SAR probe calibration: the results of an inter-comparison study

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***Abstract*— This paper gives the results of an intercomparison of the calibration results for four specific absorption rate (SAR) probes as measured by three independent laboratories. The artefact standards used for the calibration were matched waveguide cells that generate a calculable SAR level in a liquid phantom, and these systems are described, together with the measurement uncertainties. The results were found to be consistent with the quoted measurement uncertainties of the laboratories.**

Key words: Specific Absorption Rate, SAR, mobile phone, intercomaprison.

I. INTRODUCTION

Excessive exposure to electromagnetic fields can cause heating of tissues in the human body and result in adverse health effects. The degree of heating is related to the specific absorption rate (SAR) of energy in the body, with units watts per kilogram, and for this reason SAR forms the basic restriction for human exposure given by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) for frequencies between 100 kHz to 10 GHz [1]. In Europe, the occupational exposure limits of the ICNIRP will become mandatory for workers as a result of a European Directive [2]. SAR measurements are used for compliance testing of products such as mobile phones, for human exposure assessment, and for calibrating the exposure levels used in experimental studies into possible health effects of electromagnetic fields. Such studies provide the scientific basis for the exposure limits, and can be human volunteer studies, animal studies or in vitro studies.

The SAR level from a device, such as a mobile phone, is assessed by placing it in close proximity to a liquid phantom having similar electrical properties to the human tissues and measuring the resulting E-field distribution in the liquid [3]. The SAR is related to the Hermitian magnitude electric field, E, in a dielectric material with conductivity σ and density ρ, by

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

Measuring the electric field yields higher sensitivity than measurement of the temperature rises. Since exposure guidelines seek to prevent excessive heating of tissues, and perfusion and diffusion effects occur in the biological materials, the SAR values are averaged over the entire body, or for local SAR limits a 1 g or 10 g mass. This can either be a cube [3] or a contiguous volume [1]. Thus the SAR measurement system incorporates a robot to move the electric field probe accurately within the required volume.

The electric field probes used to measure SAR in liquids contain three orthogonal dipole antennas, *X, Y, Z*, each with a diode detector. To obtain a linear response, the output voltages from the diodes, V_N, are corrected using

$$V_{LIN,N} = V_N\left(1+\frac{V_N}{DCP_N}\right) \qquad {}_{N=X,Y,Z} \tag{2}$$

where V_{LIN} is the linearised voltage and DCP_N is the diode compression point. The SAR reading is calculated from the linearised voltages using

$$SAR = \frac{\sigma}{\rho}\times\sum_{N=X,Y,X}\frac{V_{LIN,N}}{CF_N} \tag{3}$$

where σ is conductivity of the liquid, ρ is its density and CF_N is the calibration factor. Because the calibration factor depends on the complex permittivity of the liquid, it must be measured with the probe in the liquid, and this calibration should be traceable to primary national standards. This paper describes the systems for calibrating SAR probes in liquid, and presents the results of an intercomparison of the calibration results obtained by three independent laboratories, namely NICT (Japan), NPL (UK) and SPEAG (Switzerland).

II. DESCRIPTION OF THE SAR CALIBRATION SYSTEMS AT NICT AND NPL.

NPL, NICT and SPEAG have matched-waveguide systems to generate known electric fields in the phantom liquid [4], [5]. The systems consist of a coaxial to waveguide adapter and section of waveguide with a dielectric slab that is sealed to the waveguide, so that the section of waveguide with the open end can be filled with liquid. The volume specific absorption rate SAR^v (unit watts per meter cubed) in the liquid can be calculated at centre of the cross-section of the waveguide using

$$SAR^V = \frac{4(P_w)}{ab\delta} e^{-2x/\delta} \tag{4}$$

where a and b are the internal dimensions of the waveguide cross-section, x is the distance from the liquid boundary with the dielectric spacer to the probe sensor elements and P_w is the power delivered to the waveguide. The value of skin depth (δ) is obtained by measuring the electric field (E) at a number of distances from the dielectric slab. The power measurement uncertainty is reduced if the system is well matched, and this is achieved by the use of multiple dielectric spacers with different permittivity in the waveguide systems at NICT and NPL. Fig. 1 shows the SAR probe calibration system in the SAR measurement laboratory at NICT.

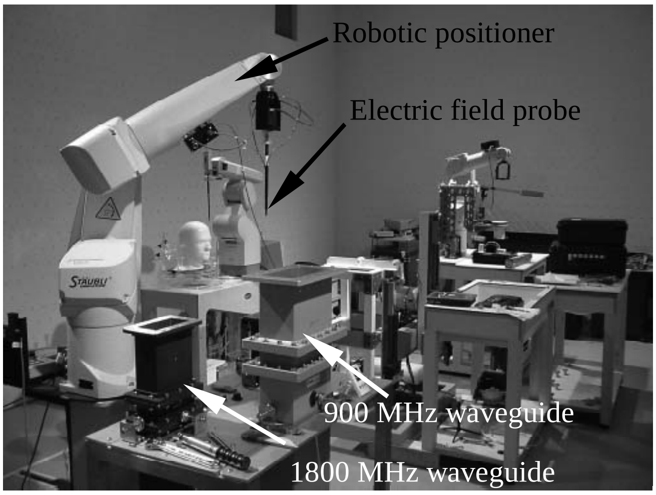

Fig 1. SAR probe calibration at laboratory at NICT

Table 1 gives the quoted measurement uncertainty for SAR of the three laboratories at each frequency. Table 2 shows the main contributions to the measurement uncertainty for the NPL system at 5.8 GHz. For the waveguide systems the power measurement, the dielectric properties of the liquid and the variation in the theoretical mode distribution in the waveguide are the main uncertainty components.

TABLE 1: QUOTED MEASUREMENT UNCERTAINTIES FOR SAR PROBE CALIBRATION

	Expanded uncertainty for SAR for a coverage factor of k = 2, which corresponds approximately to a 95% confidence interval		
Frequency (GHz)	NPL	NiCT	SPEAG[1]
0.450	± 10%	-	± 13.3%
0.900	± 10%	± 7.5%	± 11.0%
1.950	± 10%	± 7.6%	± 11.0%
2.450	± 10%	± 7.6%	± 11.0%
5.200	± 10%	-	± 13.1%
5.800	± 10%	-	± 13.1%

[1] Accredited by the Swiss Accreditation Service.

TABLE 2: UNCERTAINTY BUDGET FOR SAR PROBE CALIBRATION AT 5.8 GHZ (NPL)

Source	Description	u_i (±%)
Liquid	Temperature coefficient (1.5% per °C)	0.9
	Difference from target permittivity	2.0
	Measurement of conductivity	1.0
Power	Measurement of power to the liquid	2.2
Probe related	Measurement of decay depth	1.0
Field distribution	Variation from TE_{01} field distribution	2.8
Dimensional	Distance from matching window	1.1
	Setting the probe at the centre of the waveguide	0.2
	Waveguide dimensions	0.9
Combined		± 4.6
Expanded	(k = 2)	± 9.2%

III. INTERCOMAPRISON OF THE SAR CALIBRATION STANDARDS

Four SAR probes manufactured by SPEAG were calibrated at NICT and NPL, and the results were also compared to the calibration provided by the manufacturer. The average of the calibration factors for the three sensors in the probe, as defined in Eq. 3, were compared. Fig. 2 to 5 show the calibration factors as measured by NICT, NPL and SPEAG at each frequency for the four probes. The horizontal lines on the graphs indicate the unweighted means of the data for each frequency, and the vertical bars indicate the extent of the 95% confidence intervals for the measurements. In all cases, the unweighted mean lies within the 95% confidence interval of each of the laboratories, indicating that there is agreement within the quoted uncertainties. The average calibration factors of probe B, Fig. 3, are higher in 2007 than in 2006, and this may indicate a change in the performance of this probe. The results are consistent with the quoted uncertainties for the laboratories.

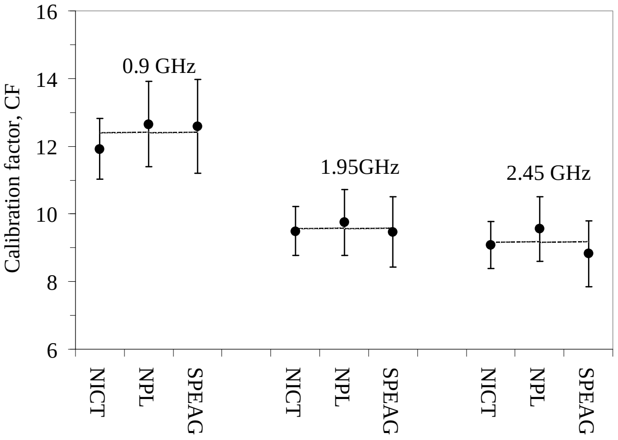

Fig 2. Calibration factor of Probe A, model ET3DV6, measured at NICT, NPL, and SPEAG in 2005. Vertical bars indicate the extent of the 95% confidence interval for each measurement. The horizontal lines show the average of the calibration factors for each frequency.

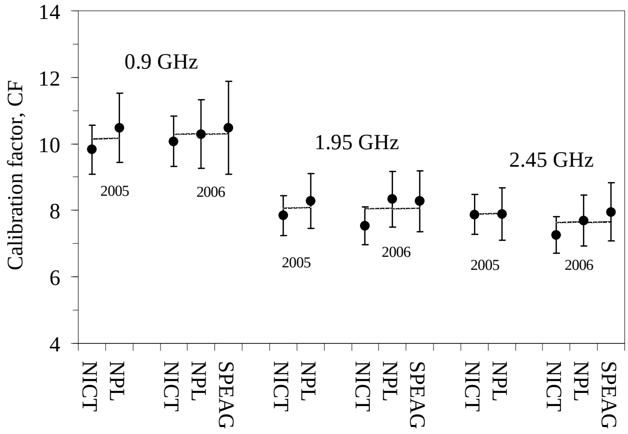

Fig 4. Calibration factor of Probe C, model ET3DV6, measured at NICT, NPL, and SPEAG in 2005 and 2006. Vertical bars indicate the extent of the 95% confidence interval for each measurement. The horizontal lines show the average of the calibration factors for each frequency.

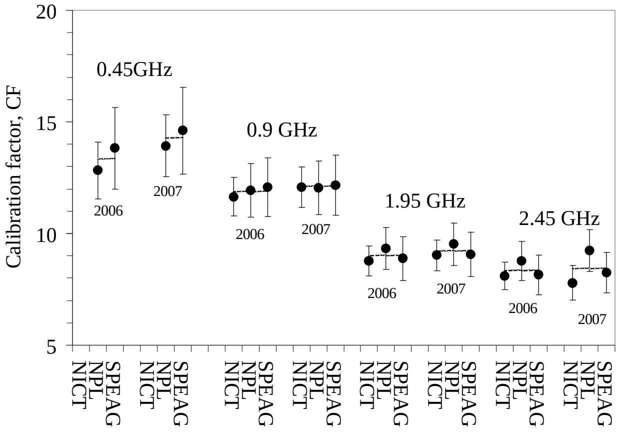

Fig 3 Calibration factor of Probe B, model ET3DV6, measured at NICT, NPL, and SPEAG in 2006 and 2007. Vertical bars indicate the extent of the 95% confidence interval for each measurement. The horizontal lines show the average of the calibration factors for each frequency.

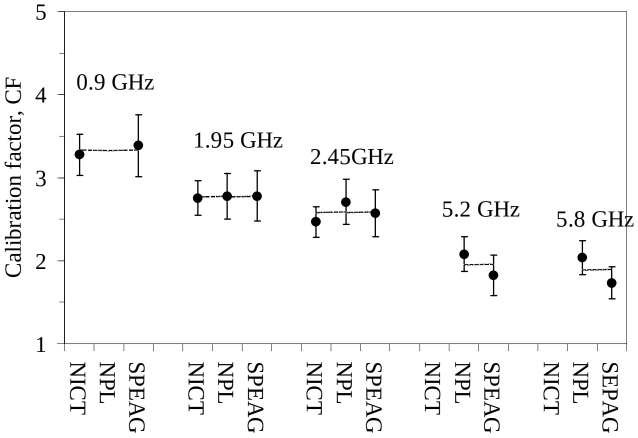

Fig 5. Calibration factor of Probe D, model EX3DV4, measured at NICT, NPL, and SPEAG in 2007. Vertical bars indicate the extent of the 95% confidence interval for each measurement. The horizontal lines show the average of the calibration factors for each frequency.

IV. CONCLUSIONS

Artefact standards for the calibration of electric field probes used to assess specific absorption rate in a liquid are based on matched waveguide cells, since these give low measurement uncertainties. The calibration factors obtained by three independent laboratories, NPL, NICT and SPEAG were compared for frequencies between 450 MHz and 5.8 GHz and for four SAR probes. In all cases, the unweighted mean of the calibration factors obtained by the three laboratories lie within the 95% confidence intervals quoted. Thus the calibration factors obtained by the three laboratories agree to within the measurement uncertainties quoted for the SAR probe calibrations. Future work is planned to extend the comparison to lower frequencies, and include additional laboratories.

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