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Effect of metabolite and temperature on artificial human sweat characteristics over a very wide frequency range (400 MHz–10.4 GHz) for wireless hydration diagnostic sensors

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ABSTRACT

Sweat is an important biofluid that is excreted by the human body. It contains physiological biomarkers that provide vital information on the general health condition of the body. As a result, analysis of electrolytes in this biofluid is gaining traction in the development of non-invasive sweat diagnostics to determine level of dehydration, cystic fibrosis and illicit drugs. This paper presents a wireless measurement modality of permittivity properties of sweat of different metabolite concentration levels exemplifying the full spectrum of human sweat. The artificial sweat used in the study is an analogue of actual human sweat. It is synthesized from a composite mixture of metabolites and minerals including sodium chloride, potassium chloride, Urea and lactic acid. The effect of ambient temperature on the permittivity measurements of the various sweat solutions are studied across a frequency range of 400 MHz to 10.4 GHz. This information is important in the development of wireless radio frequency (RF) non-invasive biosensors.

1. Introduction

Sweat evaporation is essential to regulate heat generated within humans. Sweat contains important biomarkers that can give insight in the health of people. One technique to analyse the sweat is by measuring its permittivity (ε). Permittivity can be determined by analysing the electromagnetic wave interaction with biological tissues. This information is now being exploited in the development of healthcare wearable non-invasive diagnostic tools [1–7]. Sweat can be used to track physiological biomarkers including drugs, potassium, sodium, calcium, chlorine, lactic acid, glucose, ammonia, ethanol, urea, cortisol, and various neuropeptides and cytokines. The health condition of people is reflected in the concentration of the sweat. In fact, the alcohol concentration in sweat is correlated with the level of alcohol in the blood, and the level of urea in the sweat informs condition of the kidney. The sweat of people with cystic fibrosis has high levels of chlorine. Also, calcium indicates the condition of the cardiovascular system and other important functions of the body [8].

Old people in hospital and care homes as well as people taking strong medication can lose the sensation of thirst. Infants too are unable to express when they are thirsty. Old people and infants are at increased risk of dehydration, which has potentially serious health consequences. Hydration is important to maintain the overall health and cognition of individuals [9]. When optimal hydration is not maintained, thermoregulatory stress, hyperosmolality, and other biophysical conditions can impair. In fact, mild dehydration of −1% to −2% of body mass can significantly compromise alertness and cognitive responses and affects performance [10]. Chronic dehydration can increase the risk of infection, particularly of the urinary tract. Moreover, the kidneys and other major organs that receive a decreased blood flow are in danger of failure. The existing techniques to measure hydration are invasive, time consuming procedures like analysing urine, and measuring bodily fluids such as tears, water, and sweat.

The advances made over recent years in the field of bioelectronics and electromagnetic engineering has made it now possible to apply this technology for application in the development of non-invasive biosensors for healthcare monitoring [4,5]. Wearable biosensors therefore have great potential for personal real-time point of care diagnostics of

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body sweat. A controlled standardised test medium is therefore needed to calibrate such biosensors based on artificial sweat that is an analogue of real perspiration excreted by eccrine glands. Different formulations of artificial sweat have been reported in literature where the major components are sodium chloride (NaCI), potassium chloride (KCI), urea and lactic acid [7,11].

The measurement of properties of human perspiration, real and artificial, have been studied in both in-vivo and ex-vivo. Permittivity of sweat collected from different parts of the body is reported in Ref. [3]. The authors in Ref. [3] used a phasemeter to measure transmission coefficient of sweat to calculate its permittivity across a frequency range of 300 MHz to 3 GHz. Investigated in Ref. [12] is the permittivity of NaCI and KCI solutions over a temperature of between 10 °C and 60 °C and concentrations levels ranging from 0.001 to 5 mol/L between frequency band of 100 MHz to 40 GHz. In Ref. [3] the permittivity of aqueous solutions of NaCI is measured in the millimetre-wave band between 26 GHz and 110 GHz and at a temperature range between 0 °C and 25 °C. Dielectric properties of aqueous solutions of NaCI, KCI, urea and lactic acid simulating sweat is reported in Ref. [6] where the complex dielectric permittivity of ionic solutions of 0.01–1.7 mol/L concentrations was studied across 1 GHz–20 GHz at room temperature of 23 °C. The above studies however fail to investigate the frequency and temperature dependency variation with change in concentration of metabolites (NaCI, KCI, Lactic acid & Urea) contained in sweat.

The study in this paper presents the empirical results of the permittivity and conductivity of artificial human sweat metabolite of different concentrations as a function of frequency and temperature. The artificial sweat was constituted from a formulation of NaCI, KCI, lactic acid and urea. The permittivity and conductivity parameters were measured over a frequency range of between 400 MHz and 10.4 GHz. This information is important to develop highly accurate non-invasive wireless hydration sensors.

2. Materials and methods

Artificial human sweat used in the study was synthesized according to the EN1811:2011 European Standard [14]. Table 1 lists the aqueous solutions that were prepared to synthesize perspiration. The recipe consisted of dissolving in 1 L of distilled water 0.5% of NaCI, 0.1% of KCI, 0.1% of lactic acid and 0.1% of Urea.

Five solutions were synthesized with different concentrations of metabolites and minerals. These solutions covered the spectrum of perspiration concentration found in humans under different hydration conditions. Aqueous solution representing diluted sweat was prepared by dissolving 2.5 g of NaCI, 0.5 g of KCI, 0.5 g of lactic acid and 0.5 g of Urea in 1 L of distilled water. Over diluted solution comprised 1.25 g of NaCI, 0.25 g of KCI, 0.25 g of lactic acid and 0.25 g of urea dissolved in 1 L of distilled water. In the case of concentrated sweat the percentage of metabolites and minerals dissolved in 1 L of distilled water were increased, i.e., 10 g of NaCI, 2 g of KCI, 2 g of lactic acid and 2 g of urea. Lastly, to account for over-concentrated sweat, 20 g of NaCI, 4 g of KCI, 4 g of lactic acid and 4 g of urea mixed in 1 L of distilled water. The pH level of all artificial sweat solutions was made to be consistent with real sweat, i.e., 6.00 ± 0.05.

3. Experimental setup

The real part of the permittivity and conductivity of the artificial sweat solutions were measured using a high-precision measurement coaxial probe by SPEAG over a wide frequency range from 400 MHz to 11 GHz. The coaxial probe was connected to a vector network analyser (VNA) to measure the complex reflection coefficient (S_{11}), as shown in Fig. 1. Before the measurements were taken the probe was first calibrated according to SPEAG's high-quality standards. The electromagnetic (EM) fields at the probe end penetrate the artificial sweat solution under test and the reflected signal was measured with the VNA. The reflected signal was converted to the complex permittivity of the artificial sweat using Nicholson-Ross-Weir method using [15,16]:

$$\varepsilon_r = \mu_r \left(\frac{1-\Gamma}{1+\Gamma}\right)^2 \left(1-\frac{\lambda_o^2}{\lambda_c^2}\right) + \frac{1}{\mu_r}\left(\frac{\lambda_o}{\lambda_c}\right)^2 \tag{1}$$

$$\sigma = \omega \varepsilon_o \varepsilon_r^{''} \tag{2}$$

Where ε_r is the relative permittivity, μ_r is the relative permeability, Γ is the reflection coefficient, λ_o is the wavelength in the sample, λ_c is the cut-off wavelength of the coaxial probe, σ is the electric conductivity, ε_o is the vacuum permittivity, and $\varepsilon_r^{''}$ is imaginary part of the relative permittivity.

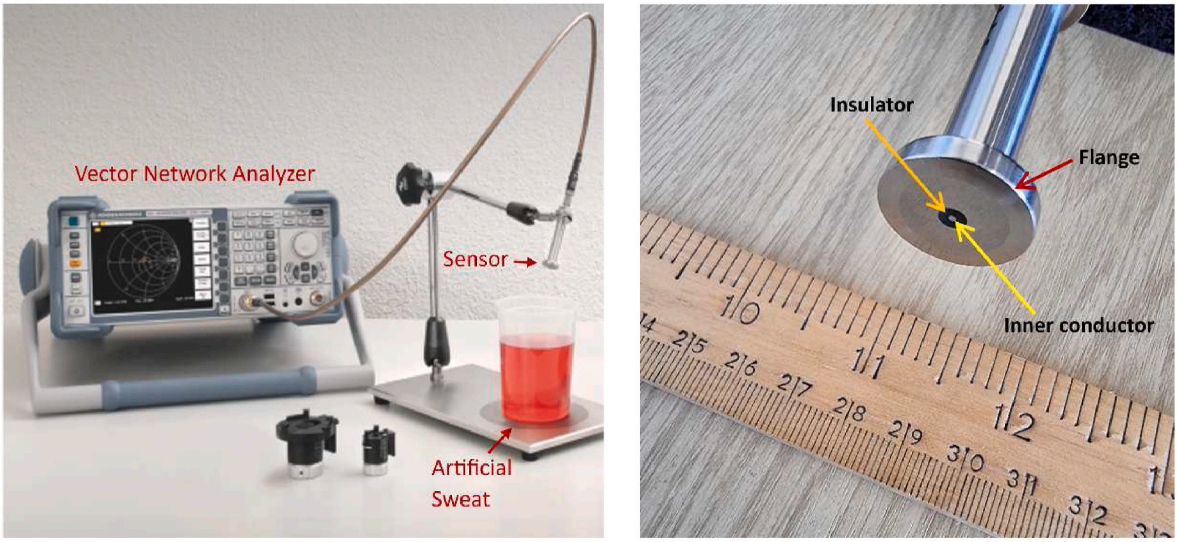
The permittivity of the artificial sweat solutions of volume 50 ml was measured in a glass beaker. All permittivity measurements were made at room temperature of 23 °C. Each measurement round involved in collecting 212 quantization points from 400 MHz to 11 GHz. The permittivity and conductance of each sample was an average of the three measurements. To maintain the integrity of the measurements the DAK probe was cleaned with distilled water each time it was used with different solution samples.

4. Experimental results

The real and imaginary part of the permittivity, i.e., ε′ and ε'', and conductivity σ (S/m) of the of the artificially engineered human sweat solutions of different concentrations were measured at room temperature. Table 1 above gives the standardised recipe for artificial sweat for different hydration state found in humans. Fig. 2 shows how the permittivity vary across a frequency range from 400 MHz to 10.4 GHz. The measured results in Fig. 2(a) shows the real part of the permittivity to decline with increase in frequency. The real part of the permittivity at 0.4 GHz is 80 for 0.25% solution and approximately 74 for the 4% solution. The decline in the real part of the permittivity can be approximated to a linear curve. The decline in permittivity is due to complex electrolyte-water-ion interactions. The oscillations of the time-varying electromagnetic field 'flip' and 'twist' the water molecules to affect its dipole moment. As the frequency of the electromagnetic field is increased the interaction diminishes the polarization of the solution resulting in a fall in the permittivity. It can also be observed in Fig. 2(a) that the magnitude of the permittivity of deionized water is higher than the artificial sweat for concentrations above 2%. This is because the metabolite concentration greater than 2% degrades the orientation of the polarization such that the sweat solution is no longer able to remain in phase with the applied electric field from the sensor. This causes the

Table 1
Artificial sweat solutions under test.

Base component	Concentration of components (g/L)				
	Over-Concentrated (4%)	Concentrated (2%)	Standard (1%)	Diluted (0.5%)	Over-diluted (0.25%)
NaCI	20 g	10 g	5 g	2.5 g	1.25 g
KCI	4 g	2 g	1 g	0.5 g	0.25 g
Urea	4 g	2 g	1 g	0.5 g	0.25 g
Lactic acid	4 g	2 g	1 g	0.5 g	0.25 g



(a) (b)

Fig. 1. (a) Experimental setup showing Speag's dielectric probe sensor (DAK 3.5 mm) inserted in a solution of artificial sweat to measure its permittivity (please note, red dye was added to the artificial sweat solution shown in the picture for the purpose of clarity here), and (b) close up view of the probe sensor. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

drop in the relative permittivity [17]. Fig. 2(b) shows the real part of the permittivity of the sweat with the permittivity of the deionized water subtracted. The differential in the permittivity is observed between 0.4 GHz and 2.4 GHz. In fact, the differential is greatest for sweats with greatest metabolites concentration. Fig. 2(c) shows how the various sweat concentrations affect the imaginary part of the permittivity. For concentration levels higher than 1% the imaginary part of the permittivity declines rapidly from 0.4 GHz to 2.4 GHz, and it stabilizes at around 30 at higher than 2.4 GHz. At 0.4 GHz, the imaginary part of the permittivity highest having a value of is approximately 130 for the 4% solution. The next highest having a value of 100 is the 2% solution.

The effect of temperature on the real part of the permittivity of artificial human sweat solutions of 1% and 8% concentration is shown in Fig. 3(a) and (b). It is observed that as the temperature increases the permittivity decreases. This is because on the increase in the dipole movement with increase in temperature. The measured results reveal the effect of temperature is more pronounced at low and high frequencies. Moreover, at low frequencies the samples measured at low temperature exhibit a high dielectric constant whereas at higher frequencies it is vice versa. This phenomenon is attributed to the delay in the dipole rotation of water molecules with respect to a changing electric field in a dielectric medium at lower and higher frequency [18]. Compared in Fig. 3(c) is the permittivity of the 1% and 8% concentration metabolites. It shows that the maximum variation in the permittivity is between 400 MHz and 5 GHz, and the variation is greatest for the metabolite with the 8% concentration.

The measured results in Fig. 4 show how the conductivity of the artificial human sweat solutions vary with frequency. The conductivity approximately increases in a linear fashion with increase in frequency. This is because electrolyte-water-ion polarization diminishes at higher frequencies resulting in higher ionic presence in the aqueous solution. More ions present in the solution limits the resistivity of various solutions resulting in higher conductivity [19]. The conductivity is higher for artificial sweat solutions of higher concentration of metabolite over a frequency range from 0.4 GHz to 10.4 GHz. Moreover, the difference in conductivity between the different concentrations metabolites reduces with increase in frequency.

5. Sensitivity, selectivity and reproducibility analysis

The experimental results presented in section 4 of the permittivity of the artificial sweat solutions were measured with the probe sensor in a beaker with 50 ml of artificial sweat solutions at room temperature of 23 °C. The sensitivity of the probe sensor was determined by using the permittivity of various volumes of sweat solutions. Fig. 5 shows the percentage error in the permittivity measurement of the various volumes of artificial solution of 2% metabolite concentration with reference to permittivity of the 50 ml of artificial sweat solution. The results in Fig. 5 shows the measurement error to be negligible. From these results it can be surmised that the probe sensor used to measure the parameters is highly accurate as long as the end of the probe is in contact with the sweat. In terms of the selectivity and reproducibility, the results obtained were identical to those presented in Figs. 2–4. These results confirm the probe sensor that was employed can measure the dielectric parameters with a high precision. Moreover, cable movement attached to the sensor had no effect on the measurements. This is because the phase distortion of the reflected signal from the probe due to movement of the cable is eliminated by the sensor's vector reflectometer.

6. Modified Debye Equation model for artificial human sweat mixture

The dependency of the complex permittivity with frequency can be described by the modified Debye model given by Ref. [20]:

$$\varepsilon^* = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau} + \frac{\sigma}{j\omega\varepsilon_o} \tag{3}$$

Where ε_∞ is the permittivity at high frequency, ε_s is the DC permittivity, ω is the angular frequency, τ is the relaxation time, ε_o is the permittivity of free space, and σ is the ionic conductivity. Exact expressions that accurately model the measured results of artificial sweat solutions for various concentrations was obtained through curve fitting. The relationship between permittivity and conductivity as a function of metabolite concentration is given by:

$$\boldsymbol{\varepsilon}' = -6e^{-20f^5} + e^{-14f^4} - 2e^{-10f^3} + e^{-6f^2} - 0.0027f + 81.391 + \alpha \tag{4}$$

Where $\alpha = -0.1288c^4 - 1.294c^3 - 4.223c^2 + 2.6403c - 0.5799$

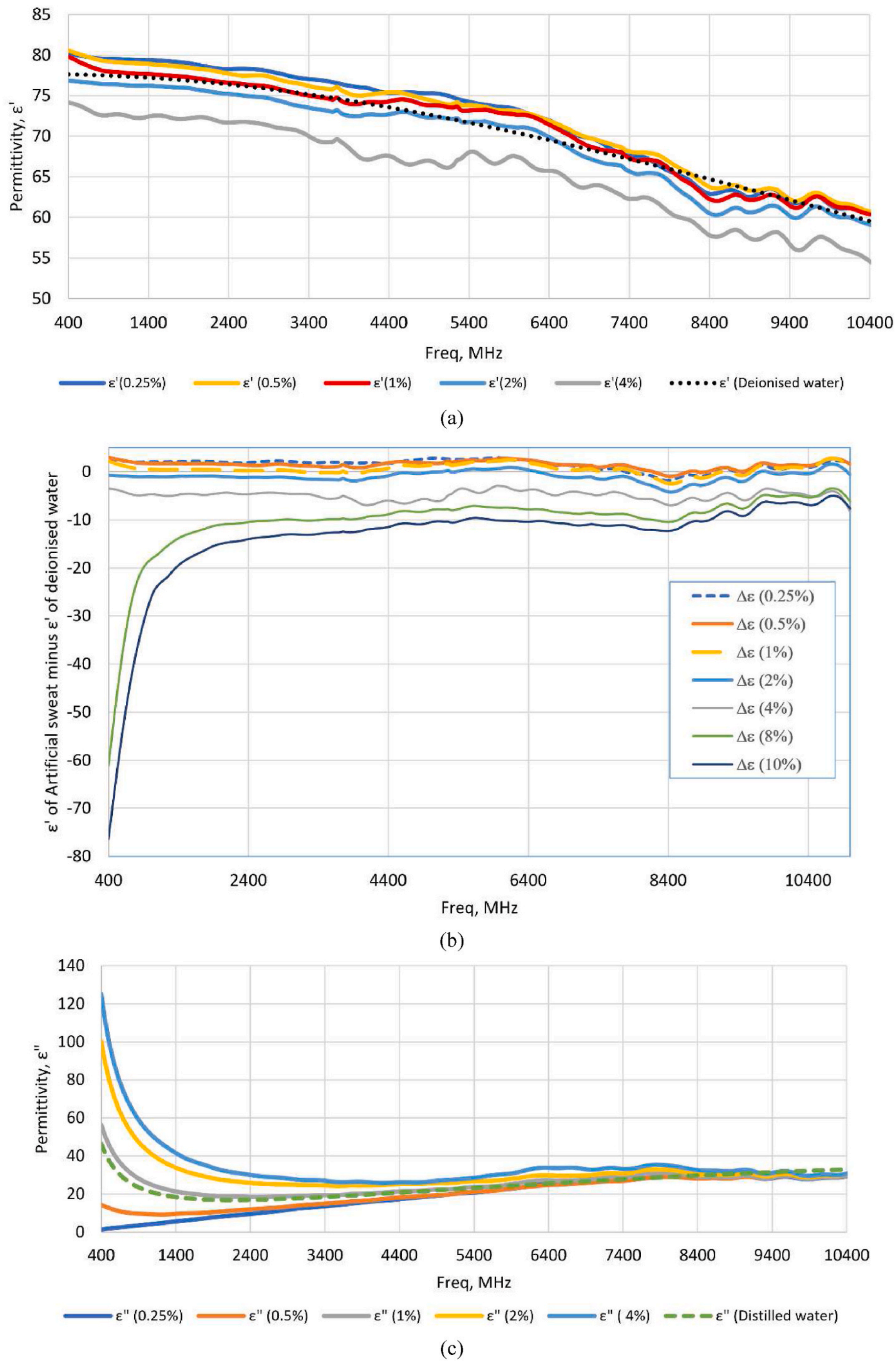


Fig. 2. Measured permittivity of artificial human sweat solutions of different metabolite concentrations from 400 MHz to 10.4 GHz, (a) real part of the permittivity, (b) Δε representing the real part of the permittivity of the sweat minus the permittivity of the deionized water, and (c) imaginary part of the permittivity.

The corresponding expression for the conductivity is given by:

$$\sigma = 5e^{-15f^4} - e^{-10f^3} + e^{-6f^2} - 0.0026f + 10.644 + \beta \quad (5)$$

where

$$\beta = 0.0004c^6 - 0.0095c^5 - 0.0836c^4 + 0.2258c^3 - 0.3069c^2 + 2.4406c - 10.298$$

Where f is the frequency in MHz and c is the concentration level between 0.25% and 10%. The error margin of Eqn. (3) is 2% between 0.4 GHz and 6.4 GHz. The worst-case error is 5% between 6.5 GHz and 10.4 GHz. The maximum error with Eqn. (4) is 2% between 0.4 GHz and 6.4 GHz. However, between 6.5 GHz and 10.4 GHz the error climbs to 35% at 10.4 GHz. More accurate expressions can be determined for frequency range between 6.5 GHz and 10.4 GHz.

The development of wireless biomedical sensors for healthcare applications are designed at the licence free Industrial, Scientific and Medical (ISM) band. In Fig. 6 shows the measured permittivity (real part) of the artificial sweat solutions for various metabolite concentrations at the ISM frequency of 2.45 GHz. Table 2 gives the values of the corresponding conductance. The given sweat solutions carry significance as they correspond to hydration and dehydration levels in humans. Fig. 6 shows the viability of using permittivity measurements to determine the level of dehydration in humans. Even though the

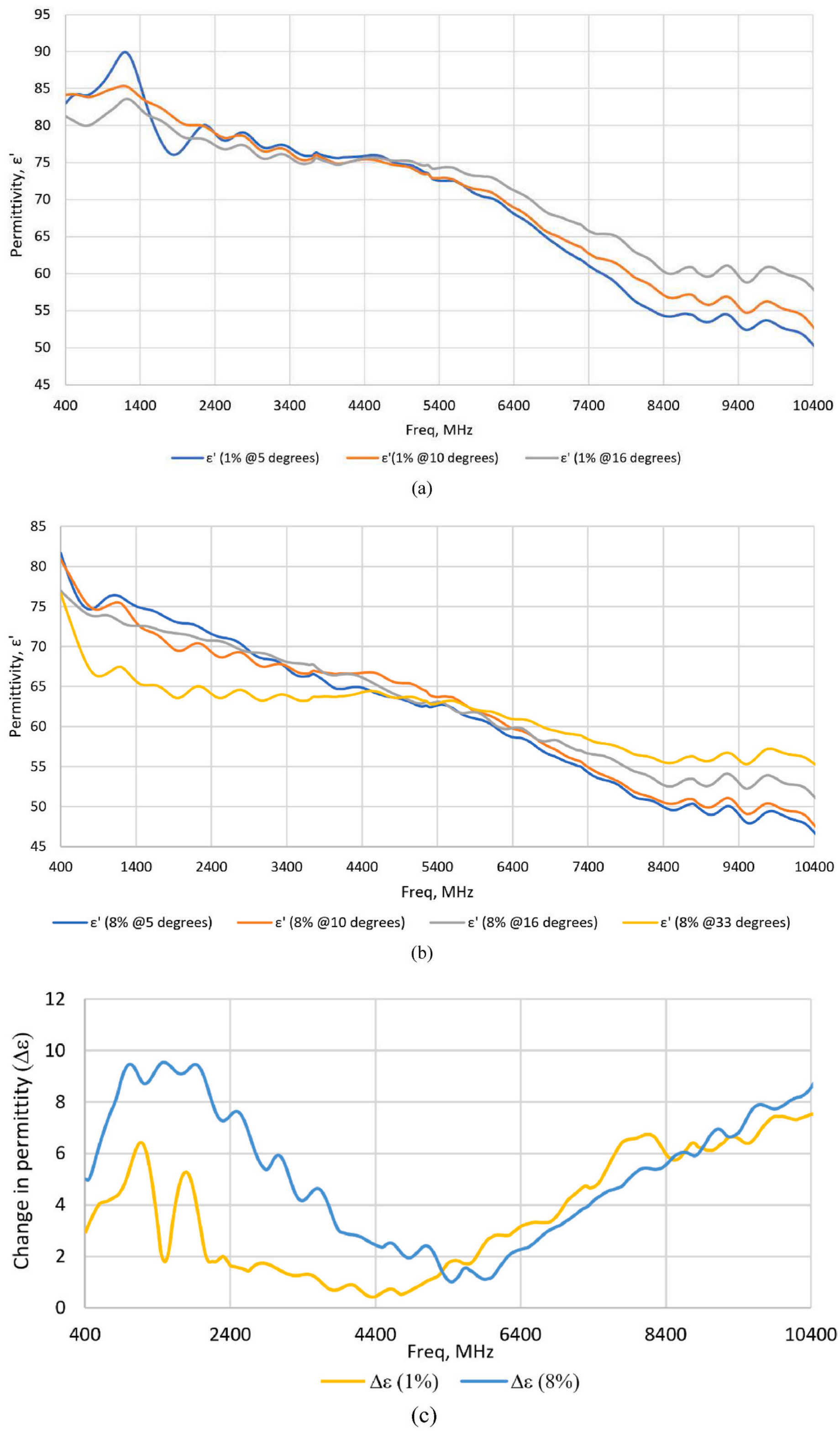


Fig. 3. Measured real part of the permittivity of artificial sweat solutions of metabolite concentrations, (a) 1%, (b) 8%, and (c) permittivity comparison between the 1% and 8% concentration metabolites.

differential between normal hydration and dehydration is marginal the results show that a sensitive sensor would be required.

7. Conclusion

This paper provides measured data on the permittivity and conductivity of artificially synthesized sweat of different concentrations for wireless hydration sensors. We have also shown how temperature can affect the permittivity readings. The ingredients used in concocting the artificial human sweat are identical as the real human sweat, which includes NaCl, KCl, urea, lactic acid in the band. Other literature reported to date on the composition of artificial sweat only confine their

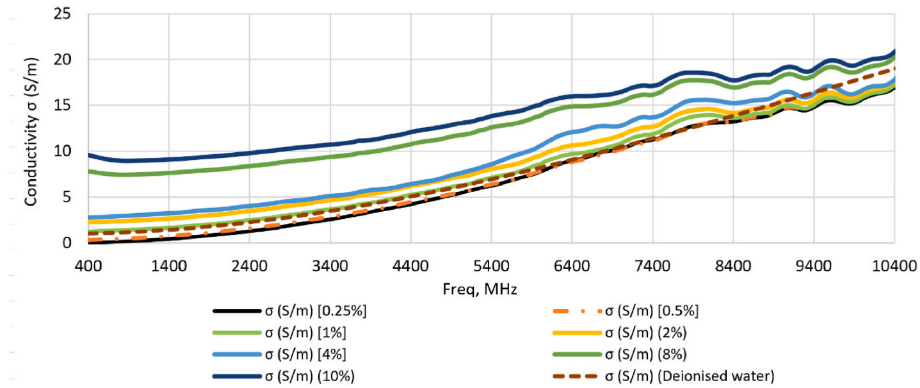


Fig. 4. Measured conductivity of artificial sweat solutions of different metabolite concentrations from 400 MHz to 10.4 GHz.

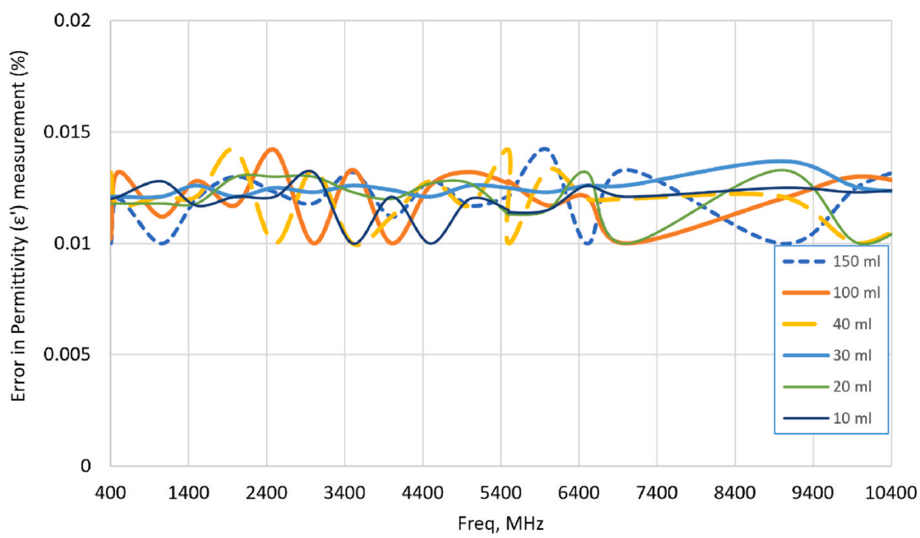


Fig. 5. Error in the relative permittivity measurements with reference to 50 ml of artificial sweat solution of 2% concentration.

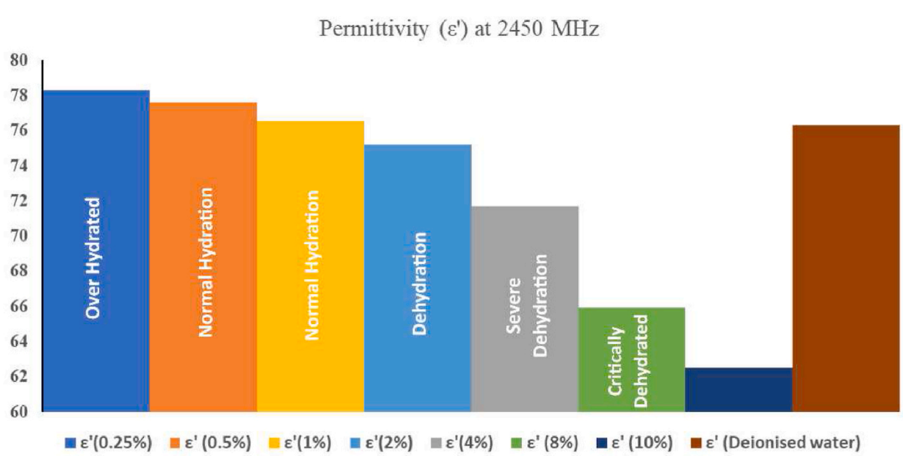


Fig. 6. Measured permittivity of the five artificial sweat solutions at the industry, scientific and medical (ISM) frequency of 2.45 GHz.

studies to two components specifically NaCl or KCl, which is not a true equivalence of actual sweat. The measurements here were done over a wide spectrum from 400 MHz to 10.4 GHz at room temperature of 23 °C. Based on the experimental results expressions are provided that accurately predict the permittivity and the level of dehydration. The data presented in this study should provide a better understanding which will benefit in the development of wireless non-invasive hydration sensors. Such biosensors should have a need in the monitoring the hydration of infants and the elderly to prevent health issues associated with dehydration.

Credit author statement

Innocent D. Lubangakene: Investigation, Methodology, Validation,

Table 2
Permittivity of artificial human sweat solutions at ISM frequency of 2.45 GHz.

Tested solution	ε′	σ (S/m)
4% conc. sweat	76.0625	3.24606
2% conc. sweat	76.0328	3.25045
1% sweat	77.1450	2.36587
0.5% diluted sweat	77.8133	1.75342
0.25% diluted sweat	78.1402	1.52443

Formal analysis, Writing, Bal S. Virdee: Conceptualisation, Supervision, ethodology, Writing. Renu Karthick Rajaguru Jayanthi: Software, Methodology, Validation, Data Curation, Priyanka Ganuly: Resources, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Further reading

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