Variation in the electromagnetics signatures of the human skin with physical activity and hydration level of the skin

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ABSTRACT

Our recent studies in the human skin signatures indicate a strong correlation between the human skin emissivity and factors such as the body mass index, the gender, the age, and the ethnicities of the participants. The key innovation in this is in recognising that signatures from the human body enable regions of the body to be identified as skin. This will enable increased the detection probabilities of anomalies, and reduced the false alarm rates in security screening portals. This is a capability that is being demanded internationally by governments and in the UK by the Home Office Future Aviation Security Solutions (FASS) programme and the Joint Security and Resilience Centre (JSaRC).

In this paper, radiometric measurements conducted on human skin in the millimetre wave band region (80-100) GHz show variation in the human skin emissivity before and after conducting physical activity (jogging) subject to the same participant. The measurements were conducted on the palm of the hand and the back of the hand skin. The measurements reveal that the emissivity of the skin is significantly lower in the rest state of the body compared with the active state by mean values of 0.088 and 0.07 for the palm of the hand and the back of the hand skin respectively. The differences in the mean emissivity values were found to be linked to the length of time exercising and the hydration level of the skin i.e. (sweat). Radiometric measurements on palms of the hand and on the back of the hand skin before and after the application of an aqueous gel indicate a strong correlation between the human skin signature and the hydration level of the skin. The mean differences in emissivity values before and after the application of an aqueous gel indicate a scatter in the range of 0.02 to 0.26. These findings suggested trends in the human skin emissivity and indicate the potential of a new non-contact passive method for remote sensing of the physical state of human beings. Understanding these signatures and variations of the human skin emissivity are very important for both security screening (anomalies detection) and medical applications (non-invasive diagnosis of human body).

Keywords: skin signature; millimetre waves; physical activity; sensors; security screening.

INTRODUCTION

Active millimeter wave (MMW) imaging used for anomalies detection and security screening relies on the reflection from the target object [1, 2]; the level of reflected radiation from the target is dependent on the target structure and size. The system is usually signal to clutter limited in the performance, in contrast to a radiometric system which is signal to noise limited [3, 4]. In addition, active system is sensitive to the alignments. The use of passive millimeter wave sensor has several advantages: free from artefacts such as speckle and sensitivity to the alignment; environmental and user friendly as there is no need to expose the human skin to any type of manmade radiation; and technically less complex compared with the conventional active sensors. In addition, radiometry is used in the estimation of emissivity; any attempts at deception, by substituting a human skin surrogate over the body will be recognised as it will not fit the expected characteristics. This is because the emissivity is derived from the amount of radiation emitted by the body, not just from its reflection properties [5, 6]. This means skin surrogates will be recognised even if they have exactly the same electrical properties as human skin. An active (coherent wave) illumination system will not have this capability, as it measures the reflectivity directly [7].

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Human skin emissivity and reflectance provide important diagnostic information and they have served as useful diagnostic tools in modern clinical medicine such as monitoring the wound healing under dressing materials [8, 9], early detection of skin diseases [10, 11], and identifying the mental state of the human [12].
In this paper, the signature of the human skin was measured before and after jogging on a treadmill and under normal and moistened skin conditions i.e. (after the application of an aqueous gel) to assess possible variation in the human skin signature over the band 80-100 GHz. The experimental result demonstrates the potential usefulness of the proposed radiometer to be used for security screening and medical applications.

THE SYSTEM (PASSIVE SENSOR)

The in vivo measurements of the MMW emission from the human body were made using a single channel radiometer operating over the frequency band 80-100 GHz. Such an instrument comprises of a receiving horn antenna (which collects the radiation), an amplifier, radio frequency filters, a detector (a square law detector that uses for generating an output voltage proportional to the input noise power), further video amplifiers, an integrator (which uses for averaging and smoothing the fluctuating voltage of the detector), and a data-recording device as illustrated in Figure 1.

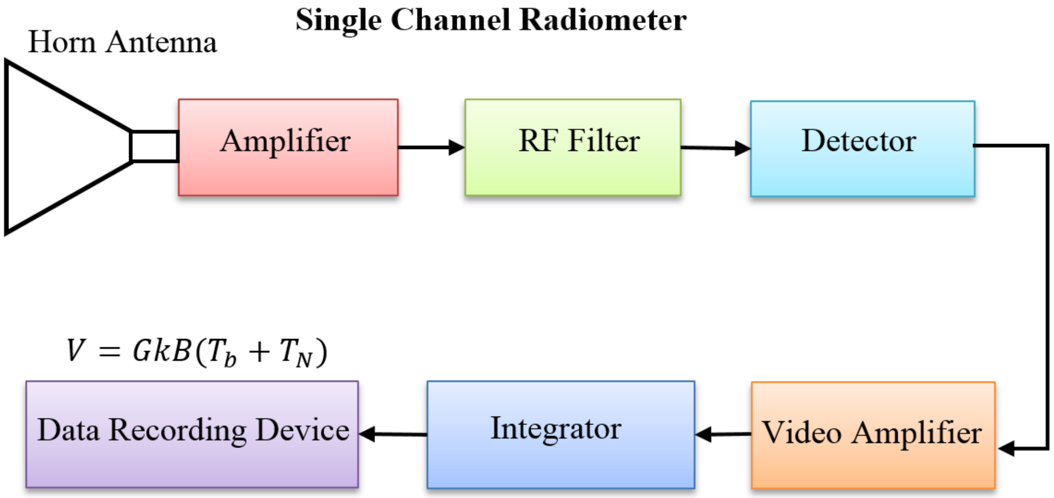

Figure 1. Block diagram shows the main components of the single channel radiometer.

The minimum detectable radiation temperature variation ΔT_{min} for a radiometer (thermal sensitivity) is given by the radiometer equation, namely [13, 14]:

$$\Delta T_{min} = \frac{T_A + T_R}{\sqrt{Bt}} \quad (1)$$

Where, t is the post-detection integration time, T_R is the receiver noise temperature, B is the receiver bandwidth, and T_A is the antenna radiation temperature, effectively the radiation temperature of the source in front of the antenna [14].

In the general radiometric measurement scenario of a single channel radiometer, the horn antenna collects thermal radiation from a target, a general descriptor for the object under investigation. In this case, the target is the human skin and in these experiments, the area of skin to be measured is larger than the antenna pattern at the skin.

Materials in the MMW band have certain reflectance ranging from almost zero for highly absorbing materials to unity for metals. The level of reflectance is dependent on the dielectric properties of the materials and is described by the Fresnel equations [14]. The skin also has a reflectance and as such measurement will include emission from the skin but also emission from the surroundings which becomes reflected from the skin into the radiometer antenna. The horn antenna is directed toward radiating thermal emissions from a target object, collects the emission, and generates a fluctuation voltage (the fluctuating voltage is a result of the radiometer equation i.e. (Equation 1)). Then the voltage level is amplified and detected through the receiver [3].

The emissivity of the sample is defined as the fraction of thermal electromagnetic (Planck) radiation relative to the thermal blackbody radiation for a source at the same thermodynamic temperature [15]. The target area of the skin was located 5.0 cm from the horn antenna of the radiometer, and the measurements were done indoors in an anechoic environment, and therefore the system response is assumed to be linear. Under these circumstances, the output voltage when measuring the liquid nitrogen and ambient temperature calibration sources can be expressed in terms of the receiver noise temperature T_N in K, and the receiver responsivity, α in V/K [5, 6, 14]:

$$V_C = \alpha(T_C + T_N) \quad (2)$$

$$V_H = \alpha(T_H + T_N) \quad (3)$$

From Equations (2) and (3) the receiver responsivity, α, and the emissivity of the skin, η, are [5, 6, 14]:

$$\alpha = \frac{(V_H - V_C)}{(T_H - T_C)} \quad (4)$$

$$\eta = \frac{(V_S - V_H)(T_H - T_C)}{(V_H - V_C)(T_S - T_H)} \quad (5)$$

An infrared thermometer was used to measure the temperatures of the skin; T_S and also the temperature of the hot and the cold calibration sources; T_H and T_C respectively. A digital voltmeter with a precision of 0.1 mV was used to measure the output voltage for the target area of the skin; Vs and the voltage level for the hot and the cold calibration sources; V_H and V_C respectively. Error propagation through Equation (5) indicates the uncertainty on the measured emissivity is ± 0.005.

EXPERIMENTAL METHODOLOGY

The objectives of the experimental work are: 1) to assess the feasibility of using the 90 GHz calibrated radiometer as a non-contact technique to distinguish between skin signatures under normal skin and moistened skin conditions (skin after the application of an aqueous gel) and also before and after conducting physical activity, and 2) to investigate possible correlation between skin signatures and the hydration level of the skin that links to other factors such as the skin location, the level of sweating, the temperature of the skin, and the blood pressure of the human body. To achieve these objectives, the experimental work presented in this paper is divided into three parts; 1) calibration measurements of the 90 GHz radiometer, 2) emissivity measurements for the human skin before and after conducting physical activity, and 3) emissivity measurements for the human skin before and after the applications of an aqueous gel.

The radiometer was calibrated using liquid nitrogen and ambient temperature sources. The horn antenna of the radiometer may be placed at distance (~ 5.0 cm) from two different radiation sources located in the same plane: “Hot” black body (ambient temperature source calibration). A piece of carbon loaded foam absorber with T_H=*Tambient* =293 K, and “Cold” black body (liquid nitrogen source calibration). A piece of carbon loaded foam absorber was dipped in liquid nitrogen at T_C= 77 K. The cold load calibration measurements were taken within 5 seconds or less before the liquid nitrogen evaporates. Foam absorbers had a rectangular shape and emissivity values greater than 0.99 over the frequency band 80-100 GHz, thus they behave as good approximations to a black body emitter. The difference in temperature between the hot and the cold load is ~216 K. This large difference is important to provide an accurate calibration. The calibration *Y*-factor, defined as the ratio of receiver output when measuring the hot black body source, to that measuring the cold source was 1.408. This gives a receiver noise temperature of 453.7 K and noise figure of 2.55. These measurements were taken from ten separate experiments and at each experiment, the calibration measurements were repeated 5-10 times so the device was stable and the measurements were consistent [5, 6].

Measurements of human skin emissivity were made using the calibrated radiometer of Figure 1 and Equation (5). The measurements were performed over the frequency band (80-100) GHz and they were repeated (5-10) times on the palm of the hand and the back of the hand under normal and moistened skin conditions and before and after conducting physical activity. These locations were chosen since the water content and the skin thickness varies at these regions.

Once the radiometer is calibrated, the emissivity of the skin were obtained in regular periods of up to 15 minutes before and after jogging on a treadmill as follows: 1) measurements of the emissivity were obtained at a rest state and before the participant conducting any physical activity for both the palm of the hand and the back of the hand skin. 2) Second measurements of the emissivity were obtained directly after the participant jogging on a treadmill for a period of 15 minutes with speed of 6.5 miles per hour. 3) Third emissivity measurements were obtained after 15 minutes of jogging on a treadmill i.e. (in relax state). Then 4) Steps 1 to 3 were repeated four times continuously on four healthy participants. The mean emissivity values of the palm of the hand and the back of the hand skin in rest and after exercising on a treadmill are shown in Figure. 2.

Water content of the skin dominates its electromagnetic behavior in the millimeter wave band [16], so a measurement was made to quantify this statement over the band (80-100) GHz. Firstly the emissivity measurements of normal skin on the palm and the back of hand were made. Then these areas of the skin were covered with an aqueous gel (a mixture that consists mainly of water with a thickener), which was then left to be absorbed for 5 minutes. After such time, when there was no gel left visible on the skin, second measurements of the emissivity were made. The measurements were repeated 5 times to obtain a mean value. This methodology was applied on 16 healthy participants (10 male and 6 female) and the mean emissivity values for the males and females are shown in Figure. 3.

EXPERIMENTAL RESULTS

This section presents emissivity measurements obtained from the palm of the hand skin and the back of the hand skin before and after jogging and for the skin under normal and moistened conditions.

Human skin signature before and after jogging

Measurements of human skin emissivity of a sample of 4 healthy participants are presented in Figure 2. The measurements show variation in emissivity between individuals, locations on the hand i.e. (the palm of the hand and the back of the hand), and more importantly before and after jogging. Variations in emissivity between individuals and locations on the hand are due to the skin thickness and blood vessels (water content) that varies from location to location across the human body and between individuals [5, 6] whereas variations in emissivity before and after jogging are due to the level of thermal emission i.e. (voltage level V_s) that increases with jogging on a treadmill. The emissivity from the palm of the hand skin was found to range from 0.45±0.005 to 0.56±0.005 and from 0.51±0.005 to 0.67±0.005 before and after jogging respectively. The emissivity from the back of the hand skin has similar trends and the mean emissivity value was found to range from 0.40 ±0.005 to 0.48±0.005 in a rest state and from 0.43 ±0.005 to 0.57±0.005 in active state i.e. (after jogging). Experimental measurements show that radiometric sensitivity is sufficient to detect instantaneous variation in the emissivity of the skin as the mean emissivity value increases after jogging and then retain to the original value after 15 minutes of exercising when the human body is relaxed. In general, the increases in the mean emissivity value of the skin after jogging varies between locations, individuals, and with repeating the physical activity. This was found to be linked with the hydration level of the skin i.e. (sweat), the temperature of the skin, and the blood pressure in which all of these factors were found to be increased in different amount between individual and with exercising on a treadmill. These factors are subject to be investigated in the next phase of our research. In this paper we will focus on the signature of the skin and how the signature of the skin varies with daily activity i.e. (rest and jogging).

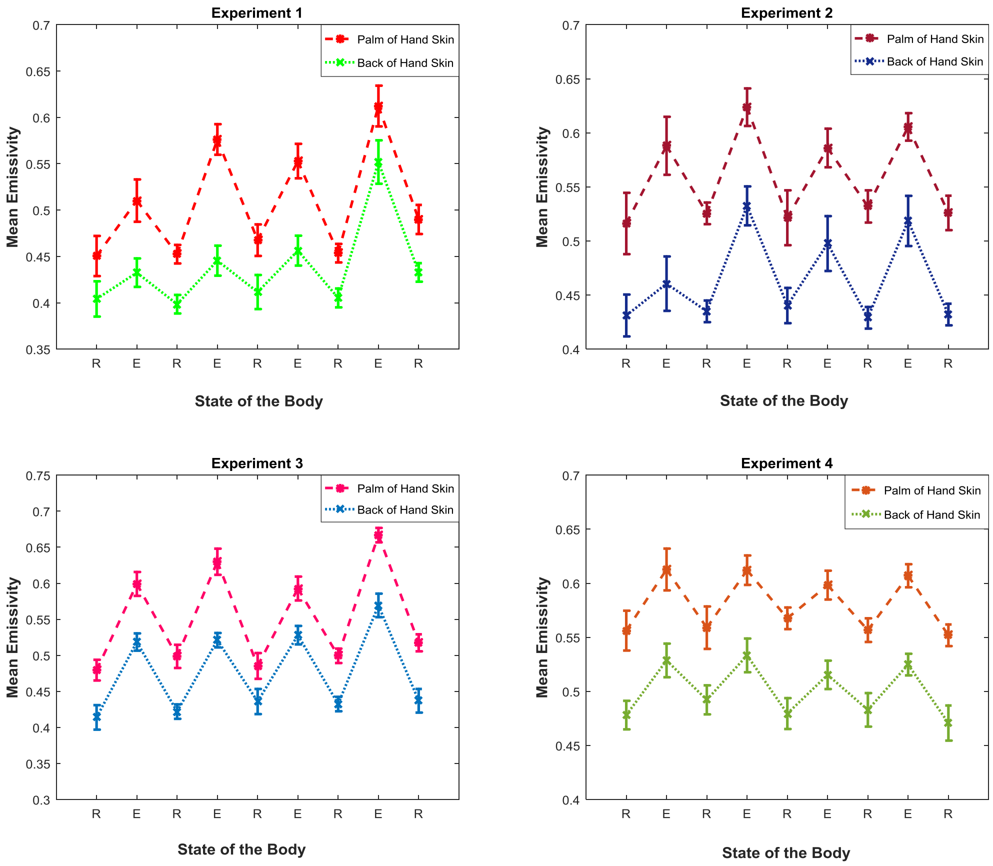

Figure 2. Human skin emissivity measurements over the frequency band 80-100 GHz on the palm of the hand and the back of the hand regions obtained from four participants in a rest state (R) and after jogging on a treadmill or exercising (E).

The measurements indicate the differences in the mean emissivity values before and after jogging on a treadmill are in the range from 0.048 to 0.13 for the palm of the hand skin and from 0.043 to 0.11 for the back of the hand skin. The results also confirm that there is a signature between the thinner and the thicker skin regions as the measurements show well define differences in the mean emissivity values between the palm of the hand and the back of the hand skin in all cases i.e. (before and after jogging on a treadmill). The measurements show an increase in the mean emissivity value after jogging for all participants and measurement locations. The presented signatures might be useful for identifying anomalies on the human body as well as the state of the health of the human body as variation in human skin emissivity are linked to blood pressure, temperature of the skin, and sweating. This can be done by comparing the measured emissivity of the subject area of the skin with the standard values of population, so any value higher or lower than the standard values might identify anomalies, unhealthy human body, or it might reveal new facts about the signature of the skin.

Human skin signature after the application of an aqueous gel

Measurements of human skin emissivity of a sample of 10 males and 6 females before and after adding gel to the palm of the hand and the back of the hand skin are presented in Figure 3.

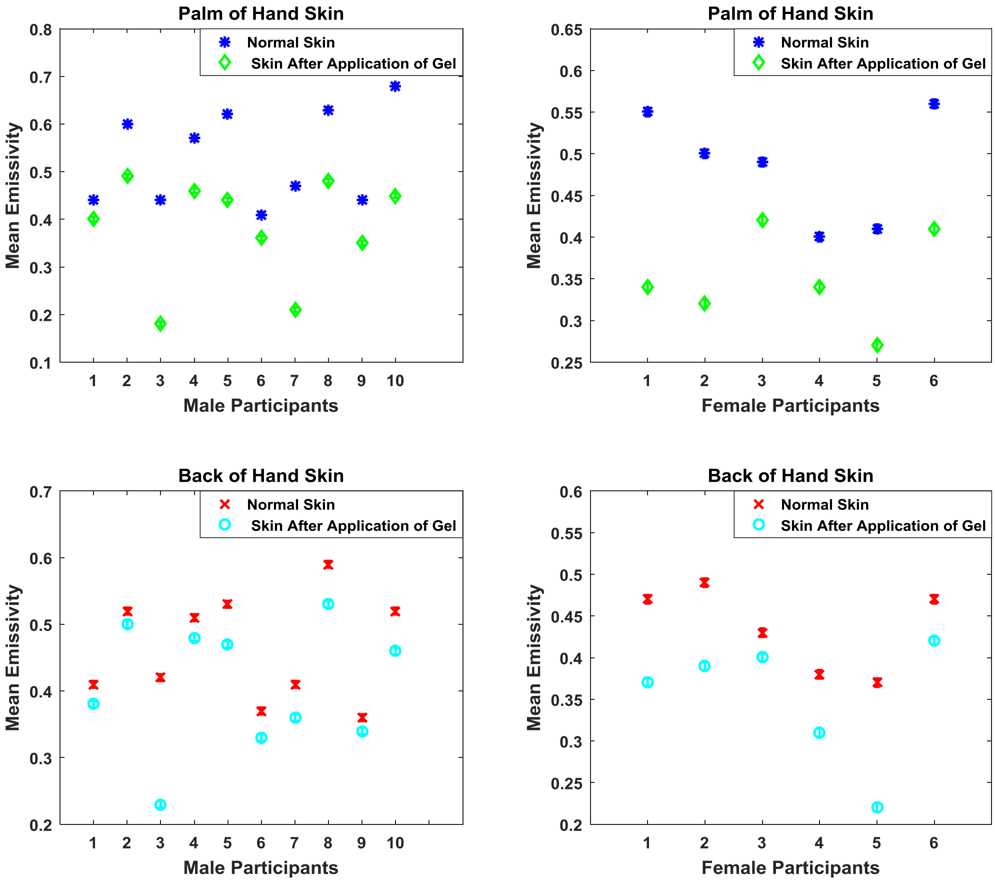

Figure 3. Emissivity measurements for 10 males and 6 females before and after the application of an aqueous gel over the frequency band 80-100 GHz.

The measurements in Figure 3 show the mean emissivity values of the skin before and after the application of an aqueous gel. Adding gel to the human skin increases the hydration level of the stratum corneum (SC) layer of the skin and reduces the inhomogeneity of the skin [10]. The gel that consists mainly of water can be used in the measurements of the dielectric properties of the skin in a wet state as it can stay adhered to the skin surface longer than the water. Measurements of human skin emissivity indicate that the emissivity over the band 80 GHz to 100 GHz is decreased after adding gel. The mean differences in emissivity values before and after the application of gel for the palm of the hand skin were found to be 0.15 and 0.14 for male and female participants respectively whereas these differences were found to be 0.06 and 0.08 for the back of the hand skin. The lower mean emissivity value for the skin with gel is consistent with the high relative permittivity of water resulting in higher reflectance and therefore, lowers emissivity. Moreover, the measurements show that variation in emissivity between individuals and locations on the hand are consistent for both genders. Understanding of human skin signature at the MMW frequency bands is useful for increasing the detection probabilities and reducing the false alarm rate at security screening portals.

DISCUSSION

Human skin signature over the frequency band 80-100 GHz shows a strong correlation between the skin emissivity, thickness, water content, hydration level of the skin, sweating, skin temperature, and level of thermal emission. As an imaging sensor, radiometry can deliver spatial resolutions down to around half of the wavelength of the radiation used, which can be ~1.0 mm for the MMW band (Abbes' microscope resolution limit) [17]. This property enables highly localized, non-contact measurements to be made just below the skin surface. This indicates that radiometry could be used as a non-contact viable technique to detect and monitor skin disease or damage. It may complement established methods on the optical band that have difficulty in measuring the dermis and the ultrasound techniques which measure different physical properties in the skin.

Variation in the mean emissivity values before and after jogging as well as with and without gel indicate that radiometric sensitivity is sufficient to detect instantaneous variation in the human body and also to identify normal skin and skin coated with gel. The implications of having emissivities profile for different regions of the human body and different genders, ethnicities, and age groups in rest and active states, is that security screening of persons can become more of an automated process. As radiometry is used in the estimation of emissivity, any attempts at deception, by substituting a human skin surrogate over the body will be recognised as it will not fit the expected characteristics. This is because the emissivity is derived from the amount of radiation emitted by the body, not just from its reflection properties. This means skin surrogates will be recognised even if they have exactly the same electrical properties as human skin. An active (coherent wave) illumination system will not have this capability, as it measures reflectivity directly. In a walk-through portal screening system, a machine would process in a matter of seconds the radiometric measured emissivity from all regions of the human body together with a profile of the individual derived from gender, age and ethnicity. This will increase the detection probabilities and reduce the false alarm rates in security screening portals.

CONCLUSIONS

A radiometer operating over the band from 80 GHz to100 GHz has been calibrated and used for measuring the human skin emissivity. Radiometric measurements presented in this paper show that the emissivity of the skin varies with the physical activity and hydration level of the skin. These factors were found to be linked with the level of thermal emission emitted from the human body and the temperature of the skin. The Measurements also show that the emissivity of the palm of the hand (thick layers of skin) is higher than that of the back of the hand skin (thinner layers of the skin) before and after jogging. Experiment measurements for a sample of 16 healthy participants indicate that the mean emissivity values for the palm of the hand skin and the back of the hand skin after the application of gel is significantly lower than the mean emissivity of the skin in normal state for the two measurement locations. These measurements indicate that skin thickness and hydration level of the skin are strongly dominating the level of thermal emission emitted from the human body at the millimeter-wave band.

FUTURE WORK

It is recommended that emissivity measurements be made on different regions of the human body such as the chest, the belly, the arms, the legs, the back, and the foots for healthy participants and participants having diseased skin such as eczema, psoriasis, malignancy, and thermal burn. This will demonstrate the signatures of healthy and non-healthy skin over the MMW. This might be done at a range of frequencies (35 GHz, 60 GHz, 90 GHz, and 120 GHz). It is also recommended that emissivity measurements be made during daily activities i.e. (rest, walking, jogging, and swimming) and under different conditions i.e. (relax, stress, happy, sad, as well as normal and wet skin conditions).

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