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Reproducibility of Electrical Caries Measurements: A Technical Problem?

M.C.D.N.J.M. Huysmans[a] J. Kühnisch[c] J.J. ten Bosch[b]

[a]Department of Dentistry, Division of Cariology and Operative Dentistry and [b]Department of Biomedical Engineering, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands; [c]Department of Conservative Dentistry and Periodontology, School of Dentistry, Ludwig-Maximilians University of Munich, Munich, Germany

Key Words

Caries lesion detection · Electronic Caries Monitor · Electrical resistance measurement

Abstract

The currently available instrument for electrical detection of occlusal caries lesions [Electronic Caries Monitor (ECM)] uses a site-specific measurement with co-axial air drying. The reproducibility of this method has been reported to be fair to good. It was noticed that the measurement variation of this technique appeared to be non-random. It was the aim of this study to analyse how such a non-random reproducibility pattern arises and whether it could be observed for other operators and ECM models. Analysis of hypothetical measurement pairs showed that the pattern was related to measurements at the high and low end of the measurement range for the instrument. Data sets supplied by other researchers to a varying degree showed signs of a similar non-random pattern. These data sets were acquired at different locations, by different operators and using 3 different ECM models. The frequency distribution of measurements in all cases showed a single or double end-peaked distribution shape. It was concluded that the pattern was a general feature of the measurement method. It was tentatively attributed to several characteristics such as a high value censoring, insufficient probe contact and unpredictable probe contact. A different measurement technique, with an improved probe contact, appears to be advisable.

Electrical resistance measurement (ERM) is one of the techniques proposed for occlusal caries lesion detection. It depends on the permeability changes due to demineralisation of the tissues. Several instruments have been developed, but the current standard instrument is the Electronic Caries Monitor (ECM). The basic measurement technique is a measurement of the resistance at a site in the fissure, using a probe with a co-axial airflow in order to dry the tissue around the probe and to prevent current leakage. Many in vitro and in vivo studies have evaluated the diagnostic performance of the method [for a review, see Huysmans, 2000].

Reproducibility is an important parameter determining measurement quality. A measurement technique with poor reproducibility can never show good diagnostic performance. Reproducibility of ERM has been assessed in a number of studies and has been rated good to excellent [Verdonschot et al., 1992; Ekstrand et al., 1997; Ricketts et al., 1997]. The statistic most frequently used to describe reproducibility in such studies was Cohen's kappa. However, for this statistical analysis, the continuous measurement results are reduced to 2 (or sometimes 3) scores.

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Prof. Dr. M.C.D.N.J.M. Huysmans
Department of Dentistry and Dental Hygiene
Division of Cariology and Operative Dentistry, University of Groningen
A. Deusinglaan 1, NL–9713 AV Groningen (The Netherlands)
Tel. +31 50 3633203, Fax +31 50 3632696, E-Mail m.c.d.n.j.m.huysmans@med.rug.nl

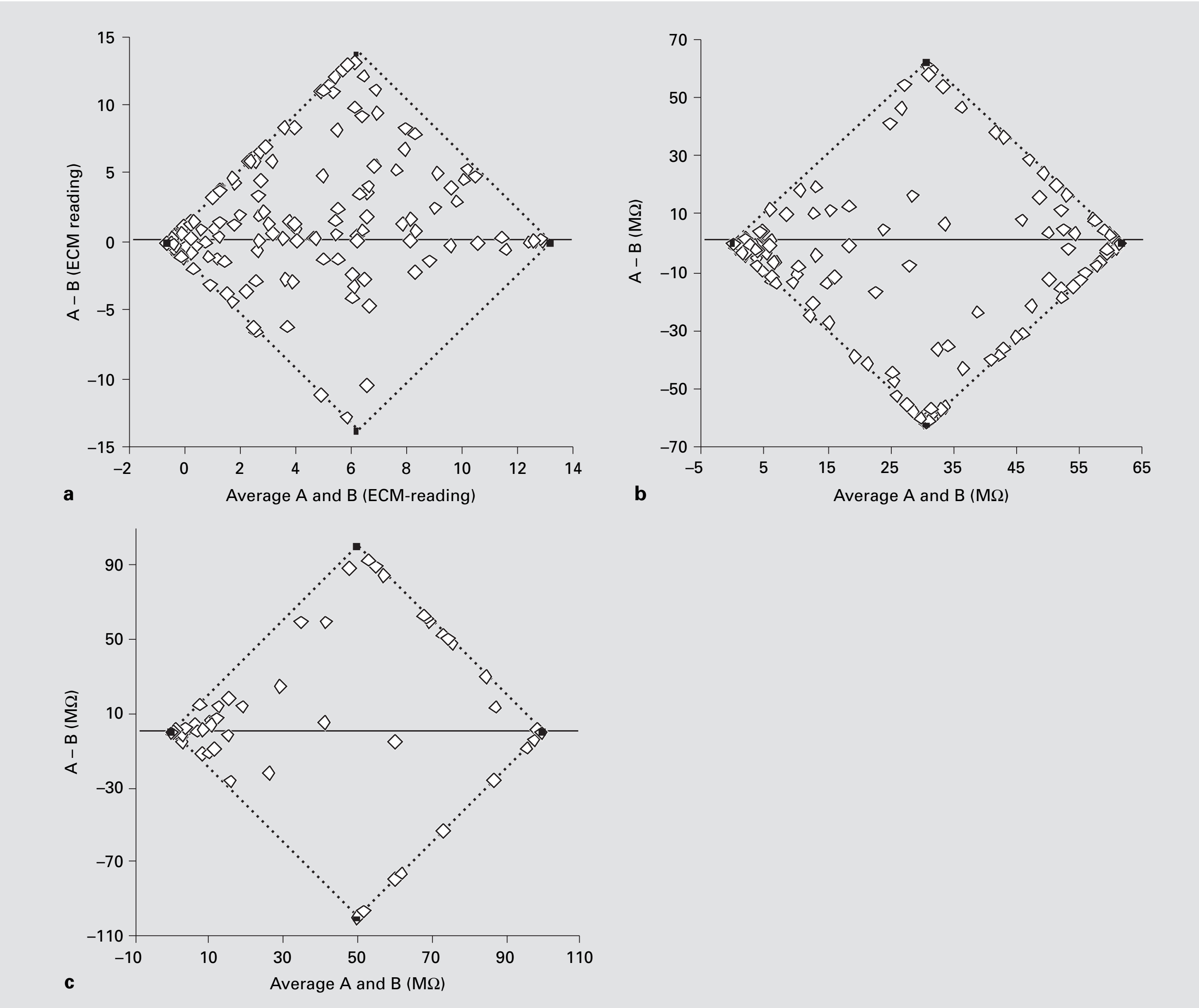

Fig. 1. B&A plots of ECM reproducibility results. Plotted are the differences between two measurements on the same tooth site against the mean of the two measurements. The dotted lines enclose the area of all possible data points. **a** Pereira et al. [2001]. Original ECM readings. **b** As **a**, but data transformed to resistance values. **c** Kühnisch et al. [submitted].

This is not really suitable for continuous data, nor is the calculation of correlation between repeated measurements, as this ignores systematic bias and may be unexpectedly inflated by measurements at the extremes of the scale. A suitable method for assessing the agreement between two sets of measurements is described by Bland and Altman [1986]. It evaluates the actual differences between paired measurements. The results are usually plotted as difference between two measurements as a function of the average of the two: the 'Bland and Altman' plot (B&A plot). This enables the researcher to evaluate whether there is a relationship between the value of the measurement and its reproducibility. Usually, one would expect a mean difference of about 0 (no systematic difference between measurements) and a random spread of positive and negative differences, with no correlation with the average measurement. Limits of agreement can then be calculated as mean difference ± 2 standard de-

Table 1. Overview of methodologies used in studies for included data sets, and the caries lesion depth distribution as confirmed by histological evaluation

	Pereira et al. [2001]	Ricketts et al. [1997]	Huysmans et al. [1998a]	Lussi [unpubl. data]	Kühnisch et al. [submitted]	Ellwood and Cortes [2004]
Operator	AP/MH	DR	CL/MH	AL	MT	DC
ECM model	II	II	II	III	III	IV
Storage solution	physiological saline	physiological saline	physiological saline	–	physiological saline	isotonic solution
Drying method	drying to stable end reading	drying to stable end reading	drying to stable end reading	5 s drying	drying to stable end reading	5 s drying
Airflow, l/min	7.5	7.5	7.5	7.5	7.5	5
Reading type/ measurement range	ECM reading/ –0.63 to 13.2	ECM reading/ 0–13.2	ECM reading/ –0.63 to 13.2	resistance/ 0–100 MΩ	resistance/ 0–100 MΩ	resistance/ 0 to >10 GΩ
In vitro/in vivo	in vitro	in vitro	in vitro	in vivo	in vitro	in vitro
Intra-/interexaminer	inter	intra	inter	intra	intra	intra
Number of sites	230	27	107	39	117	28
Time between measurements	not relevant	>1 week	not relevant	unknown	>1 week	>1 week
Histological lesion depth distrubution[1]				not available		
Sound	35%	36%	9%		11%	22%
Enamel caries	44%	33% (13% outer 1/2, 20% inner 1/2)	49% (22% outer 1/2, 27% inner 1/2)		40%	28% (12% outer 1/2, 16% inner 1/2) ADJ 25%
Dentine caries	21%	32%	41% (37% outer 1/2, 4% inner 1/2)		49% (31% outer 1/2, 18% inner 1/2)	25% (10% outer 1/3, 8% middle 1/3, 7% inner 1/3)

ADJ = Lesions reaching the amelo-dentinal junction.
[1] This distribution refers to the complete study sample. Reproducibility evaluation was sometimes performed on a random subsample, for which exact lesion depth distribution is not recorded.

viations. This method has been used in a few papers on ERM [Ricketts et al., 1997; Ekstrand et al., 1997].

The performance of site-specific ERM has been reported to be moderate, due to insufficient correlation with histological lesion depth and insufficient reproducibility [Huysmans, 2000]. In the course of its existence, 3 models of ECM have been used in dental research (II–IV). The types vary mostly in their display of the results (from ECM reading to resistance values) and in their options for measurement technique (volume of airflow, stable reading or reading after fixed drying time). No obvious improvement of diagnostic performance with newer ECM models has been observed.

When making a B&A plot of recent ERM data, the first author noticed a very special, obviously non-random pattern as illustrated in figure 1a. The data points seem to be arranged in a diamond shape, with a cluster of points at the left corner. When ECM readings were expressed as resistance values (fig. 1b, calculated according to Huysmans et al. [1995]), the diamond shape was still visible, now with clusters at the left and right corner. The second author confirmed the observation in one of his own studies (fig. 1c: example for one operator, but similar for other operators). It was decided to look at the non-random reproducibility pattern more closely.

It was the aim of this study to analyse how such a non-random B&A plot pattern arises and whether it could be observed for other operators and ECM models.

Materials and Methods

An analysis of hypothetical reproducibility data was performed to evaluate the cause of the diamond shape.

To evaluate whether the observation was limited to one operator and one ECM type, the authors approached those researchers who had a body of published research on site-specific use of the ECM. As the field is limited, this group consisted of 5 researchers. They were asked to provide one set of intra- or interexaminer re-

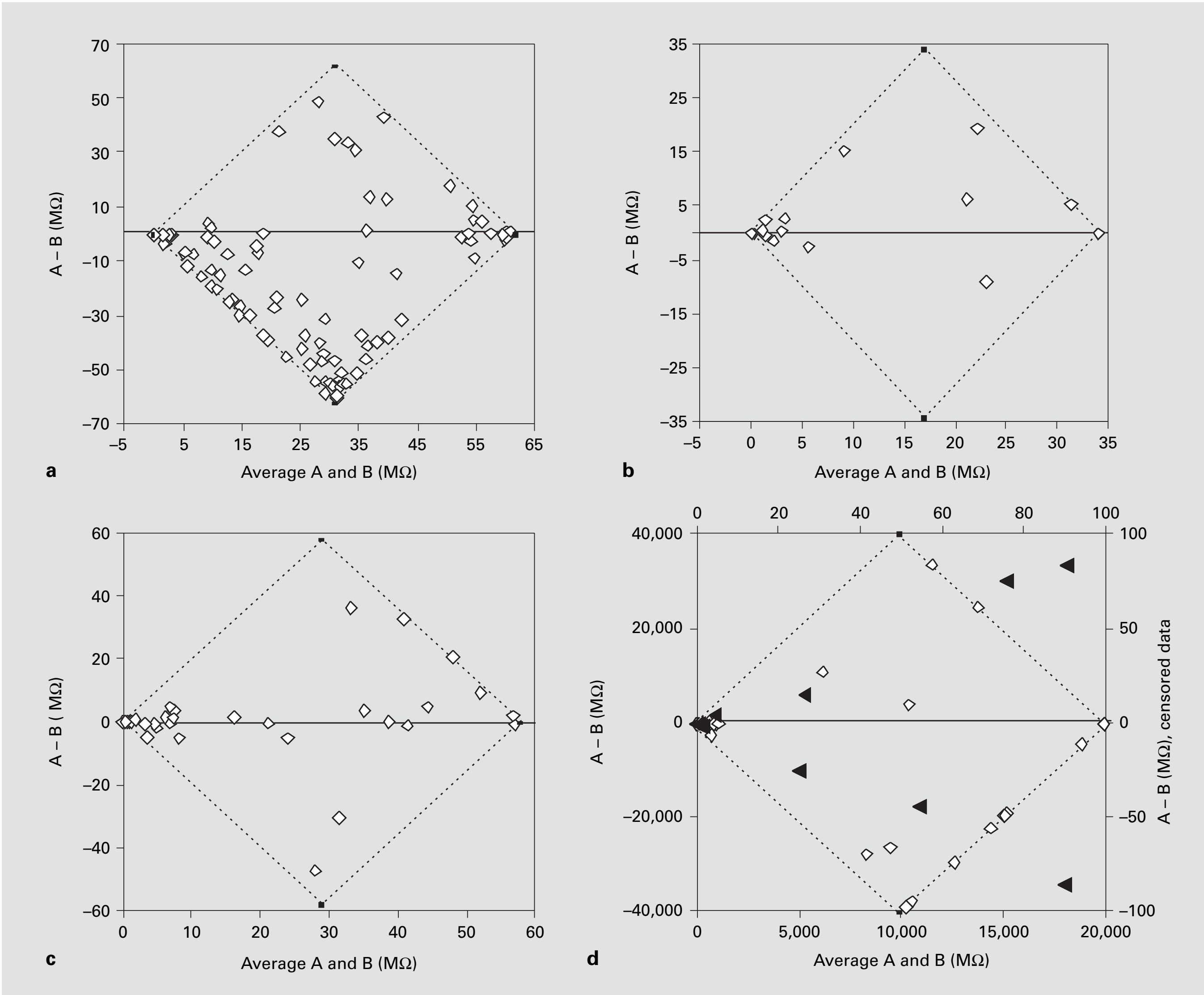

Fig. 2. B&A plot of ECM reproducibility results from different research groups. Where ECM readings were reported, these were transformed to resistance values. The dotted lines enclose the area of all possible data points where censored data are used. **a** Dundee, Scotland [Huysmans et al., 1998b]. **b** London, UK [Ricketts et al., 1997]. **c** Bern, Switzerland [A. Lussi, pers. commun.]. **d** Manchester, UK/Rio de Janeiro, Brazil [Ellwood and Cortes, 2004]. Black symbols show uncensored data, open symbols show data censored at 100 MΩ.

producibility data, randomly chosen from their own work. They were not informed in advance about the aim of the study, so as to avoid bias in data set selection. The received data sets were analysed for data frequency distribution and B&A plot non-random patterns. Limits of agreement were not calculated as the reproducibility values as such were not of relevance to this study.

Four researchers supplied data sets, of which 3 originated from previously published studies. In order to be able to compare the methodologies and ECM models used, relevant details are given in table 1, including those for the data sets shown in figure 1.

Results

Analysis of the hypothetical data showed that the non-random pattern could be related to the range and distribution of the measurements. The regularity of the plot depends on 2 features. The left and right corners of the diamond shape on the 0 line represent perfect agreement of extreme measurements: measurement pairs of minimum and minimum or maximum and maximum. Data points at the top and bottom corners of the diamond represent disagreement of extreme measurements: minimum and maximum. All the data points along the sides of the diamond represent measurement pairs where one measurement is an extreme and the other is some value in between the extremes. The area enclosed by the lines connecting the diamond corners thus covers the entire range of possible measurement combinations, for a method with a limited measurement range.

For ECM models II and III, such limited measurement ranges can be observed. The ECM II calculates from the measured resistance values a reading between –0.63 and ~13.2 (some researchers reduce the low end further to 0, including all readings <0). These readings correspond to resistance values of about 62 MΩ and 50 kΩ, respectively. That means that resistances higher than 62 MΩ are censored and set down to 62 MΩ/–0.63 ECM reading and resistances lower than 50 kΩ are set up to 50 kΩ. Thus, if resistances outside the measurement range occur, they will all receive the same output value, resulting in a clustering of measurements at the ends of the range. The ECM III records resistance values between 0 and 100 MΩ, thus showing only censoring at the high resistance end. The ECM IV has no relevant high-end censoring and recorded resistance is almost infinite (gigaohm range). For the instruments used in this paper, the measurement range was used to calculate the 'diamond edges' and these are shown with dotted lines in figures 1 and 2.

The B&A plots for the data sets supplied by other researchers are shown in figure 2. For easier comparison, the data for those studies where the ECM reading scale was used were turned into resistance values. The non-random pattern can be observed clearly in figure 2a and, albeit vaguely, in figure 2b and c. Figure 2d illustrates the effect of censoring data at the high resistance end. The scale of the ECM IV as it was used in figure 2d was not censored. The resulting B&A plot shows only half a diamond shape (black symbols in figure 2d). The complete diamond appeared when the data were censored (by the authors) at 100 MΩ as for the ECM III (open symbols in figure 2d).

The frequency distribution of measurement 1 of each data set used in figures 1 and 2 is shown in figure 3. It can be observed that in all cases there is a clustering of data points at one or both ends of the frequency distribution. The effect of censoring at the high resistance end can be seen in figure 3g and h, where censoring reduces the peak at the low resistance end, but creates a new peak at the high resistance end.

Discussion

The relationship of the non-random pattern of the reproducibility data was shown to depend on two features: high frequency of extreme measurements and also the tendency for measurement pairs to include one (or even two different) extreme measurement. This last feature appears to be a little more common at the high resistance end (fig. 2). Such a concentration of measurements at the ends of the range could be a genuine feature of the study sample, reflecting a higher frequency of completely sound and deeply carious sites. However, this is not supported by the histology data in table 1. Although two studies do show a relatively high proportion of sound sites, which could result in high resistance end peaks [Pereira et al., 2001; Ricketts et al., 1997], this does not explain the peak at the low resistance end. Other studies show a fairly even distribution of histological lesion depths. The frequency distributions in figure 3 do not match these even distributions, which is in accordance with the observation that ERMs do not correlate well with histological lesion depth.

It is interesting to note that in successive ECM models, the range of possible resistance outcomes was extended upwards: from ~60 MΩ for the ECM II, to 100 MΩ for the ECM III, to more than 30 GΩ for the ECM IV. It seems likely that this was done because such high resistance values were being measured. However, it must be seriously doubted whether measurements of even 10 MΩ and higher are at all relevant and have a meaningful relationship with the tissue resistance. In the surface-specific method of ERM, where a conducting gel is used in the occlusal fissure system, the maximum observed resistance is ~2.5 MΩ [Huysmans et al., 1998a]. More likely, therefore, the extremely high resistance measurements in site-specific ERM reflect a failure to establish a good contact between the probe and the tooth.

The clustering at the low end of the scale was partly caused by censoring in the ECM II, with the reading scale, which ended at 13 (lowest resistance ~50 kΩ). In later models with a measurement scale starting at 0 kΩ, the clustering could still be seen (fig. 3d, f and h) and may also be related to the complete extent of the measurement scale. When the total measurement scale is large, these low values are all clustered together.

The above considerations would imply that if the measurement technique was changed so that a better probe contact was possible, measured resistances would probably be lower and the frequency distribution of measured resistance values more evenly distributed. It can be spec-

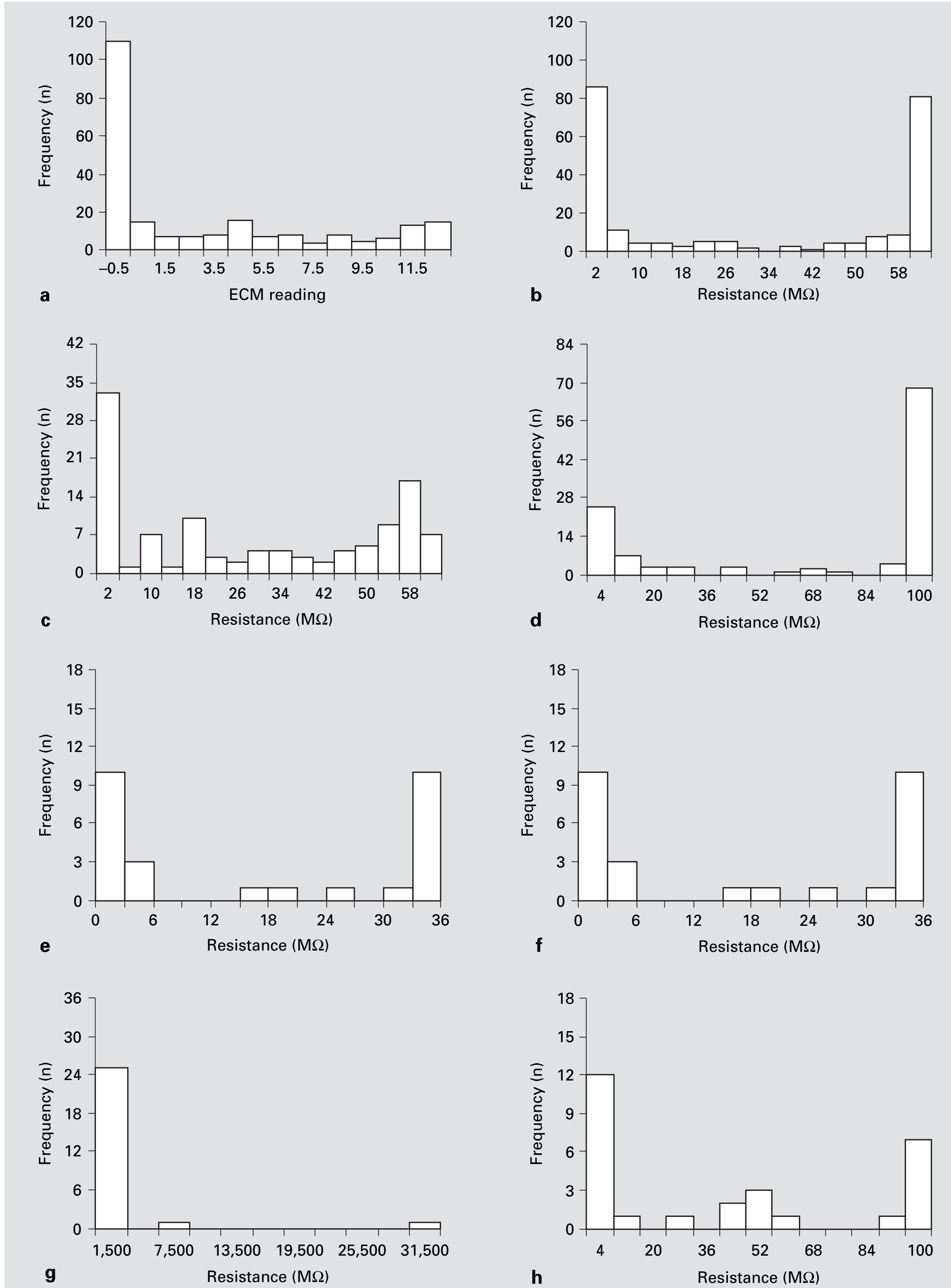

Fig. 3. Frequency distribution of the first measurement of each data set as used in figures 1 and 2. **a** Pereira et al. [2001]. Original ECM readings. **b** Pereira et al. [2001]. ECM readings transformed to resistance values. **c** Huysmans et al. [1998b]. ECM readings transformed to resistance values. **d** Kühnisch et al. [submitted]. **e** Ricketts et al. [1997]. ECM readings transformed to resistance values. **f** A. Lussi [pers. commun.]. **g** Ellwood and Cortes [2004]: uncensored data. **h** Ellwood and Cortes [2004]: data censored by authors at 100 MΩ.

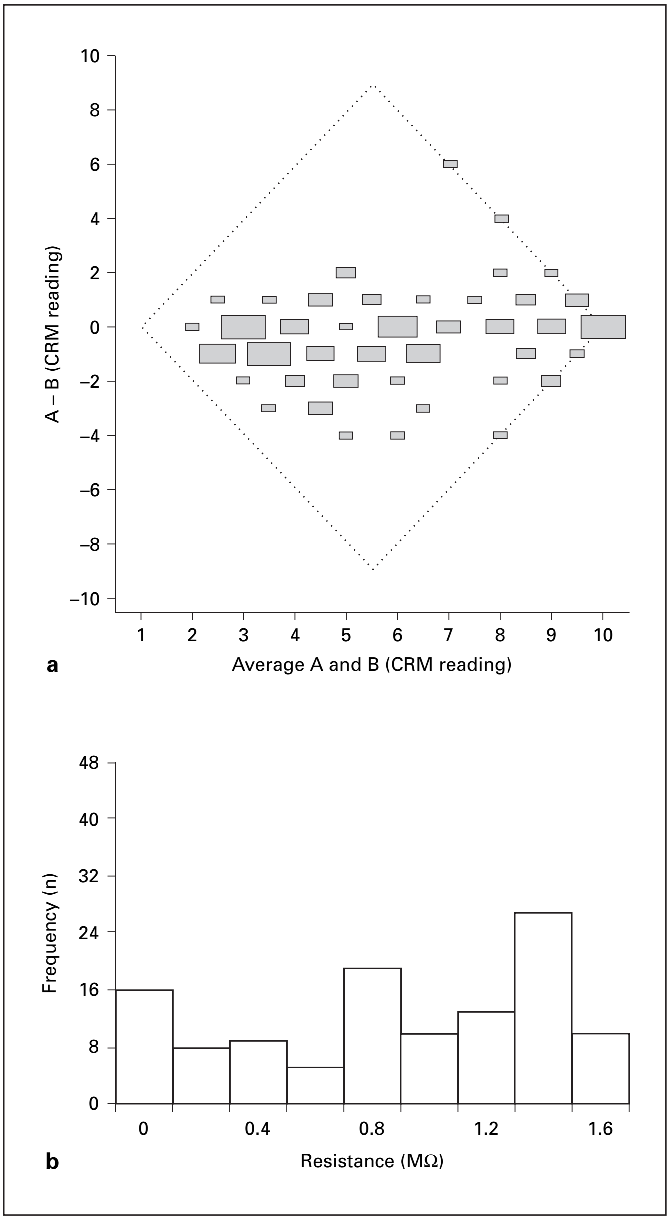

Fig. 4. Reproducibility of ERMs using a Cariometer 800 prototype, from a recent study [Kühnisch et al., submitted]. **a** B&A plot. As the output of this instrument is ordinal [1 (high resistance) to 10 (low resistance)], the plot is modified and the size of the symbols indicates the number of data pairs at that position. **b** Frequency distribution of the first measurement of the data set.

ulated that this would improve diagnostic performance, as far as correlation of measurements with caries lesion depth is concerned.

The most undesirable characteristic of the data presented here can be found in the cause of the vertical points and the sides of the diamond. Obviously, it is not uncommon that different extremes occur in repeated measurements. A combination of one extreme and one non-extreme measurement appeared to occur mainly for high resistance extremes. This has also been the subjective experience of authors of this paper: it appears to depend very much on the manner of making probe contact, whether a 'sound' (high resistance) or a 'lesion' measurement is made. Again, this points in the direction of a failing probe contact.

How could the probe-tooth contact be improved? The surface-specific method described above could be suitable, but it has an important drawback. As the whole occlusal surface is measured at once, it is impossible to detect the site of deepest lesion extension. Another instrument for ERM has been described, but is only available as a prototype at the moment: the Cariometer 800 (CRM prototype, University of Marburg, Germany) [Schulte and Pieper, 1997]. It uses very brief air drying and scans the fissure with a capillary probe with saline, has a measurement scale in the clinically relevant range (0–2 MΩ) and it appears to yield fewer extreme results while still being site-specific (fig. 4) [Kühnisch et al., submitted]. Improvement of this method could be envisaged in a probe that deposits a standardised amount of conducting fluid or gel at every measurement site.

In conclusion, ERMs with the ECM with the technique using co-axial airflow show a non-random pattern of measurement variation. It was related to the frequency distribution of resistance measurements, showing low and high end clustering. The pattern was found in data from different observers, using different ECM models and varying measurement techniques. Several factors appear to be contributing to the measurement distribution and reproducibility pattern: high value censoring, insufficient probe contact and unpredictable probe contact.

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