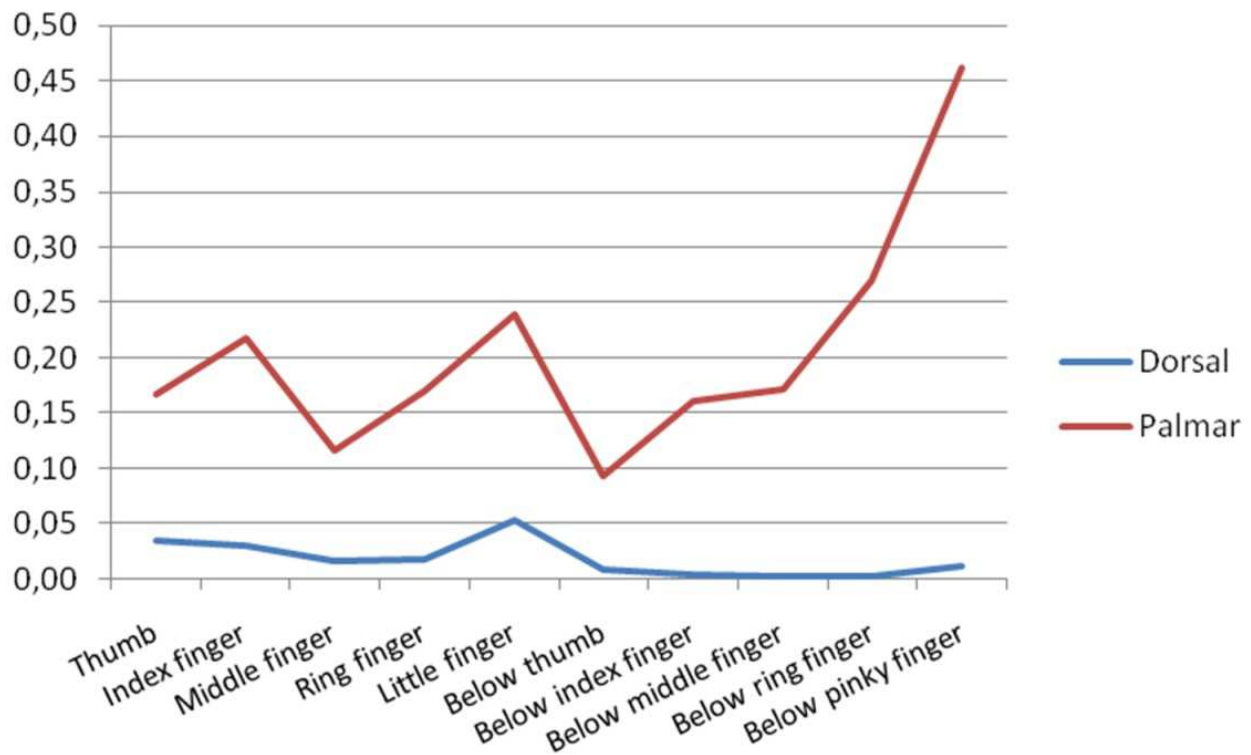
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Fig. 6. Statistical significances of differences between segment temperatures in patients' and volunteers' hands (Mann-Whitney-Wilcoxon test, p=0.05), for dorsal and palmar side.

Segment	Mild-Normal	Moderate-Normal	Severe-Normal	All CTS-Normal
Whole hand	0,237400	0,285800	1,79E-006	0,007162
Thumb	0,244800	0,509300	5,07E-005	0,034990
Index finger	0,295100	0,449800	6,19E-005	0,029850
Middle finger	0,470900	0,397900	4,90E-005	0,017270
Ring finger	0,550600	0,557500	3,49E-005	0,017840
Little finger	0,473400	0,619200	4,03E-004	0,053060
Below thumb	0,111200	0,165400	2,32E-006	0,008782
Below index finger	0,166000	0,218600	3,36E-007	0,004250
Below middle finger	0,175600	0,228700	1,42E-007	0,003147
Below ring finger	0,176200	0,279400	1,24E-007	0,003551
Below pinky finger	0,132300	0,318200	1,69E-006	0,011470

Table 2. Statistical significances of differences between dorsal segment temperatures in different NCS severity levels (Mann-Whitney-Wilcoxon test, p=0.05).

After repeated learning and testing of the neural network on the basis of these reduced results (dorsal images of the severe CTS and healthy hands; n = 185), we have achieved our best results. The efficiency of classification has exceeded 83% (Table 3).

Classification run	Incorrectly classified	Correctly classified	Success rate (%)
1	6	31	83,78
2	5	32	86,49
3	8	29	78,38
4	5	32	86,49
5	7	30	81,08
Mean	6.2 ± 1.30	30.8 ± 1.30	**83.24 ± 3.52**

Table 3. CTS diagnosis success rate when only dorsal segments of severe cases and healthy hands were used (n=37, 20% of all hands, each success rate percentage is the mean of five repeat runs).

5. Discussion

On the basis of such results, we can claim that thermography is a useful method for assessing severe CTS levels, even without using a preliminary stress test. Our attention has to be directed to the interpretation of thermograms in relation to the clinical picture, because pathological thermographic samples can be a result of neuropathic changes, local inflammation, or vascular diseases.

In terms of pathophysiology, we differentiate between four basic thermographic patterns of neuropathic origin (Rosenbaum & Ochoa, 2002):

1. Warm pattern I: sympathoparalytic vasodilatation;
   It occurs due to the loss of vasoconstrictor activity of sympaticus, (such as blockade of sympaticus or local blockade of somatic nerve). The skin is warm. Mechanism of action: the result of reduced vasomotor tonus of arteriolesis vasodilation, which is expressed as increased blood flow to the skin.
2. Cold pattern I: Denervation supersensitive vasoconstriction;
   The result of chronic interruption of postganglionic sympathetic neuron, which supplies the skin, leads to hypothermia of denervated area (sympathetic denervation supersensitivity). The skin is cold. Postsynaptic abnormality in the smooth muscles. Mechanism of action: the result of increased vasomotor tonus of arterioles is vasoconstriction, which is expressed as reduced blood flow to the skin.
3. Cold pattern II: Somatosympathetic reflex vasoconstriction;
   It is the result of the excitation of sensory receptors from the skin or irritation of sensory nerve, which is reflected as sudden cooling of skin on the area, where afferent impulses originate from. It is a reflex action, and afferent sensory fibres in this case are sympathetic.
4. Warm pattern II: Antidromic vasodilatation;
   Hyperthermia occurs due to vasodilatation, which does not depend on sympathetic activity, but on neurosecretion of vasodilatatory substances. Every stimulus, which reaches sufficient intensity to stimulate noniceptive nerve endings, can induce neurosecretory functions and consequently antidromic vasodilatation. The skin, which is cold due to symptomatic vasodilatation, retains the capacity for reflex sympathetic vasoconstriction.

In CTS, including rare cases of painful MN entrapment, we can come across any of the pathological samples mentioned above. However, further attention is required for the interpretation of results, because changes in vasomotor tonus are not exclusively the result

of stimulation of sympathetic nerve fibres (Aminoff, 1979; Ochoa & Verdugo, 1995; Ochoa, 2002). And namely:

1. Reflex sympathetic activity can merely be physiological response to pain;
2. Vasoconstriction is often the result of denervation supersensitivity rather than of sympathetic hyperactivity;
3. Antidromic vasodilatation can also be caused by stimulation of sensory nociceptors;
4. Vasomotor disorders can simply be a result of the non-use of hand (Ochoa & Yarnitsky, 1994).

Giordano and others (Giordano et al., 1992) examined 40 patients with idiopathic CTS by applying electroneurography and thermography, and compared them to 30 healthy volunteers. Abnormal hypothermia and hyperthermia were attributed to changes in vasoconstrictor tonus caused by the compression of thin non-myelinated sympathetic fibres. With regard to complex thermoregulation mechanisms, autonomous activity of vegetative nervous system and individual reaction of individuals, the interpretation of thermograms is not uniform and must be done in conjunction with anamnesis, clinical picture and/or electrodiagnostics. It is commonly known that clinical signs for CTS are highly specific, but also not sensitive (Gunnarsson et al., 1997; Kuhlman & Hennessey, 1997; Kuntzer, 1994; Seror, 1993; Uncini et al., 1993). D`Arcy and Mc Gee have published work in which they present an overview of literature covering the period from April 1966 to December 2000, which discuss symptoms and signs for CTS diagnostics, in comparison to electrodiagnostic testing. They have established that sensitivity and specificity of clinical investigation vary considerably (D'Arcy & McGee, 2000). As part of our research we decided to compare thermograms with electrodiagnostics, since the latter is considered the most specific, sensitive (over 90%), and objective test for CTS diagnostics (Cassvan et al., 1988; Hennessey & Johnson, 1996; Hilburn, 1996; Jackson & Clifford, 1989; Johnson, 1993; Lew et al., 2005; Seror, 1987).

Rosenbaum and Ochoa warn that thermography cannot simply be equated with the CTS diagnostics, because it does not say much about the patophysiological basis of thermographic changes and entrapment, other than presenting changes in body temperature in a very precise and spectacular manner (Rosenbaum & Ochoa, 2002). In currently published clinical studies on CTS it has been reported that many patients with the clinically and electrodiagnostically confirmed CTS had normal thermographic samples (So et al., 1989; Myers et al., 1988). Thermograms were manually read. Y.T. So and others registered pathological samples in no more than 55% (So et al., 1989. In 1992 Tchou and others compared thermograms of 61 patients with CTS and 40 volunteers. Thermograms were considered abnormal, if at least 25% of distal median area was affected by temperature increase by more than 1°C. They have noted 93% sensitivity and 98% specificity of the thermographic method in impaired MN in the carpal tunnel, but only in the case of unilateral CTS (Tchou et al., 1992).

Our study also includes use of artificial intelligence, because we wanted to avoid the provocation cold stress test and manual interpretation of thermograms. By using neural networks of the multi-level perceptron type, we have, after preliminary supervised training, automated the analysis of thermograms and the CTS diagnosis procedure. As it turned out, by using a new software tool we were able to register very discrete temperature changes, which are not perceived macroscopically on the thermogram, and which the neural network successfully classified into the pathological sample. By using artificial intelligence we were able to abandon the need for contralateral comparison with the "healthy" side, which represented reference values in currently manually analysed thermograms. With regard to

the findings of our research we can claim that the use of thermography in detecting CTS is useful even in the case of bilateral impairment. Considering this, the method achieved wider indication area, as by its definition CTS is more frequently bilateral (Rosenbaum & Ochoa, 2002). Our neural network was used on a group of patients with predominantly bilateral impairment, and the threshold for successful classification was set at 80%.

The assessment of the autonomous nervous system, in MN entrapment, was evidenced only by few authors (Aminoff, 1979; Verdugo et al., 2004; Verghesse et al., 2000). As a matter of fact, the incidence of these symptoms is not completely clear both in healthy people and in people with some other hand pathology. Burke and other discuss that more than a half of all patients with electrodiagnostically confirmed CTS, and also approximately two thirds of those without CTS, mentioned hand sweating. The entrapment of autonomous median fibres in the carpal tunnel was assessed with the sympathetic skin response, which was pathological in one third of all those patients with CTS, who stated symptoms, consistent with vegetative symptomatics (Burke et al., 1999). Yarnitsky and Ochoa claim that symptoms, which potentially belong to the autonomous nervous system disorder (finger sweating, dry palms, Raynaud's phenomenon, and finger pallor), can only be noticed in 17% to 32% of patients with CTS, and don't have high diagnostic value (Yarnitsky & Ochoa, 1991). But on the contrary, Verghese and others point out that the involvement of autonomous nervous system in CTS is frequent (55%), especially in the group of people with severe neurophysiological level of entrapment (Verghesse et al., 2000).

The results of our research are in line with the latter; as a matter of fact, the classification was by far the most successful in the group with the most severe level of entrapment in terms of electrodiagnostics (Table 3). In this group, even pathophysiologically, we can already expect impairment of thin, non-myelinated, autonomous, nerve fibres.

6. Conclusion

After an in-depth deliberation we believe that a pathophysiologically-substantiated doubt, with regard to the mechanism of the incidence of temperature changes in CTS, doesn't diminish the applicability of thermography in diagnosing MN entrapment by using artificial intelligence. As is often the case in medicine, temperature is a symptom and reflects a certain condition. By using artificial intelligence, considering reliable electrodiagnostic criteria, we have succeeded in classifying the discussed condition on hands as the result of severe level of MN entrapment in the carpal tunnel. Doctrinally, even though this is the best and the most frequently researched entrapment neuropathy on hands, there is currently no consensus reached with regard to treatment (Gerritsen et al., 2002; Gunnarsson et al, 1997; Hui et al., 2005; Kanaan & Sawaya, 2001; O'Gradaigh & Merry, 2000; Padua et al., 2001). Usually, mildly expressed CTS symptomatics in clinical terms is initially treated conservatively. With regard to the decision when and which type of operative relaxation of MN is the most appropriate, there are no uniform scientifically-supported evidences (Chang et al., 2008; Finsen & Russwurm, 2001; Iida et al., 2008; Mondelli et al., 2001). In patients, who refuse surgical procedures, neurophysiological investigation with a very clear clinical picture makes no sense, because it doesn't change their treatment in any way. Not taking into account results of neurophysiological measurements, it is conservative (disburden, braces), which means cheap, non-invasive, and completely reversible. Likewise, it also does not make sense to refer patients with CTS symptoms, which last less than six months, to neurophysiological measurements, because the probability of spontaneous healing is

particularly high in the early period (Padua et al., 2001). Considering the described doctrine, recommendation, and clinical practice, we can diagnose CTS in cases of severe entrapment with a high level of reliability by using thermography and appropriate software tool. Simultaneously, critical interpretation of thermograms, considering anamnesis and clinical picture, is also sufficient for the beginning of CTS treatment. Patients with severe level of entrapment (where typical thermogram is registered), if they consent to the operative procedure, are referred to EMG investigation and then to decompression; all others are treated conservatively for the next six months.

On the basis of the conducted study, IR thermography cannot be recommended as an equal diagnostic method to the already established EMG investigation. However, we are determining that it can be used as a successful, non-invasive method for detecting severe CTS cases. It could also be useful in preventive examinations of a wider population, such as in different industries, where ergonomic conditions of work represent a major risk for the development of CTS (repeating hand and wrist movements, work with vibration machines, work in extreme wrist positions along with simultaneous pressure on palms, work in cold atmosphere, professional drivers, etc.), as well as in pregnant women and children and those symptomatic patients, who as a principle reject EMG and operative therapy.

Considering good results we have obtained by using neural networks in the group of severe entrapments we recommend thermography as a screening method for determining CTS. Indirectly, the method can also be useful in reducing long waiting periods for EMG investigation, which is the major deficiency of this generally established, standard diagnostics. By using non-invasive thermography we would focus on the group of patients most at risk, who would be given priority for EMG investigation.

The method we have developed with a clear indication for or restriction only to severe cases of entrapment is recommended as a screening method for determining CTS and as pre-level of EMG investigation, which otherwise still remains the most reliable standard in the area of diagnostics of entrapment neuropathies.

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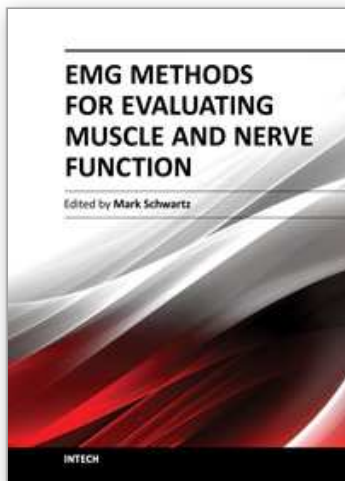
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