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H. Knaf, P. Lang, S. Zeiser

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Hagen Knaf, Patrick Lang, Stefan Zeiser

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Abstract

The objective of the present article is to give an overview of an application of Fuzzy Logic in Regulation Thermography, a method of medical diagnosis support. An introduction to this method of the complementary medical science based on temperature measurements – so-called thermograms – is provided. The process of modelling the physician's thermogram evaluation rules using the calculus of Fuzzy Logic is explained.
Keywords: fuzzy logic, knowledge representation, expert system.

1 Introduction

Fuzzy Logic is an extension of Boolean Logic: logical statements in Boolean Logic are either true or false. In Fuzzy Logic every such statement has a truth value typically lying in the interval $[0, 1] \subset \mathbb{R}$, where the value 0 represents a false while 1 is assigned to a true statement. Truth values like 0.5 or 0.8 reflect the degree of belief in certain statements occurring for example in the medical science or in Quantum Physics.

Clearly when passing from binary to multi-valued logic the logical operators $\vee$ (OR), $\wedge$ (AND) and $\neg$ (NEGATION) must be redefined. The same is true for the logical implication $A \Rightarrow B$, where A, B are two logical statements. It turns out that there are infinitely many ways to extend the boolean logical operators. The concrete choice depends on the specific situation in which Fuzzy Logic is applied.

Throughout the present article we will assume some familiarity of the reader with the basic concepts of Fuzzy Logic as found in introductory books like [1] or [4]. More specialized expositions are [3] or [5].

Fuzzy Logic can be applied in various ways and in a variety of areas. In the context of diagnosis support that we describe in the present article, Fuzzy Logic provides a convenient way for the representation of human knowledge within an Expert System.

An Expert System can be defined as a collection of data and rules to deal with this data, that allows to simulate an expert in a specific field. Such a system could for example consist of the precise description of a method for the diagnosis of malaria. In this sense every book on the diagnosis of tropical diseases is an Expert System. However usually this term is used in the more restricted sense of a software package into which data and rules are implemented, and that allows the user to »simulate the expert« by running the program as well as to view and edit data and rules.

We should mention at this point that the approach to Expert Systems just described is called »rule-based« in contrast to the »object oriented« one. We will utilize the rule-based approach throughout the whole article.

When building an Expert System the problem of formally representing the expert's knowledge in a convenient way within the system arises. Here the adjective »convenient« means that the formal representation should be easy to read and to understand for the experts in the considered field, as to allow them direct access to the knowledge stored in the system. Depending on the type of knowledge Fuzzy Logic provides a possible solution for this representation problem.

Usually the calculus of Fuzzy Logic is not only used to represent expert knowledge within a system, but the representation is coupled with software that allows to compute the truth values of statements formulated in this calculus – a so-called Fuzzy Inference System.

Medical diagnosis is a typical field of application for various types of Expert Systems: on one hand the daily work of a physician produces a large amount of data that can be used to test existing or to establish new medical hypothesis. On the other hand long-term experience often yields extensive systems of rules helping in the task of early and secure detection of specific diseases. In this situation an Expert System can be useful in several ways. It serves as an easy to use database that allows to run simulations based on the incorporated knowledge. Novices may use it in their training. Groups of scientists can share one Expert System thus facilitating the process of objectifying knowledge. These examples do only form a part of the possible applications.

Regulation Thermography is a diagnostic method that utilizes the behavior of the human body's skin temperature distribution under the influence of a cold stimulus. The observed temperature patterns are classified according to their types and degrees of pathology. Eventually a set of interpretation rules is applied to gain diagnostic statements. The whole process is based on a double measurement of the skin temperature at 110 locations (»areas«) of the body leading to a so-called thermogram. The temperature at each area is measured before and a certain time after the cold stimulus. The interpretation rules involve both the absolute temperature values and the differences between the measurements before and after the cold stimulus.

At present Regulation Thermography as a method is not generally accepted among physicians partly due to the fact that its diagnostic power is not yet verified by standard medical means. However especially in the field of female breast cancer diagnosis some effort is going on to improve this situation. One activity in this trial consists of the BMBF-project »Datenbasierte Diagnoseunterstützung in der Regulationsthermographie« having the aim to implement a complete set of thermogram interpretation rules for the diagnosis of female breast cancer into a rule-based Expert System using Fuzzy Logic and Neural Nets.

At the time of writing this article approximately 130 interpretation rules as used by thermographers have been incorporated into a Fuzzy Inference System. This system takes the 220 values of a thermogram as input and determines a »probability« for the presence of a Mamma Carcinome on a 6-stage scale. In the sequel this risk class is abbreviated by RC.

The process of implementation demands a continous dialog between physicians and mathematicians since the mathematical modelling requires the determination of numerical constants and functions that cannot be extracted from the rules directly.

The structure of the Fuzzy Inference System reflects the procedure a physician is applying when classifying a thermogram with respect to RC. Roughly speaking the RC is determined by combining several thermogram properties each of them typically involving only a subset of all of the 110 areas. Consequently the expert's interpretation rules can be grouped according to the areas involved, obtaining 13 different groups. In the Expert System this structure is represented by first calculating 13 so-called partial fuzzy values each of them »measuring« the »degree of pathology« of either a single thermogram part or of several thermogram parts with respect to a specific property like for example asymmetry. Afterwards these 13 values are combined using some global rules to obtain the RC. Mathematically the step of computing the partial fuzzy values from the whole thermogram can be understood as a dimension reduction given by a non-linear function $p: \mathbb{R}^{220} \to \mathbb{R}^{13}$.

2 Regulation Thermography

Regulation Thermography (RTG) is a diagnostic method in the medical science based on the hypothesis that diseases of the human body (or their prephases) entail characteristic changes in the body's ability to adapt respectively react to the current ambient temperature. Roughly speaking a comparison of the body's actual »thermoregulation ability« with the expected healthy »regulation ability« should give information relevant for the diagnosis of certain diseases.

In this section a brief overview of the physiological basis of RTG is provided. Furthermore, the process of measuring thermograms is described in some detail and necessary terminology is introduced. Finally the »normal« regulation pattern and the basic types of deviations from it are described.

The pictures 1, 2, 3 and 4 are taken from [6].

2.1 Physiology of thermoregulation

The healthy body continously regulates the heat production and loss with the aim to keep up a specific temperature pattern. This pattern is determined by function, anatomy and thermodynamics (figure 1): the temperature of the body's core as well as that of the head must be kept constant as to ensure the unrestricted functioning of the inner organs and the brain. Arms and legs as the other extreme underly rather strong variation of temperature. The axial symmetry of the temperature distribution has simple anatomic reasons, while the radial decrease of temperature values represents the flow of energy from their source through the body's surface into the ambient space.

The regulation of the heat distribution inside the body is performed by a multitude of components of the human organism forming a complex control system: the center of this system is constituted by the Hypothalamus, a particular part of the brain. Via nerves it is connected to cold and heat receptors distributed

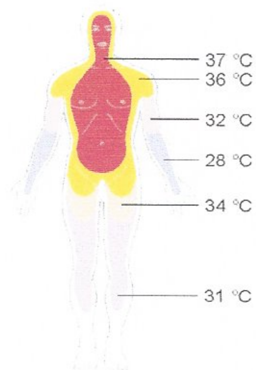

Figure 1: heat distribution

throughout the body and continously providing a »picture« of the heat distribution. Depending on this picture the Hypothalamus de-/activates the metabolic activity, sends commands to open/close sweat glands or to expand/contract the diameter of blood vessels to mention only a few of the possible regulation mechanisms. Some of these mechanisms are to a certain extent self-sufficient, some others can directly interact with each other. Moreover the communication within the control system is not only conducted via nerves but also via slower chemical channels involving hormons. Altogether the regulation system enables the body to keep its heat distribution constant for ambient temperatures between $26°C$ and $32°C$; outside this interval deviations from the normal distribution appear. However the organism still keeps functioning properly in a wide temperature range.

To understand in which way a disease can influence the ability for thermoregulation one has to take a look at the body's innervation: nerval channels connect the brain with for example inner organs and the skin. Such a channel typically starts in the brain, runs along the spinal cord to a specific point, and leaves the spine between two intervertebral disks to reach its final destination. Due to reasons lying in the embryonal evolution of humans, all nerves leaving the spine between two specific intervertebral disks innervate a »horizontal slice« of the body. The head is an exception from this principle. Moreover the slices might be deformed in vertical direction – see figure 2. The main consequence of this segmentation is that different nerves running to or coming from points in one and the same segment can interact in the spinal cord. An impulse sent by an inner organ can induce an impulse running to a specific part of the skin say. This impulse can alter various properties of the skin, like the temperature, the mechanical tonus and sensivity, the amount of sweating and so on. The structure just described is called a **reflex arc** and is schematically shown in figure 3. Comprising one can state that pathological changes of an inner organ can locally influence the metabolism, temperature and other properties of the skin via reflex arcs. This fact is the basis of Regulation Thermography.

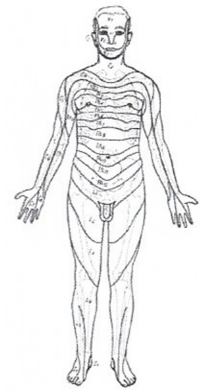

Figure 2: horizontal segmentation

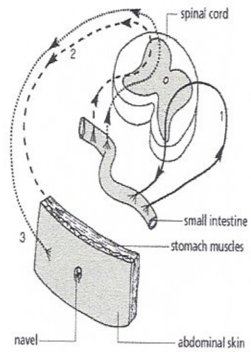

Figure 3: reflex arc

The primary hypothesis of RTG can now roughly be formulated like this:

An ongoing or emerging disease influences the thermoregulation property of specific areas of the skin in a distinguished way. The knowledge of the abnormally reacting areas combined with a classification of the type of reaction they show in response to a temperature stimulus allows diagnostic conclusions.

2.2 Measurement of the thermoregulation ability

The description of thermoregulation given in the preceeding paragraph shows, that the thermoregulation ability cannot be measured *directly* without massive intervention into the body. Instead one investigates the Input-Output behavior of the body's regulation system to judge its status: basically this is done by exposing the proband to a cold stimulus, and measuring the surface temperatures of the body shortly before and a defined amount of time after the onset of the stimulus. Infrared cameras as well as various types of contact thermometers can be used to perform this task. In spite of the advantages of using an infrared camera – it gives a snapshot of the temperature distribution over the whole body and allows the observation of the dynamics of the regulation process – contact thermometers are right now and to our knowledge the preferred method used to retrieve temperatures in RTG. This partially has »historical« reasons, but most likely costs do also play a significant role.

Using a contact thermometer the surface temperature of the body can only be determined at a specified (finite) set of points. In RTG these points are called **areas**, an expression that is used from now on throughout this article. It should however be emphasized that in spite of the misleading name the areas have a well-defined anatomic position. Having fixed a set of areas one measures the body temperature twice at each area: one measurement before and one after the cold stimulus. The set of temperature values so obtained is called a **thermogram.**

To achieve comparability in RTG a standard set of areas was defined by A. Rost in 1975 (see [6]); the thermograms dealt with in the present article are based on this set. It consists of the following members grouped into three subsets:

The standard areas

The 60 different standard areas are distributed over the whole body in an axial symmetric manner. Since these areas will frequently occur in the subsequent paragraphs, their names and abbreviations are provided in table form below: the areas fall into 8 different subgroups that are shown in the first column of the table. Axial symmetric areas are listed as pairs – like (T1,T2) for the tonsils – occupying only one row in the table. Moreover some areas are grouped together to keep the table short.

The areas at the elbows are measured twice, at the beginning and at the end of each the first *and* the second measurement (El1 equals El3, El2 equals El4). This is done for control purposes: significantly different values at the beginning and the end of a measurement indicate that either the velocity in measuring was too slow or that the regulation equilibrium was not reached yet (second measurement only).

Group	No.	Abbrev.	Name
	1	ST	forehead
	2	NW	root of nose
	3+4	(El1,El2)	elbows
Head	5+6	(SH1,SH2)	frontal sinus
	7+8	(S1,S2)	temples
	9+10	(Aw1,Aw2)	canthus
	11+12	(M1,M2)	mastoids
	13+14	(Sie1,Sie2)	ethmoid bones
	15+16	(KH1,KH2)	maxillary sinus
Throat/ Neck	17+18	(T1,T2)	tonsils
	19-22	L1-4	lymphatic vessels
	23-24	L5-6	supraclavicular fossa
	25-26	L7-8	lymphatic vessels
	27+28	(SD1,SD2)	thyroid gland
	29	Thy	thymus gland
Thorax	30	St	sternum
	31+32	(Mp1,Mp2)	pectoral muscles
	33	He1	atrium/right
	34	He2	atrium/left
	35	He3	cardiac muscle/right
	36	He4	cardiac muscle/left
Upper Stomach	37	Sol	solar plexus
	38	Ma	stomach
	39	Le1	liver
	40	Le3	liver
	41	Gbl	gallbladder
	42+43	(Pa1,Pa2)	pancreas
Intestine	44	Int	intestinum
	45-50	Da1-6	intestine
	51	App	appendix
Lower Stomach	52	Ut/Pro	uterus/prostata
	53+54	(Ov1,Ov2)	ovaria
	55+56	(Nie1,Nie2)	kidneys
	57+58	(Isc1,Isc2)	iliosacral joint
	59+60	(El3,El4)	elbows

Table 1: standard areas

The breast areas

There are 18 such areas, 9 at each breast, named A1,B1,C1,D1,a1,b1,c1,d1,E1 for the right and with the 1 replaced by 2 accordingly for the left breast. The breast areas are mainly measured for female persons in particular in the context of breast cancer diagnosis.

The tooth areas

One such area is located in the face near each of the teeth. The tooth areas play no role in the course of this article.

A rough idea of the location of some of the areas is given by figure 4.

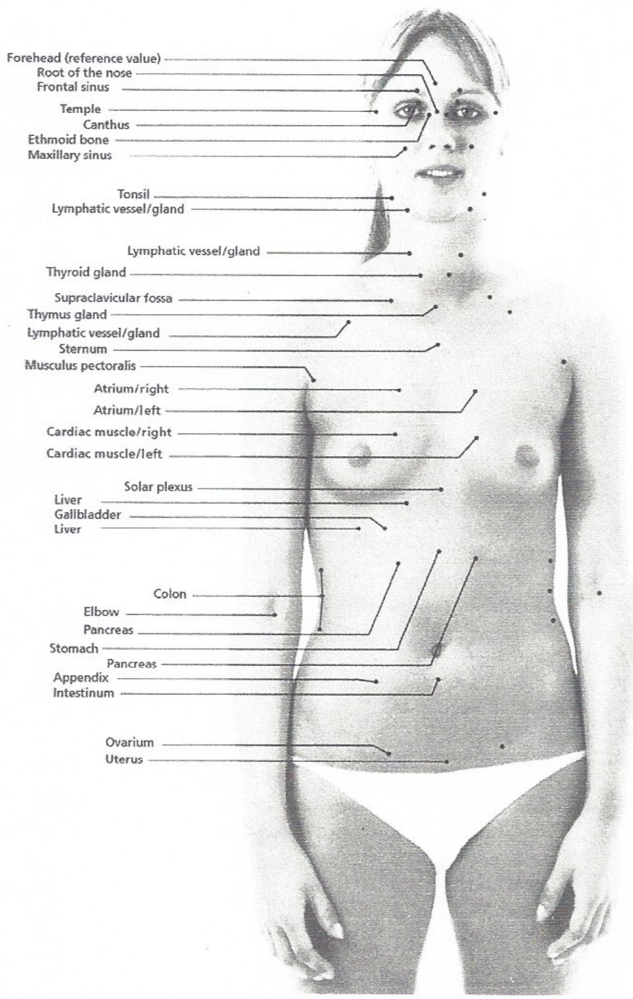

Figure 4: areas at the front of the body

Obviously the process of creating a thermogram needs also to be standardized to produce comparable results: the proband undresses in a room with normed temperature ($20° - 22°$ C) and air humidity ($\sim 60\%$) – since the ambient temperature is significantly lower than the mean body temperature a cold stimulus is caused this way. Immediately after undressing the temperatures of the different areas are determined. The measurement should be performed rather quickly to make sure that the onset of thermoregulation does not already influence the temperature values. The measurement is repeated after 20 minutes when the temperature distribution of the body has reached the new equilibrium.

Clearly there are some other points the investigator should care for during the process of thermogram creation. We refer the interested reader to Rost's book [6] for more details.

The totality of 220 values obtained by measuring at Rost's areas twice is called a **regulation thermogram** (RT).

The thermograms evaluated at the ITWM were measured using an electronic preheated thermometer with an adaption time smaller than 0.5 seconds. The temperature values are directly transferred to a Personal Computer and stored together with relevant proband information like age, gender, diseases, ongoing medication etc..

2.3 Regulation patterns

In order to quickly gain an overwiew over the bunch of temperature values a thermogram consists of one frequently uses bar plots like the one shown in figure 5: The different areas are listed on the horizontal axis – area abbreviations as well as their numbers are shown – while the vertical axis shows the corresponding temperature values. More precisely bars starting from a line determined by the pre-stimulus-value at the St-area (forehead) depict the pre-stimulus-values in black and the post-stimulus-values in red colour. The St-value normally is not influenced much by stimuli and therefore serves as a **reference line** in the RT.

In figure 5 only the standard areas are shown; they are ordered essentially with respect to their anatomic position from top to bottom. When evaluating an RT the physician has to identify patterns among the temperature values at different areas. Clearly the appearance of a pattern in the bar plot depends on the ordering of the areas. For a human expert it is therefore of importance to always work with one fixed ordering.

For the sake of simplification in the sequel we refer to the pre-stimulus-value of an area A as its **first value** abbreviated by **A(1st)**. The post-stimulus-value consequently is called **second value** and is abbreviated by **A(2nd)**. We shall also use the differences A(1st)-St(1st) and denote them by **A(temp)**. Finally we are interested in the difference between the second and the first value at the area A. This quantity is called the **regulation at A** and is denoted by **A(reg)**.

Figure 5 demonstrates the normal reaction of the human body to a cold stimulus as well as the expected symmetries. The reader can easily recognize the following overall patterns:

- Areas in symmetric anatomic position have almost equal temperature values. Thus also their regulation almost coincide.

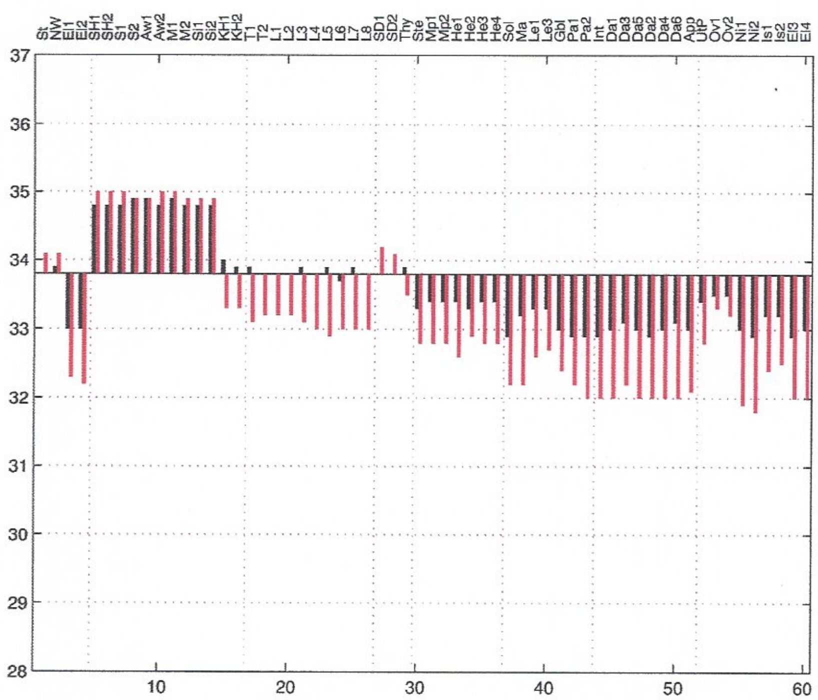

Figure 5: ideal thermogram

- The regulation shows a tendency to increase from top to bottom: while the head areas show only small regulations, the regulation values are around $-1°K$ for the upper and lower stomach areas.
- Most of the regulation values are negative (cold stimulus !) except for the head and the thyroid gland.
- The 1st values of the areas in the thorax, intestine and upper and lower stomach groups are below the reference line.

The reasons for the observed axial symmetry and the top-down pattern visible in the ideal RT are already mentioned in subsection 2.1. As a consequence of the organisms trial to protect the brain against malfunction due to cooling, 1st and 2nd values of the head areas are only slightly differing. At the thyroid gland (areas SD1, SD2) the regulation is positive. As already mentioned one reaction to a cold stimulus is the increase of metabolic activity, a process that involves the hormons produced in the thyroid gland. Therefore increasing metabolic activity yields higher activity of this gland and thus warming up. The distribution of the 1st values about the reference line again mainly has anatomic reasons.

We next take a closer look at the main deviations from normal thermoregulation. Clearly in thermogram interpretation the precise temperature resp. regulation values are used. However in the present subsection we focus on the qualitative presentation of the most important RT-patterns and postpone a more quantitative description to subsection 3.1.

The »deviations from normality« roughly fall into two classes: local patterns that involve only one area, and patterns that apply to a group of areas or even the whole RT. We start with the explanation of the different

Local patterns

Cd-regulation: the abbreviation »cd« stands for »contra directional« meaning that the sign of the regulation value is the opposite of the expected one. For most of the areas A cd-regulation therefore means A(reg)> 0, i.e., as a reaction to the cold stimulus the temperature increases.

An example of cd-regulation can be seen in figure 6 at the areas (Si1,Si2) and at the area UtP. At Si1 and Si2 the regulation values are negative while they should be around zero or slightly positive (head area !). At UtP the regulation value is approximately $+0.8°K$ but is supposed to be negative.

Hyporegulation: regulation having the correct sign but with an absolute value being too small. An example are the areas L1 and L2 in figure 6.

This type of dysregulation seamlessly passes over into

Rigid regulation: here no regulation takes place at all although it is supposed to. Typical examples are the areas L7 and L8 in figure 6.

Hyperregulation: regulation having the correct sign but with a value being too big. An example is the area Pa2 in figure 7 with a regulation value of approximately $-2.5°K$.

Asymmetry: deviation from the general rule that anatomically symmetric areas should exhibit almost the same temperature and regulation values independently whether they are normal or pathological. This phenomenon clearly appears at the elbow areas (El1,El2) for both the 1st and 2nd values in figure 6. Moreover the areas (El3,El4) show this behavior too – recall that (El1,El2) equals (El3,El4) and that the values of (El3,El4) are the result of a second measurement at (El1,El2) for control purposes.

Hotspot: hotspots are areas with an outstandingly high 1st *and* 2nd value compared to the St-area, where the 1st and 2nd value should show only a small difference.

The local patterns just listed may be qualified further using

Attributes

As mentioned earlier the temperature values at the areas of a »normal« RT are distributed about the reference value St(1st) in a particular way. While for example the head areas typically display temperatures above the reference line, the values of the torso clearly lie below it. Taking these facts into account pathological patterns may be qualified using the adjectives »hot« and »cold«. Roughly speaking these attributes indicate whether the temperature values involved into the pattern lie above or below the reference line. The exact definition depends on the specific pathology.

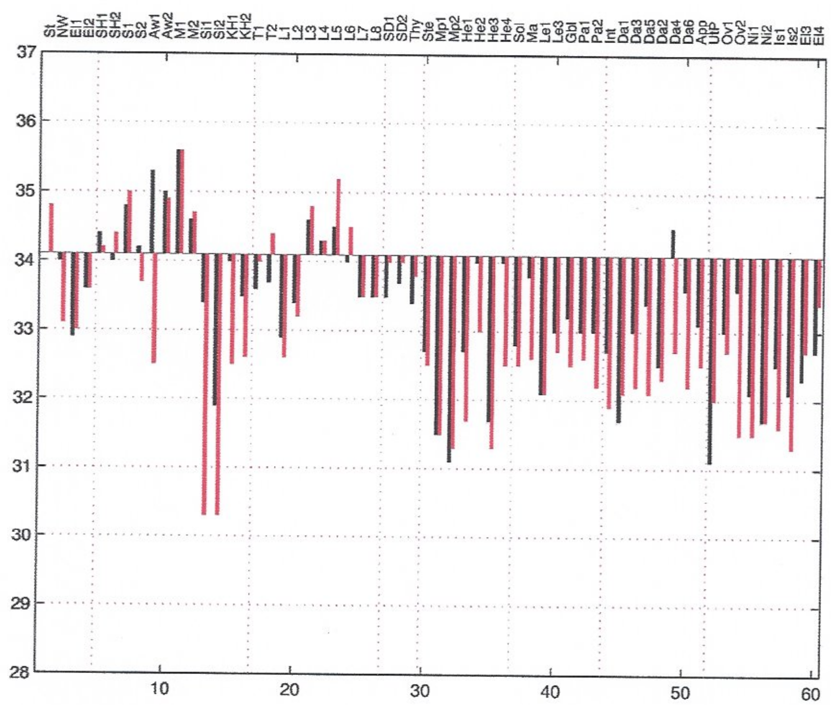

Figure 6: real thermogram, example 1

Non-local patterns

Beside the behavior of the temperature at isolated areas the experts in Regulation Thermography evaluate the regulation patterns appearing in the area groups as defined in table 1 or even within larger parts of the RT. This represents the fact that an ongoing disease influences several organs each in a specific way. In the sequel we describe some of the more important non-local regulation patterns.

Regulation type of the RT: the notions of hypo-,hyper- and rigid regulation do also exist when considering the complete RT instead of only one area. An RT showing hyporegulation for example simply shows hyporegulation at the majority of its areas. The other notions are defined similarly.

Over-Heating: this pattern is present in a certain set of areas if the majority of them (usually more than 70%) possess »hot« 1st values, »hot« being understood as an attribute as described earlier in the present section. The RT shown in figure 7 displays over-heating in the upper and lower stomach area group.

Dissociation: this rather complex pattern basically consists of a set P of areas, contained in an area group or a union of anatomically related area groups, with cd- or rigid regulations behaving inhomogeneously with respect to

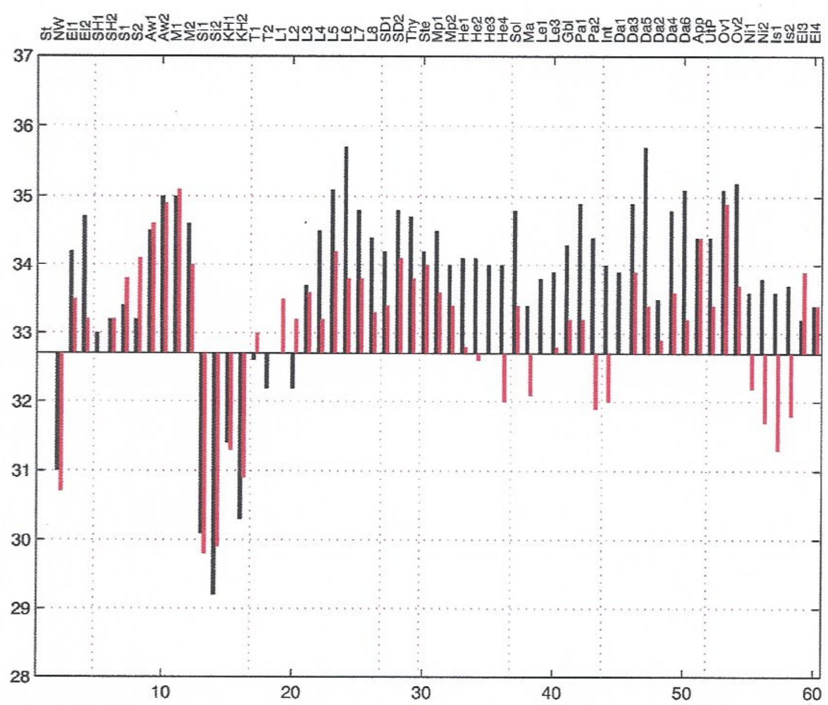

Figure 7: real thermogram, example 2

the attributes »cold« and »hot«: the 1st values of the areas $A \in P$ are sometimes below and sometimes above the reference value St(1st). Moreover ordering the set P following the anatomy from top to bottom the switching between »cold« and »hot« dysregulations should be nearly alternating.

Exhaustion: essentially the exhaustion pattern consists of a set P of anatomically related areas such that A(reg)$< c$ for every $A \in P$, where $c < 0$ is a constant typically smaller than -1.2°C. The set P can be either a complete area group or a union of such.

A word of warning concerning the terms assigned to the different patterns described in the current subsection: these terms are *not generally used* among the experts applying Regulation Thermography. They are literally translated from the german terms used in the BMBF-project »Datenbasierte Diagnoseunterstützung in der Regulationsthermographie«.

3 Regulation Thermography and Fuzzy Logic

The medical interpretation of RTs for diagnostic purposes is based on empiric rules extracted from long-term experience of specialists in the field. These rules are not »sharp« in the sense of a mathematical statement. Rather they do for example depend on only vaguely defined numerical constants or on the visual impression of certain patterns. Furthermore at present there is no commonly accepted set of interpretation rules existing among RTG experts.

In the current section it is shown how Fuzzy Logic can be used to model the expert's thermogram interpretation rules. Furthermore it is explained in which way the so-obtained fuzzy rules in turn can be used as building blocks of an Expert System. Such a system may support physicians in RT evaluation or help them to learn this subject. It can also serve as a database of known interpretation rules and thus help in the process of their critical evaluation.

3.1 Medical interpretation of thermograms

The medical interpretation resp. evaluation of an RT is a complicated process that involves at least the following main steps:

Analysis of single area groups: which types of dysregulation occur within an area group and to which extent?

Combination: which areas and area groups show significant dysregulation? Are there anatomical or functional relationships between the conspicuous areas/area groups existing?

Global properties: what is the general tendency of the thermoregulation? Are there overall patterns existing in the thermogram?

Classification: ... of the RT using some discrete disease-specific classification scheme combining all observed pathologies.

This rough evaluation scheme can of course be refined depending on the particular disease one investigates. Since the authors of the present article are no physicians and do not want to run the risk of providing insufficient or even wrong information the interested reader is once again referred to the source [6]. Instead of steeping into the details of medical RT interpretation we discuss the analysis of single area groups – step 1 in the preceeding scheme – utilizing a specific example from breast cancer diagnosis. We also provide an example for the combination process (step 2). However some general remarks about thermogram evaluation should be given beforehand.

Regulation Thermography aims to classify thermograms from a holistic point of view, not so much focussing onto single temperature values. This fact is reflected in the foregoing classification scheme. Consequently it is quite tricky to formulate the evaluation rules precisely, which in turn makes it difficult for newcomers to learn RT-interpretation.

The rules that are presented in the following subsections are quasi-mathematical versions of the rules used by physicians applying Regulation Thermography. They were created in a dialog with such a physician and therefore most likely do not comprehend the full complexity of the »real« rules for at least two reasons: first it is often difficult for a specialist to become aware of the methods utilized to perform a certain mental classification/evaluation task. Second the dialog between humans working in sciences as different as mathematics and medicine typically suffers from unrecognized misunderstandings. Moreover it is not clear that these rules represent the common sense among the various specialists in RTG. One aim when creating an Expert System for diagnosis support therefore is to provide a tool that helps to fix a common knowledge base.

The evaluation rules themselves partially depend on the kind of disease one wants to investigate. Clearly there is some overlap between the sets of rules for different diseases. For example the lymphatic areas L1-8 are involved in the diagnosis of various types of cancer with similar rules. *In the sequel we are exclusively considering female breast cancer.*

The eventual result of the evaluation of an RT in the situation discussed in this article is a **risk class (RC)** for the presence of breast cancer. Within the BMBF-project mentioned earlier six risk classes numbered from 1 to 6 with increasing risk are used. Thus RC = 1 means that no pathological patterns pointing to breast cancer can be observed in the RT, while RC = 6 expresses the presence of various strongly pronounced breast cancer patterns.

3.2 Evaluation of the Thorax group – an example

As an example of the local evaluation rules applied to a single area group we describe the set of rules used to evaluate a part of the Thorax area group. This part consists of the area Sternum (Ste) and the axial symmetric Musculus pectoralis areas (Mp1, Mp2). For reasons of brevity we set $G := \{\text{Ste,Mp1,Mp2}\}$ for this area group.

The rules themselves can be divided into three groups according to the specific qualities of the areas $A \in G$ they refer to. A fourth set of rules deals with the combination of the observed regulation pathologies.

Absolute value: here the differences $A(\text{temp}) = A(\text{1st}) - \text{St}(\text{1st})$, $A \in G$, between the 1st temperature values and the 1st temperature value at the St-area (forehead, reference line) are evaluated.

The normal range for each of the three areas is approximately covered by the interval $[-0.4\text{ K}, -0.2\text{ K}]$. Values above $+0.2$ K and below -0.8 K are considered as pathological and are referred to as **hot** resp. **cold** areas. The degree of pathology depends on how much the actual value exceeds resp. lies below the given bounds. The maximal degree of pathology is reached at $+0.6$ K resp. -1.2 K.

Regulation: here $A(\text{reg})$ for $A \in G$ is taken into account. Again independent of the particular area one has a normal regulation range of $[-0.8\text{ K}, -0.5\text{ K}]$. Hyper regulation sets in at approximately -1.1 K with an increasing degree of pathology the lower the values are; the maximum is attained at approximately -1.4 K. Rigid and cd-regulation are not treated separately. Instead all values above approximately -0.25 K are classified as deviations from normal behavior, the worst case being values above 0 K.

Asymmetrie: this property involves the values $\text{1stD} := |\text{Mp1}(\text{1st}) - \text{Mp2}(\text{1st})|$, $\text{2ndD} := |\text{Mp1}(\text{2nd}) - \text{Mp2}(\text{2nd})|$ at the Musculi pectorali discarding the sign of the potential asymmetry. The values of 1stD, 2ndD are supposed to lie below 0.3 K, otherwise pathological asymmetry is present depending on the amount of deviation from normality and reaching the maximal degree at 1.2 K.

Combination:

1. The behavior of the three areas $A \in G$ with respect to their absolute temperatures is summarized in one evaluation treating the areas as follows: if the two Musculus pectoralis areas differ in their behavior only the worst case is taken into the bargain. The evaluation of the area Ste and that of {Mp1,Mp2} are of equal importance. The same procedure applies to the regulation behavior.
2. Pathologies in regulation are considered as being more relevant than pathologies in the absolute temperature values.
3. The total asymmetry in the Musculus pectoralis areas is given by the mean of the asymmetries in the single areas.

Of course the example just presented is rather simple in that it involves only a few areas. In general area groups can be significantly larger than G as one can see in table 1. Moreover the example does not show the interconnection between the different area groups. However the main principles of RT interpretation are clearly visible already on the presented level.

3.3 Fuzzy evaluation rules

In the sequel the representation of RT-interpretation rules in terms of Fuzzy Logic is demonstrated utilizing the example given in subsection 3.2.

All diagrams presented in this subsection were produced using the Fuzzy Logic Toolbox version 2.0 of MATLAB version 5.3, Math Works Inc.

For the convenience of the reader we start by recalling some basic notions of Fuzzy Logic: A **fuzzy set** F is the graph of a map $\mu : X \to [0,1]$, i.e. $F := \{(x, \mu x) \in X \times [0,1] \mid x \in X\}$. The set X frequently is called the **universe** and μ is the **membership function of** F. Fuzzy sets occur naturally when modeling properties that are not sharply defined, like for example the property of »being tall« of a human being. In this example the universe X consists of all human beings and the value μx may be interpreted as the »tallness« of the individual $x \in X$. It is frequently useful to think of μx as a »truth value« for a statement made about x, where $\mu x = 0$ and $\mu x = 1$ are interpreted as »false« resp. »true«. The statement itself depends on the fuzzy set F – in our example it is somethink like »the person x is tall«.

The binary variables of Predicate Logic are replaced by so-called **linguistic variables (LVs)** in Fuzzy Logic: a linguistic variable V takes values in a finite set L, whose elements are fuzzy sets; these elements are called **linguistic values.** (Remark: the definition of a linguistic variable just presented is a simplified version of the usual one.)

Clearly when replacing binary with linguistic variables one has to redefine the meaning of the basic logical operations »and«, »or«, »negation« and »implies«. If for example V_1, V_2 are linguistic variables and L_1, L_2 possible values of these variables, then the statement »$(V_1 = L_1) \Rightarrow (V_2 = L_2)$« yields a fuzzy set instead of one of the values »true« or »false«. The method that produces this fuzzy set given the ones of L_1 and L_2 is called the **implication method**. In contrast to Predicate Logic the implication method as well as the definitions of all other logical operations is not unique but can be choosen subject to certain axiomatic conditions. The choice itself depends on the specific application one has in mind.

The evaluation of a Fuzzy Logic statement typically yields a fuzzy set as a result. On the other hand in applications one wants to get back a single number. This number is derived from the given fuzzy set by application of the **defuzzification method**, which could for example consist of assigning the ordinate of the centroid to a fuzzy set A.

Finally we have to mention **aggregation** of fuzzy sets: in a system of fuzzy implications the conclusion parts (»right sides«) of the implications yield various fuzzy sets that must be merged or aggregated to obtain the »overall conclusion« of the system – a fuzzy set too. One of the favorite methods to determine the aggregation of fuzzy sets is to take their pointwise maximum.

In order to translate the RT-interpretation rules of subsection 3.2 into Fuzzy Logic we first have to fix a set of linguistic variables sufficient to describe the thermoregulation behavior. In the present case to describe the behavior of the absolute temperature the experts are using the terminology »cold«, »normal« and »hot«, while for the regulation the expressions »hyper«, »normal« and »paradox« apply, where »paradox« regulation comprehends rigid and cd-regulation – see subsection 2.3. We therefore introduce two linguistic variables T and R taking values in the sets

$$X_T := \{\text{Cold, Normal, Hot}\} \text{ and } X_R := \{\text{Hyper, Normal, Paradox}\} \quad (1)$$

respectively. T describes the absolute temperature behavior and R the regulation. Note that the linguistic value »Normal« can be attained by T and R, but this does not necessarily mean that the value »Normal« in both cases is given by the same fuzzy set. From a mathematical point of view we should therefore use different variable names, but for the sake of readability of the fuzzy statements we keep the mathematically ambiguous version.

Next the observed degree of pathology is modelled using the linguistic variables P_T (absolute temperature) and P_R (regulation) taking the linguistic values

$$X_{P_T} := \{\text{Negative, Positive}\},\ X_{P_R} := \{\text{Negative, Suspicious, Positive}\}. \quad (2)$$

The membership functions of the linguistic values appearing in (1) and (2) are chosen to be trapezoidal: this provides the simplest way to treat those parts of the experts knowledge consisting of critical bounds for temperatures and regulations. The universe of the fuzzy sets in X_{P_T} and X_{P_R} are compact intervals – for example the interval $[-1.5, 0.1] \subset \mathbb{R}$ in the latter case. Once a measurement lies outside the respective interval, it is mapped to the nearest interval border. This procedure reflects the fact that from a medical point of view there is no difference (anymore) between for example a hyperregulation of $-1.6K$ or a hyperregulation of $-2.1K$.

The fuzzy sets in X_{P_R} are depicted in figure 8.

In terms of Fuzzy Logic the RT-interpretation rules for absolute temperature and regulation at the thorax areas $A \in G$ now read as follows:

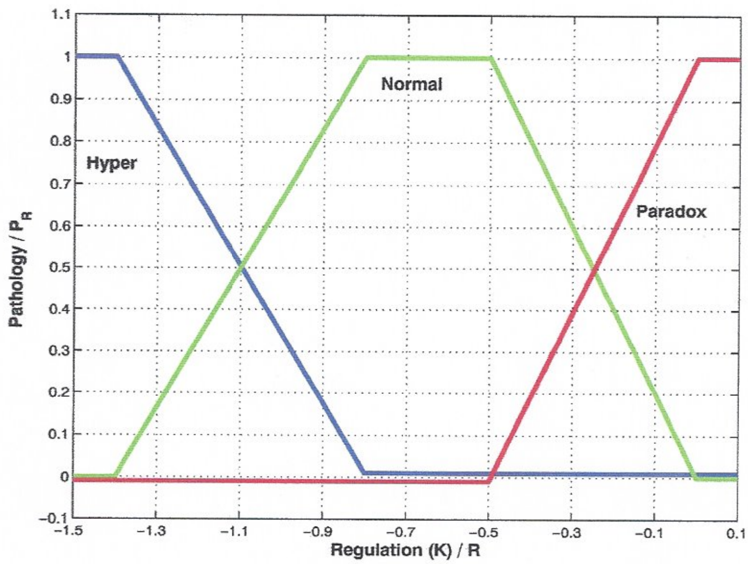

Figure 8: membership functions for the values of R

Absolute temperature: If (T=Cold) Then (P_T=Positive)
If (T=Normal) Then (P_T=Negative)
If (T=Hot) Then (P_T=Positive)

Regulation: If (R=Hyper) Then (P_R=Suspicious)
If (R=Normal) Then (P_R=Negative)
If (R=Paradox) Then (P_R=Positive)

At present no expert knowledge indicates that in the definition of the Fuzzy Logic operators one should deviate from commonly used methods. Therefore the following setting is used:

Implication: The membership function of the conclusion is cut off at the fuzzy value corresponding to the input value – so-called minimum method.

Aggregation: Maximum of the involved membership functions.

Defuzzification: Ordinate of the centroid.

The behavior of a block of rules like for example the one evaluating the regulation observed at an area $A \in G$ can be represented by graphing the function $[-1.5, 0.1] \to [0, 1]$, that assigns to each regulation value of R the degree of pathology P_R determined by aggregating and defuzzifying the fuzzy sets resulting from the three regulation rules. This function is displayed in figure 9.

The rating of asymmetry at the Musculus pectoralis areas Mp1 and Mp2 is performed by evaluating a suitably defined trapezoidal function P_A at the two observed absolute temperature differences 1stD and 2ndD between the measurements at Mp1 and Mp2. Formally the asymmetry is evaluated using an LV with

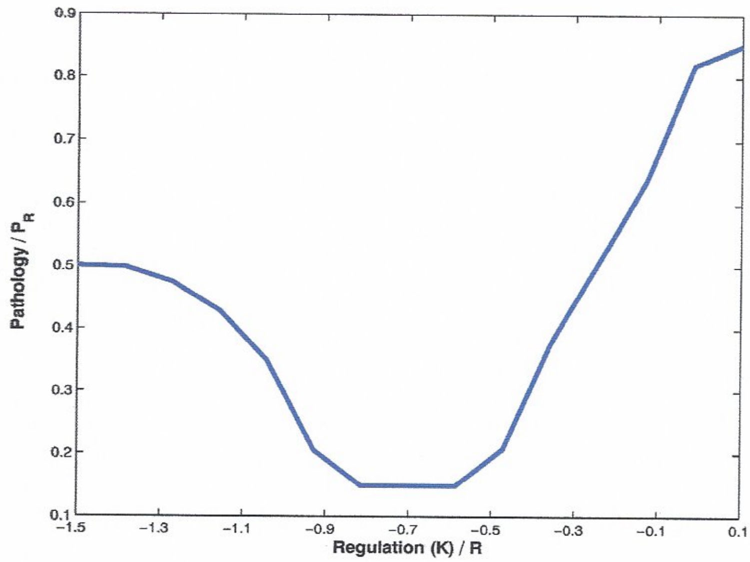

Figure 9: degree of pathology for the regulation

only one linguistic value; consequently the LV and the membership function describing the single value are identified and denoted with P_A. This function is shown in figure 10.

Eventually we have to determine a method to combine the various evaluation results that we obtain by applying the rules defined so far: the three degrees of pathology $P_T(\mathrm{Mp1})$, $P_T(\mathrm{Mp2})$, $P_T(\mathrm{Ste})$ for the absolute temperatures, the three degrees of pathology $P_R(\mathrm{Mp1})$, $P_R(\mathrm{Mp2})$, $P_R(\mathrm{Ste})$ for the regulation, and the degrees of asymmetry $P_A(\mathrm{1stD})$, $P_A(\mathrm{2ndD})$. The procedure described in subsection 3.2 to combine these values is brought into the following mathematical form:

$$\begin{aligned} P_{\text{sternum}} &:= 0.3P_T(\mathrm{Ste}) + 0.7P_R(\mathrm{Ste}) \\ P^i_{\text{mus.pec.}} &:= 0.3P_T(\mathrm{Mpi}) + 0.7P_R(\mathrm{Mpi}),\ i = 1, 2 \\ P_{\text{asymmetry}} &:= \tfrac{1}{2}(P_A(\mathrm{1stD}) + P_A(\mathrm{2ndD})) \end{aligned}$$

$$P_{\text{thorax}} := \min((P_{\text{sternum}} + \max(P^1_{\text{mus.pec.}}, P^2_{\text{mus.pec.}}) + P_{\text{asymmetry}}), 1),$$

where the values P_{sternum} and $P^i_{\text{mus.pec.}}, i = 1, 2$, denote the total scores for the Sternum resp. Musculus pectoralis areas with respect to pathologies of absolute temperatures *and* regulation, while $P_{\text{asymmetry}}$ is the total score of asymmetry at *both* Musculus pectoralis areas. Eventually P_{thorax} is the overall score for the thorax area group. We leave to the reader the task of verifying in detail, that the displayed formulae yield a meaningful model of the combination procedure.

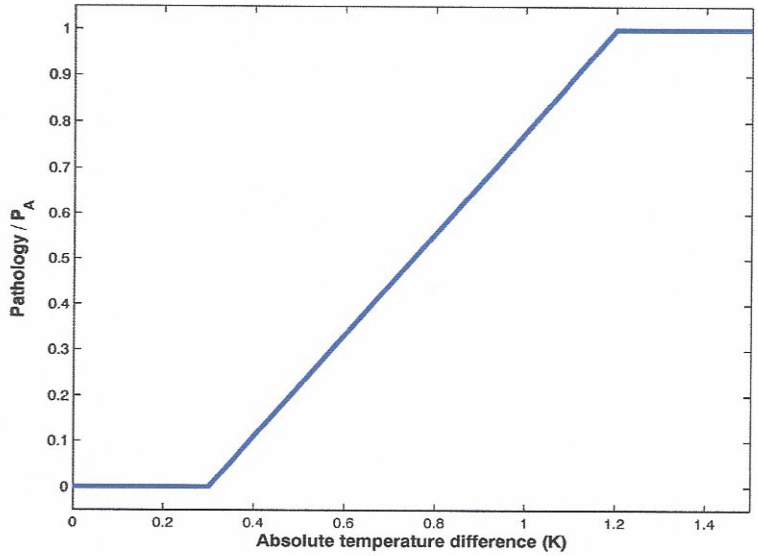

Figure 10: degree of pathology for the asymmetry at Mp1, Mp2

3.4 Rudiments of an expert system for diagnosis support

In the subsequent paragraphs an overview is given over the Matlab software package ROST [1] for diagnosis support in Regulation Thermography created by the medical diagnosis group at the department »Adaptive Systems« of the ITWM. The package forms a yet incomplete prototype applicable for the evaluation of regulation thermograms with respect to female breast cancer. Eventually ROST is supposed to contain a complete implementation into Fuzzy Logic of the available expert knowledge in this special field of RT-evaluation.

Matlab in combination with the Fuzzy Logic Toolbox is a convenient »programming language« for quickly building up such a system. As typical for Matlab applications ROST consists of a bundle of Matlab script files (»m-files«) containing the implementation of the functionality; ROST comprises approximately 100 m-files. The technical and structural details of the implementation seem to be of little interest for a reader of this article. Therefore in the subsequent description we focus on the description of ROST's functional components. However for a thorough understanding of these components we have to start our description with some technical facts.

The various components of ROST communicate with each other not only via passing parameters as usual in most programming languages, but also by accessing data that are available in the Matlab workspace of the session from which ROST has been started. The variables containing these data can be considered as global variables, since they are accessible by all m-Scripts. The Matlab work space is initialized immediately after starting ROST and of course its content changes continously while using the program.

[1] Dr. med. dent. Arno Rost, *1919, one of the pioneers in Regulation Thermography

ROST consists of four principal functional components; in the sequel we will provide a short description of each of them.

RT-database: since ROST currently is not meant to be a tool to evaluate RT's just measured for example in the doctor's practice, it takes the input thermograms from a database. This database not only contains the pure thermogram data (temperature values) but also comprises patient information like gender, age, initial diagnosis, ongoing therapy and progress of the disease resp. healing process. Of course patients *cannot* be identified personally on the basis of these data.

Matlab does not provide real database functionality. The RT-database we are discussing here consists of a Matlab workspace file (»mat-file«) essentially containing the thermogram and patient information in matrix form. The necessary database functionality is implemented in a bundle of m-scripts operating on these matrices once they are loaded into the current (active) Matlab workspace. All scripts can be used standalone, that is in particular independently from ROST itself.

The actual database, that is the thermogram data and patient information, is loaded into the current workspace at startup of ROST.

Database browser and RT-viewer: the RT-database can be accessed via a browser that allows to display the information available for a specific thermogram in several ways: on one hand the basic patient information can be shown. On the other hand three different graphical representations of the thermogram itself are available, one of which called the »standard representation« has been used for example in figure 5. The other representations depict the appearing asymmetries in the thermoregulation. Moreover it is possible to restrict the representations to certain area groups instead of the whole thermogram.

Expert rule database and RT-analyzer: at the time of writing this article approximately 130 interpretation rules for regulation thermograms with respect to female breast cancer could be formulated in terms of Fuzzy Logic. The Fuzzy Logic Toolbox Version 2.0.1 (R11) was used to implement these rules into an executable Fuzzy Inference System. This system at present consists of approximately 50 files of two types: the files of the first type (»fis-files«) contain the pure Fuzzy Logic components of the evaluation rules broken up into small units (see the subsequent paragraphs). The second group consists of scripts that perform the data pre- and postprocessing as described in subsection 3.3. Some of these scripts moreover control the sequence in which the various components of the Fuzzy Inference System are executed.

The RT-evaluation rules fall into 13 subsets: the rules in such a subset either evaluate a (part of an) area group as defined in table 1 with respect to the overall degree of pathology of the observed thermoregulation behavior, or rate a larger part of the RT with respect to the appearance of certain non-local patterns as roughly described in subsection 2.3. In the sequel the implementation of each of the 13 subsets of RT-evaluation rules is called a **partial RT-evaluation system (PES)**.

Elbows	Elbows
Head	Immunology
Throat/Neck	Tonsils, Supraclavicular fossae, Immunology
T-glands	Thyroid, Immunology
Thorax	Heart, Thorax, Stomach
Upper stomach	Stomach, Dissociation, Immunology
Intestine	Stomach, Dissociation, Immunology
Lower stomach	Ovaria
Mammae	Hotspots, Asymmetry

Table 2: area groups and partial RT-evaluation systems

The sizes of the PESs vary between 7 to 45 rules involving 2 to 25 areas; a typical PES consists of 8 rules and applies to 5 areas. The distribution of the areas within the different PESs can be seen in table 2, where the left column displays the area groups, while in the right column the names of those PESs appear, that refer to areas in the respective group. Among other things one can see from this table that currently only 3 PESs (Stomach, Dissociation, Immunology) are rating non-local patterns. This reflects the fact that complex interpretation rules are not yet completely formalized. The PES »Exhaustion« is not displayed at all due to this incompleteness.

Each of the 13 PESs associates a partial score p_i, $i = 1, \ldots, 13$, to a given thermogram. The p_i possess a certain medical meaning at least to specialists. The risk class RC for the presence of breast cancer introduced in subsection 3.1 can be considered as a further condensation of these partial scores to obtain a discrete value $\mathrm{RC} \in \{1, \ldots, 6\}$. This condensation is also realized utilizing formalized expert knowledge, but we won't go into the details here.

What we just described is the rough structure of the RT-analyzer, a program that takes thermograms as an input, applies the rules of the PESs to obtain partial scores, condensates the scores to a risk class and yields this class and the partial scores as output.

The Fuzzy Inference System itself can be considered as a database of formalized expert rules: the latter can easily be viewed and edited using the functions of the Fuzzy Logic Toolbox. In combination with the various script files mentioned above we have a system at hand that not only allows to evaluate RTs with respect to the presence of patterns characteristic for female breast cancer, but also enables an expert to critically validate or edit the implemented expert knowledge.

The RT-analyzer is linked to the database browser described previously: it can be started from the browser's user interface and analyzes the thermogram currently loaded by the browser.

Classification tool: in the current stage of development ROST is used as a tool in the communication between physicians and mathematicians. During the process of the formalization of expert RT-evaluation rules in terms of Fuzzy Logic it is frequently necessary to adapt numerical parameters like for example temperature thresholds in an appropriate way. To this end it is useful to have a sufficient quantity of RT's at hand that are classified with respect to RC and the partial evaluation scores by an expert. ROST provides an interface to the RT-database that allows to enter, edit and store these classifications. Like the RT-analyzer this classification tool can be started from the GUI of the database viewer and the data entered refer to the RT currently displayed by the browser.

4 Vista

From the medical point of view the principal purpose of research in Regulation Thermography at present lies in a scientific validation of the method, so that it eventually becomes well-accepted among physicians. The expert system ROST is a first step in that direction, since it comprehends the known expert knowledge in the RT-evaluation with respect to breast cancer in an objective manner, which in turn enables scientists to perform comparative tests with the RT-method.

Beside that ROST could also be used in the training of physicians who want to learn about Regulation Thermography.

More concretely within the BMBF-project »Datenbasierte Diagnoseunterstützung in der Regulationsthermographie« several other mathematical methods have been applied in the spirit of the ultimate aim of verification of RT:

- Neural Nets taking the partial scores as an input have been trained to estimate the risk class of a thermogram.
- Support-vector-maschines have been used to check whether the medical classification of thermograms can be recovered automatically.
- The method of classification trees has been utilized to extract new RT-evaluation rules from data and discuss them with experts.

It is planned to publish the results obtained with the methods just sketched in forthcoming preprints of the ITWM-series.

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