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A novel coplanar probe design for fast scanning of edema in human brain tissue via dielectric measurements

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ABSTRACT

As part of every standard forensic autopsy, the examination of the brain includes assessment with respect to possible edema. The quantification of edema is helpful to make a sound diagnosis in presence of multiple affections and multiple possible causes of death. The water content in certain brain regions is furthermore a promising marker to distinguish between causes of death with no visible evidence, such as suffocation, shaking impact syndrome and sudden infant death syndrome. However, in todays' forensic medicine, no technique is available for the objective and exact quantification of edema. Therefore, the aim of this work is to develop a fast and easy-to-use measuring system for the accurate determination of the water content in human brain tissue that fits into the procedure of a routine autopsy. For our setups, the dependency between relative permittivity and water content is utilized. In former works, we presented measurements of human brain tissue using a coaxial measuring chamber and an open-ended coaxial probe. However, some drawbacks of the used methods emerged. Thus, a novel probe design using a coplanar transmission line has been developed, addressing the drawbacks of the formerly used methods. This new probe is easy to calibrate and allows fast and accurate sequential scanning for edema in human brain tissue.

1. Introduction

In their fundamental work, Bogomolov et al. investigated the correlation between agony time and brain hydration [1]. They found that a slow death, e.g. caused by lethal intoxication, is accompanied by hyper hydration in the brain, because the brain is stressed during agony, causing it to expand and create edema in the tissue. A fast death on the other hand causes all bodily functions to stop immediately and therefore the brain has no time to expand. Thus, no or only little edema are created in the tissue. The human physiology allows only very small tolerances of tissue humidity. Therefore, small deviations from the norm would indicate severe disease. Although the presence of a disease in an unknown corpse cannot be excluded, water retention and generation of edema most likely represents a pathological process in the context of agony, especially in relation to cerebral edema. Therefore, the water content in the human brain tissue is a promising marker to make a sound diagnosis especially in presence of multiple affections and multiple possible causes of death. Furthermore, the degree of brain hydration can be used to distinguish between certain causes of death with no visible evidence, such as the sudden infant death syndrome (SIDS) or shaken impact syndrome. Therefore, the investigation of edema in the human brain tissue is an important task during an autopsy. However, until now there is no standardized procedure defined in forensic medicine. The degree of brain hydration is estimated by examining brain weight, turgor due to flattening of brain convolution, reduction of furrows of the brain and ventricle compression. The findings depend on the investigator's experience and are naturally prone to errors [2]. Furthermore, they are distorted by many factors, e.g. a concomitant brain atrophy can be masked by edema in a way that the brain appears inconspicuous. Therefore, the aim of our work is the development of a fast and accurate measurement procedure that fits into the procedure of a regular autopsy. The necessity of such a procedure shall be further underlined with the example of an investigation of SIDS. In case of SIDS, it always needs to be clarified if the child died of a defined illness (e.g. sepsis, myocarditis), due to choking or severe shaking (shaken impact syndrome) or an unclear cause of death,

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which defines a SIDS, a syndrome not yet fully understood. However, a clear distinction between a possible crime and a particular SIDS is of significant interest. Suffocation typically causes strong cerebral edema, whereas the SIDS is usually accompanied with only slight brain edema [2,3]. With the described techniques used for the quantification of edema in today's forensic medicine, these small but essential differences in the degree of brain hydration are virtually undetectable. Estimations from preliminary clinical trials show that the desired accuracy for determining the water content in the tissue is in the range of 1–3 wt.%.

One method that is capable of determining the water content in the human brain tissue very accurately is desiccation (oven dry method). Here, a tissue sample is dried and the water content is calculated from the weight difference before and after drying. However, the major drawback of this method is a bulky setup and long measurement times due to the drying process. Therefore, this method is too time consuming, especially when performing sequential measurements, which are required during an autopsy. However, we use a commercially available moisture analyzer, the *Smart System 5*, utilizing this method for the determination of the reference water content to calibrate our setups. It was originally designed for applications in food industry and is highly accurate with a standard deviation of $\sigma = 0.5$ wt.%. In this setup, the desiccation process is accelerated by using microwaves [4]. This way, the necessary time for the determination of the water content of one specimen is reduced to about 10 min. Even then, sequential scanning for edema is still time consuming and therefore, this method is not an option to be used in a routine autopsy.

Thinking of the development of a handheld device for fast measurements, there are generally two approaches to be considered, measuring the conductivity or measuring the permittivity of the brain tissue. Both material parameters depend on the water content in the tissue [5]. Due to the anisotropic behavior of the tissue conductivity [6], conductivity measurements are not promising. Therefore, the measuring principle of our setups is based on a high frequency permittivity measurement. In [7], a theoretical description of the dielectric behavior of tissues is given. From this model, it can be seen that the frequency range from approximately 100 MHz to 10 GHz is best suited for the determination of the water content in the tissue. In order to use solely low-cost equipment, especially for signal synthesis and analysis, the working frequency of our setups is chosen close to the lower limit of this frequency range, at a frequency of 500 MHz.

In [8], we present a preliminary measurement system for the first investigation of the dependence between water content and relative permittivity of human brain tissue. Here, the water content in the tissue is determined via permittivity measurements using a coaxial measuring chamber. The outer conductor of this chamber can be removed and used as a die cutter for tissue sampling. The filled outer conductor is then inserted into the chamber and the chamber is assembled. For determining the permittivity of the tissue sample, the scattering parameter S_{21} is measured via a transmission measurement with a low-cost vector network analyzer (VNA) *VWNA3* by *SDR kits*. We were able to show a linear correlation between the real part of the relative permittivity and the water content in the brain tissue. A statistical analysis lead to an uncertainty of 2 wt.% for the prediction of the water content from a permittivity measurement. However, the necessary tissue sampling process leads to long measuring times and thus this setup is not applicable in a routine autopsy because spatially resolved measurements are too time consuming.

Therefore, the next step is to apply a measuring technique that avoids any sampling process. The open-ended coaxial probe is a widely used technique for nondestructive dielectric measurements and is found in many applications, for example in food monitoring [9], where the aging of meat is monitored via a dielectric measurement. Furthermore, open-ended coaxial probes are used in medical applications. For example, in [10] the permittivity of rat brains is measured in order to estimate the energy absorption from electromagnetic waves in human brain tissue. In [11], a miniaturized open-ended coaxial probe is presented for dielectric spectroscopy measurements of biological tissue samples. In [12], an open-ended coaxial probe is used for detecting breast cancer. In [13], we present measurements with an open-ended coaxial probe of human brain tissue. To determine the permittivity of the specimen, the probe is simply pressed onto the specimen and the scattering parameter S_{11} is measured via a reflection measurement. We could confirm the linear dependency between the real part of the relative permittivity and the water content in the tissue. The uncertainty for the prediction of the water content from a permittivity measurement is determined to 3 wt.%. In this work, several drawbacks of this method emerged. For example, the contact pressure of the probe has an impact on the measured permittivity of the brain tissue sample. Therefore, the contact pressure has to be held constant across all measurements. Additionally, leakage currents on the specimens' surface proved to disturb the measurements. Thus, the open-ended coaxial probe needs to be electrically isolated from the specimen. Furthermore, as shown in [14], the calibration procedure is comparatively difficult. It has to be performed on a regular basis to eliminate disturbances (e.g. imperfect cables, aging effects or temperature drift of the VNA). For a sufficient calibration of the open-ended coaxial probe, reference measurements of materials with known permittivity have to be performed. The permittivity of the reference materials should be close to the permittivity of the specimen [15]. In order to find suitable calibration materials, often mixtures of liquids are used. Due to the generally strong temperature dependency of the liquids' permittivity, this calibration procedure is additionally prone to errors. However, the previously described coaxial measuring chamber is calibrated with a so-called Through Open Short Match (TOSM) calibration. Therefore, measurements on commercially available calibration standards are performed which is comparatively simple and fast. The basic idea of this paper is combining the advantages of the coaxial measuring chamber (transmission measurement, easy calibration) with the advantages of the open-ended coaxial probe (no sampling process, fast spatially resolved measurements). Therefore, a coplanar line is used and designed as a probe tailored for permittivity measurements of human brain tissue. Compared to the methods described above, the coplanar strip line is rarely discussed in literature for the use in electromagnetic material characterization and it is still a topic in current research. In [16], a coplanar sensor is used for measuring the permittivity of liquids and a possible accuracy enhancement by using corrugated coplanar structures is discussed. Other described setups are also designed for characterizing liquids [17] and/or require special sample containers [18]. Therefore, they are not suitable for tissue measurements. In [19] a coplanar probe design to characterize large sample volumes is presented.

2. Theory

In this section, the determination of the permittivity from a transmission measurement with a coplanar transmission line is described.

Fig. 1 depicts a schematic of a coplanar probe. It consists of an inner conductor centered between two ground planes, all aligned on a substrate. The permittivity of the tissue sample is determined by pressing the probe onto the specimen und measuring the transmission of an electromagnetic wave. Thereby, a quasi-transverse electromagnetic wave propagates along the inner conductor of the coplanar probe. The wave propagation is investigated with a *CST*