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Proficiency Testing for Complex Permittivity Measurements of Tissue Equivalent Liquid Used in SAR Assessment

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ABSTRACT Tissue equivalent liquid plays an important role in specific absorption rate (SAR) assessment. Proficiency tests (PTs) through interlaboratory comparison of dielectric parameters (i.e., dielectric constant and the electrical conductivity of the tissue equivalent liquid) were conducted in 2017 and 2019. We coordinated the PTs performed with traveling samples circulating among the participating laboratories. As one of the most crucial issues in the PT schemes, these samples are described comprehensively, including the realization, the assignment of reference values, and the verification of homogeneity and stability. Fifteen and eleven laboratories participated in the PTs in 2017 and 2019, respectively. In total, 74 measurement results were provided in terms of best estimate and uncertainty. This paper presents and evaluates the performance of all the participating laboratories. Additionally, the measurement results are grouped in terms of the types of measurement probes. The analysis indicates that the measurement results obtained from two most widely used types of probes are compatible.

INDEX TERMS Proficiency test (PT), specific absorption rate (SAR), complex permittivity, tissue equivalent liquid, dielectric parameters.

I. INTRODUCTION

With the increase use of wireless transmitters, such as mobile telephones, the health risk induced by generated electromagnetic fields has become a spotlight.The exposure of a person radio-frequency (RF) energy is assessed by determining the specific absorption rate (SAR) [1]. Various regulatory agencies limit the maximum value of SAR and require wireless transmitters to be assessed and comply with the limits prior to being sold in the marketplace (e.g., [2]–[4]). In order to comply with the limits (e.g., IEEE [3], ICNIRP [4]), dosimetric measurements are now routinely performed on wireless transmitters.

The electric field generated by the wireless transmitters is measured in a homogeneous phantom filled with a tissue equivalent liquid and the maximum SAR averaged over a given mass is evaluated [5], [6]. The SAR in the tissue-equivalent liquid can be determined, according to Formula (1)

$$SAR = \frac{\sigma E^2}{\rho} \tag{1}$$

where σ is the electrical conductivity of the tissue-equivalent liquid in S/m, E is the Root-Mean-Square (rms) value of the electric field strength in the tissue-equivalent liquid in V/m, and ρ is the mass density of the tissue-equivalent liquid in kg/m^3. The tissue equivalent liquid plays an important role in the measurement [7], [8], because the electric field strength E in liquid is affected by the liquid's complex permittivity ε [8]. The complex permittivity is commonly written as

$$\varepsilon = \varepsilon' - j\varepsilon'' = \varepsilon_0 {\varepsilon'}_r + \frac{\sigma}{j\omega} \tag{2}$$

The real part of the permittivity, ε', denotes the polarization of the medium resulted from charge distribution, and the imaginary part, ε', denotes ohmic losses. The real part is the product of ε_0, the permittivity of free space

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(8.854×10^{-12} F/m) and ε_r', the real part of the complex relative permittivity. For what concerns the imaginary part, ω is the angular frequency (radians/s). The key parameter are ε_r' and σ. Their target values have been standardized by two international standardization bodies, i.e., the IEEE International Committee on Electromagnetic Safety (ICES) and the International Electrotechnical Commission (IEC) [5], [6]. As a consequence, ε_r' and σ are the parameters measured in the Proficiency Tests (PT), focus of this paper.

PTs are essential for laboratories to guarantee the quality of their measurement results [9].They consist of interlaboratory comparisons specifically designed to evaluate participants' performance based on pre-established criteria. Guidelines for design, preparation, and conduct of a PT are given in [10]. Participation in PTs is a common practice for laboratories to operate in many areas (e.g., analytical chemistry [11], [12] and Electromagnetic Compatibility (EMC) [13], [14]), but this practice is not applied to laboratories operating in the complex permittivity measurements. The lack of PT in this field impedes the supervision of laboratory performance.

National Institute of Metrology, China (hereinafter referred to as NIM) focuses on physical and chemical metrology. One of the responsibilities of NIM is to coordinate PT program. Regarding this role, NIM has coordinated a biennial PT program for complex permittivity measurements since 2017.This paper presents the complete results of the PTs performed in 2017 and 2019, including interlaboratory comparisons, evaluation methods, evaluation results, and discussions.

This paper is organized as follows. In Section II, technical information about the preparation of PTs is provided, in particular related to the assignment of reference values, and the verification of samples. In Section III, an evaluation method and the results of the PTs are presented where some heuristic and didactic data are analyzed and discussed. Conclusion follows in Section IV.

II. PREPARATION OF THE PTs

The quality and adaptability of the samples are the most important issues in PT schemes. From the technical point of view, the preparation of a PT essentially consists of the realization of samples, the assignment of reference values for samples, and the verification of homogeneity and stability of samples.

A. REALIZATION OF THE SAMPLES

The samples were prepared according to the recipes provided by the standards [5]. The PTs have been performed at 900 and 1800 MHz in years 2017 and 2019, respectively. For 900 MHz, the liquids were made of nontoxic sugar (sucrose), de-ionized water, salt (NaCl), and cellulose. For 1800 MHz, the liquids were made of de-ionized water and polyhydric alcohol. To better investigate the participants' performance, two different samples with diverse complex permittivity values were prepared in 2019. The recipes were adjusted to change the complex permittivity values and the values were obtained by measurements. In this paper, what we want to emphasize is the measurement of samples, rather than the realization of them.

TABLE 1. Summary of Reference Values and Corresponding Uncertainties.

Test parameters	R	u_R
$\varepsilon'_{\text{r-2017}}$	39.98	0.21
$\sigma_{\text{-2017}}$ (S/m)	1.33	0.01
$\varepsilon'_{\text{r-2019a}}$	56.34	0.46
$\sigma_{\text{-2019a}}$ (S/m)	1.02	0.01
$\varepsilon'_{\text{r-2019b}}$	42.32	0.41
$\sigma_{\text{-2019b}}$ (S/m)	0.95	0.01

B. ASSIGNMENT OF REFERENCE VALUES

The complex permittivity measurement systems are supplied by some instrumentation manufactures such as Keysight® and Speag®. However, the distinctive feature of the PT is that the reference value is traceable and assigned by the coordinator of the PT [13]. The reliability of the measurement results of the laboratory will be confirmed if they are compatible with the reference values assigned by the coordinator, which cannot be confirmed by merely comparing individual measurement results with their average. What's more, the availability of the coordinator assigned reference value can also give evidence of the capability of the coordinator to technically manage the PT [13]. Therefore, we developed and validated a measurement system based on transverse electromagnetic model, where the singular static integral on the source domain is converted into a well-posed line integral over the circumference boundary. The fundamental information and procedural details of this measurement system has already been presented previously [15], [16]. Then the reference value R and its uncertainty u_R were obtained and summarized in Table 1 where the subscripts '2017' and '2019' represent the years of the PTs, the subscript 'a' and 'b' represent the two samples in 2019.

To validate the reference values, the coordinator compares the reference values R with R' (robust average) through the following performance statistic,

$$z' = \frac{R - R'}{\sqrt{\frac{(1.25s^*)^2}{p} + u_R^2}} \tag{3}$$

where R' is the robust average value obtained by the robust analysis (Algorithm A, i.e., the robust average is derived by an iterative calculation that updates the values several times using the modified data until the process converges) described in [17]. s^* is the robust standard deviation. p is the number of participating laboratories.

In accordance with [17], if $|z'|$ is less than 2, it means high consistency of R and R'. A quantitative summary of the statistics is reported in Table 2 where all the absolute values of z' are less than 2, indicating that the reference value obtained through the coordinator's measurement system is compatible with the average value obtained from participants' measurement results. Besides, the values of s^* are significantly greater than the values of u, signifying that the uncertainty assigned to the reference value R by the coordinator is small, compared with the average measurement capability of the laboratories.

TABLE 2. Comparison Between Reference Values and Robust Estimates.

Test parameters	R'	s^*	$\|z'\|$
$\varepsilon'_{\text{r-2017}}$	40.10	0.64	0.38
$\sigma_{\text{-2017}}$ (S/m)	1.33	0.05	0.18
$\varepsilon'_{\text{r-2019a}}$	56.35	1.21	0.01
$\sigma_{\text{-2019a}}$ (S/m)	1.02	0.02	0.39
$\varepsilon'_{\text{r-2019b}}$	42.32	1.09	0.01
$\sigma_{\text{-2019b}}$ (S/m)	0.96	0.02	1.07

TABLE 3. Summary of the Results for the Verification of Homogeneity and Stability.

Test parameters	s_s	$\|\bar{x}-\bar{y}\|$	$0.3s^*$
$\varepsilon'_{\text{r-2017}}$	0.183	0.033	0.192
$\sigma_{\text{-2017}}$ (S/m)	0.013	0.003	0.014
$\varepsilon'_{\text{r-2019a}}$	0.064	0.001	0.363
$\sigma_{\text{-2019a}}$ (S/m)	0.002	0.001	0.005
$\varepsilon'_{\text{r-2019b}}$	0.003	0.001	0.327
$\sigma_{\text{-2019b}}$ (S/m)	0.001	0.002	0.006

C. VERIFICATION OF THE SAMPLES' HOMOGENEITY AND STABILITY

There are two main criterions (i.e., homogeneity and stability) for the adaptability and the quality of PT samples. According to ISO 13528 [17], the homogeneity of the samples was verified through the measurements of 10 samples in duplicate (two test portions) taken randomly in the form of final packages. The stability was verified by measuring 3 samples in duplicate over a period of 6 months. In accordance with ISO 13528 [17], the general average of the measurements obtained in the stability test, and the between-samples standard deviation s_s were calculated, summarized quantificationally in Table 3. Since $s_s < 0.3s^*$, all the three samples were considered to be rather homogeneous. Meanwhile, the inequality that $|\bar{x}-\bar{y}| < 0.3\, s^*$ verified the stability of the samples.

III. DATA ANALYSIS FOR PERFORMANCE EVALUATION

The PTs were open to all laboratories that satisfied the following requirements:

1) The laboratory can perform complex permittivity measurements in SAR assessments.
2) The laboratory has calculated the measurement uncertainties associated with aforementioned measurements.

The minimum number of participants was set to five, in order to achieve a significant number of measurement results to be submitted to the statistical analysis. Fifteen and eleven laboratories participated in the PTs in 2017 and 2019, respectively. All the measurement results were evaluated.

A. PERFORMANCE STATISTICS

The ISO 13528 [17] proposes statistical methods that are propitious to analyze the measurement results in proficiency testing. For these PTs, based on the assignment of reference values, we evaluated the participants' performance according to z-score, which is calculated as follows:

$$z_i = \frac{x_i - R}{s^*} \tag{4}$$

where x_i is the measurement result of the ith participating laboratory. According to [17], the obtained z-score should be interpreted as follows: the measurement result of the ith laboratory will produce an action signal, if at least at one sample, $|z_i|$ is greater than 3. The measurement result will produce a warning signal, if at least at one sample, $|z_i|$ is greater than 2 and less than 3. If at all samples, $|z_i|$ is less than 2, the measurement result provided by the ith laboratory will not give evidence of any anomaly.

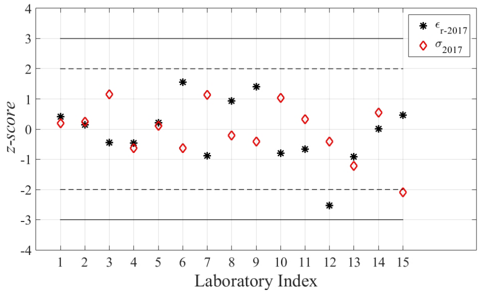


FIGURE 1. z-scores of the participants in 2017.

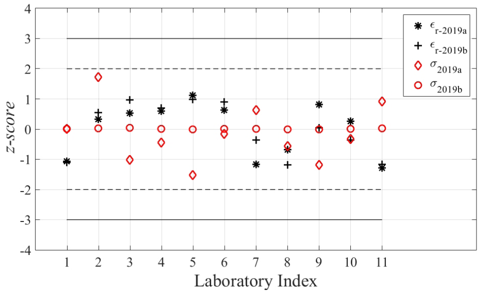


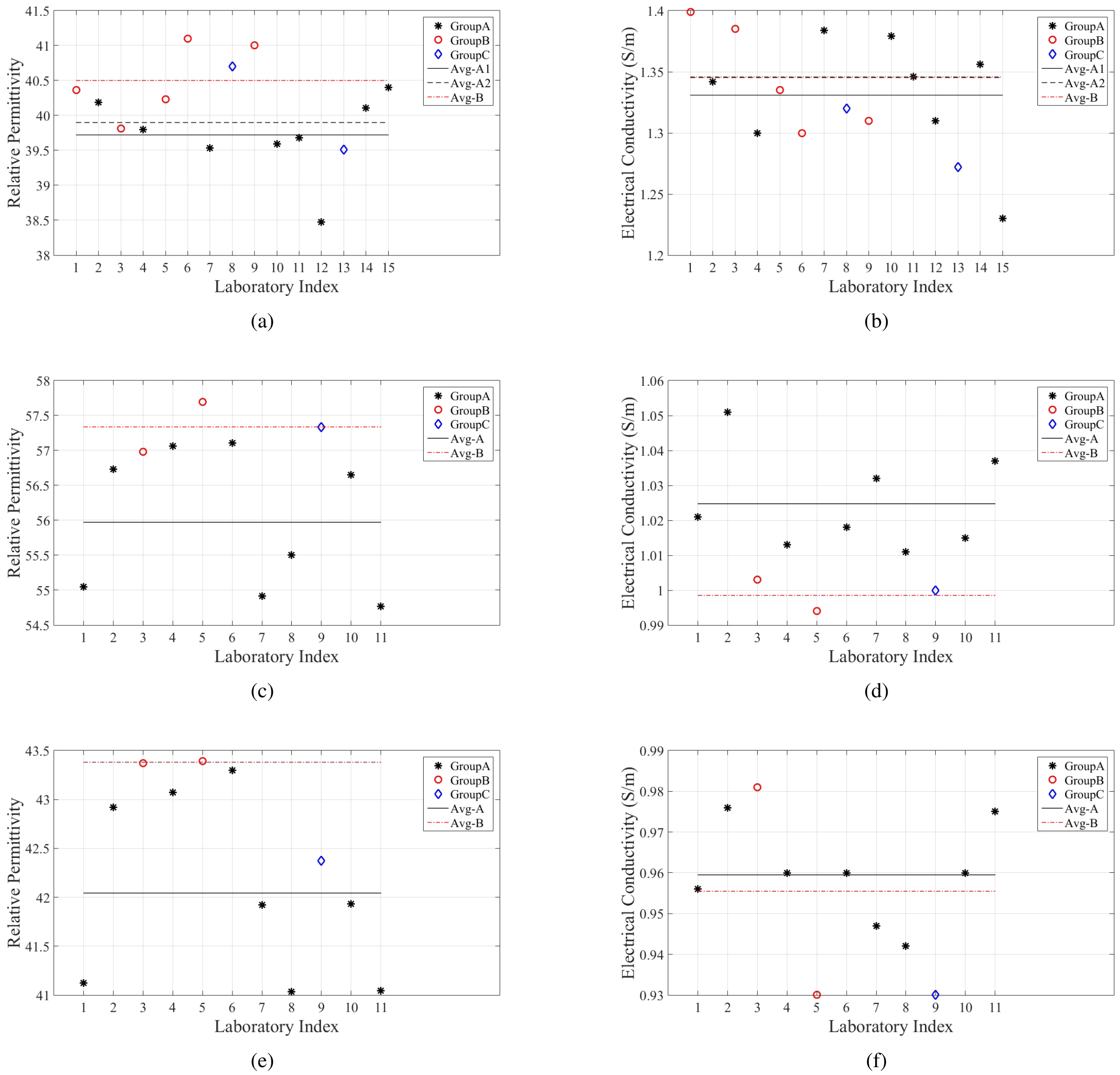
FIGURE 2. z-scores of the participants in 2019.

B. RESULTS AND DISCUSSION

In Fig. 1 and Fig. 2, z-scores are illustrated as a function of laboratory index. Black asterisks and plus signs represent the values of z-scores for relative permittivity. Red diamonds and circles represent the values of z-scores for electric conductivity. Continuous lines and dashed lines represent the limits for action and warning signals, respectively.

Figure 1 shows two warnings and no actions. Here, z-score of laboratory 12 for ε'_r and that of laboratory 15 for σ measurements triggered "warning" in 2017. The laboratory 15 in 2017 did not participate in the PT in 2019. Whereas the laboratory 12 in 2017 participated in the PT in 2019 (laboratory 1 in 2019). As is depicted in Fig. 2, the 2019 measurements results from laboratory 1 showed no criticality, indicating that the participant improved its performance. The PT could be of benefit to this improvement. At least, the participant realized its problem through the PT. Additionally, for z-scores of most laboratories, Fig. 2 exhibits the proximity in terms of the respective samples under both measured parameters (at least, the signs of both z-scores of most laboratories are identical). It indicates that the z-scores hold good consistency for the same measured parameter under different samples.

On the whole, the evaluation shows that most of the measurement results were within the range of acceptable relative deviation from the corresponding reference values R,



(a) (b)

(c) (d)

(e) (f)

FIGURE 3. Measurement results of the participants (a) ε'_r measurement results in 2017 (b) σ measurement results in 2017 (c) ε'_r measurement results for sample A in 2019 (d) σ measurement results for sample A in 2019 (e) ε'_r measurement results for sample B in 2019 (f) σ measurement results for sample B in 2019.

demonstrating that the PT was well designed and most of the laboratories were able to keep measurement process under control.

For what concerns measurements, all participants measured the dielectric parameters based on the open-ended coax method. Specifically, two types of open-ended coaxial probes (i.e., Speag® Dielectric Assessment Kit and Keysight® 85070E High temperature probe) are mostly used for this kind of measurements. For the PTs, 13 of 15 and 10 of 11 participants used these two types of probes in 2017 and 2019, respectively. To analyze the effects of the two types of probes on the measurement results, the measurement results were divided into 3 groups. Group A and Group B represent the participants who used these two types of probes, respectively. Group C represents the other participants. The measurement results in 2017 and 2019 were illustrated as a function of laboratory index in Fig. 3, where black asterisks, red circles and blue diamonds represent the measurement results of Group A, B and C, respectively. The average values (without the warned laboratories) of Group A (Avg_A) and B (Avg_B) were represented by black lines and red dashed lines, respectively. In addition, the average values with the warned laboratories were also depicted in the form of continuous lines. The distributions of the measurement results are intuitively shown in the Figure 3.

TABLE 4. Comparison Between the Measurement Results Obtained From Two Types of Probes.

Test parameters	R	Avg_A	Avg_B	Δ%
$\varepsilon'_{r\text{-}2017}$	39.98	39.89	40.50	1.53%
$\sigma_{\text{-}2017}$ (S/m)	1.33	1.35	1.35	0.04%
$\varepsilon'_{r\text{-}2019a}$	56.34	55.97	57.34	2.42%
$\sigma_{\text{-}2019a}$ (S/m)	1.02	1.02	1.00	2.58%
$\varepsilon'_{r\text{-}2019b}$	42.32	42.04	43.38	3.16%
$\sigma_{\text{-}2019b}$ (S/m)	0.95	0.96	0.96	0.42%

Table 4 summarizes the statistics. In Table 4 $\Delta\% = \frac{|Avg\_A - Avg\_B|}{R}$. According to [18], the measurement results of Group A and Group B are compatible, because all the differences (Δ%) are less than the uncertainties of the dielectric parameter measurements. The uncertainties are obtained from[6, Subchapter 7.2.6].

IV. CONCLUSION

PTs are a powerful methodology to assess the ability of a participating laboratory to provide reliable measurement results. On the one hand participants could demonstrate their capability through satisfactory results, on the other hand PTs will act as a good start to improve the work of those participants that trigger ''warning'' or ''action''.

The biennial PT program for complex permittivity measurements of tissue equivalent liquid used in SAR assessment evaluates the performance of all participating laboratories through 74 measurement results. In 2017, 28 of 30 measurement results are satisfied, while in 2019, all the 44 measurement results are satisfied, indicating that most of the laboratories were able to keep measurement process under control. Additionally, the analysis demonstrates that the measurement results obtained from two most widely used types of probes are compatible.

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