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ORIGINAL

Detecting the presence of red heart in beech (*Fagus sylvatica*) using electrical voltage and resistance measurements

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Abstract Red heart is one of the most important visual defects in beech wood. Its detection is difficult, since its mechanical characteristics do not differ significantly from sound wood. However, its electric conductivity is different, which offers an opportunity for detecting beech red heart. Initial measurements using a 24-channel impedance tomograph were very efficient in detecting red heart due to its significantly lower electric resistance. High conductivity regions on the resistance map corresponded to the size and shape of the red heart. An 8-detector setup was investigated in a laboratory setting to establish the best electrode arrangement to develop a simple and reliable on-site detection method. On-site measurements, using only four electrodes, proved to be highly reliable to detect the presence of red heart in beech trees of 40–60 cm diameter. In the meantime, the method did not seem capable of determining the extent of red heart. The diameter of the tree was found to have very little effect on the measured voltage. Therefore, there is no need for diameter-correction in the examined diameter range.

1 Introduction

Beech wood is economically very important in many countries in Europe, including Hungary (Molnar and Bariska 2002). One of the most frequent visual defects of beech is red heart (also called false heart). It is an abnormal formation, associated with the death of the living cells, and a discoloration of their contents (Panshin and DeZeuw 1980). It is almost ubiquitous in older trees at felling age, but often affects younger specimens too. Healthy red heartwood is mostly considered a visual defect only, but, since beech is most often used in the furniture industry and interior design, red heart causes a major decrease in the perceived value, and leads to a serious drop in the retail price of beech wood (Molnar et al. 2001; Hapla and Ohnesorge 2005).

There are several forms of red heart, all of which occur in beech wood. According to the characterisation by Sachsse (1991), they can be classified as red heartwood with round borders and a partly cloudy appearance on the cross-section, wounded heartwood with a small spatial extent, splashing heartwood (or dotty red heart) with jagged borders, and abnormal heartwood with black borders attacked by bacteria. In either case, the borders of red heart do not follow the annual ring boundaries. Figure 1 shows the first type, immediately after felling. In terms of its longitudinal expansion, it is most often spindle-like, but it may also be cone or upside-down cone shaped, or irregular. Red heart can also be classified as healthy or diseased, based on whether or not it has been attacked by fungi, and, as a result, they suffered some strength loss (Rumpf and Biro 2003; Wernsdörfer et al. 2005).

Beech red heart has generated considerable research interest over the past decades. Wernsdörfer et al. (2005) provided a very detailed overview of the work done up to that point. Knoke (2002) provided a thorough review of the publications on heartwood formation, and concluded that reducing the amount of discolored timber is possible only based on information about the recent formation of red heartwood. He lamented the fact that non-destructive methods are not yet far enough advanced to provide information on early heartwood formation.

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Fig. 1 Cross section of a beech trunk containing sound red heart after felling

The biggest hurdle to the nondestructive detection of red heart is that healthy red heart—unlike other internal diseases—does not affect the mechanical characteristics of wood (Panshin and DeZeuw 1980). For this reason, vibration-based methods are ineffective in detecting healthy red heart. On the other hand, red heart beech's electrical conductivity is markedly different from that of unaffected wood.

Researchers began employing electric conductivity/resistivity for testing wood as early as in the 1970s (Skutt et al. 1972). Shigo and Shigo (1974) constructed an instrument to detect discoloration in living trees and utility poles, and conducted very comprehensive research. Although the method was successful, the measurement was relatively invasive and tedious, and thus did not become popular.

More recently, electrical impedance tomography, which was originally developed for material testing, geophysics and medicine, became popular for testing standing trees. Since the first experiments by Just and Jacobs (1998), there have been several applications of this technique, for example, to detect decay (Dubbel et al. 1999; Bieker and Rust 2010a), red heartwood in beech (Weihs et al. 1999; Hanskötter 2004) and in wild service tree (Weihs 2001), and brown heartwood or the early stages of white rot in ash (Weihs et al. 2005; Bieker et al. 2010, respectively). It can also be used to determine the exact sapwood area in various species (Bieker and Rust 2010b; Lin et al. 2012).

Rust and Göcke (2007) combined electrical impedance tomography and sonic tomography to create the PiCUS Treetonic system. Their method provided even more detailed information, and allowed a better differentiation of various internal defects, as confirmed by subsequent studies (e.g. Brazee et al. 2011). Another interesting variation of the impedance tomography theme is a study by Martin (2009) using complex resistivity measurements (i.e. using a range of different AC frequencies to measure resistivity on the same specimen), with similarly good efficiency to detect fungal decay in living trees.

The capacity of electrical impedance tomography to provide valuable detailed information about internal decay and discoloration has been demonstrated in numerous studies. There are, however, certain drawbacks of this technique: it requires many sensors and sophisticated electrical circuitry, and the measurement takes a long time to set up and carry out. This makes the measurement tedious and expensive.

Researchers also use electrical conductivity measurements to detect decay in standing trees using only four electrodes (Larsson et al. 2004). The sensors are distributed along the length of the tree. Taking advantage of the decreased resistivity of decayed wood, they could detect root decay in Norway spruce with high precision, although the authors remark that many environmental factors affect the measurements, and its reliability depends on comparison to sound trees subjected to the same conditions. The Rotfinder® instrument was developed by Swedish and Danish researchers based on this principle and is mostly used to detect decay in coniferous wood (Romeralo 2010).

Some ambiguity exists in literature as to how the different types of red heart differ in moisture content and electrical conductivity. Büren's (2002) results show that the electrical conductivity of red heart beech is about four times higher than that of sapwood and about twice as high as uncolored heartwood. Unfortunately, other works are less conclusive. Weihs (2001) used impedance tomography, but only to detect abnormal (diseased) heartwood. More recently, Hanskötter (2004) concluded that only a special type of red heart (so called 'wet heart' or Nasskern in German) may be detected.

The goal of the present study was to develop a new, practical method that can be used to detect the presence and determine the extent of red heart in standing trees, based on the difference of conductivity between unaffected (henceforth called 'white') and red heart beech wood in Hungary. After verifying the applicability of traditional impedance tomography to Hungarian beech material, laboratory experiments were conducted to establish the best measurement setup to be used on site. The applicability of the new method was verified through on-site testing.

2 Materials and methods

The investigations included the following three experiments:

- Using impedance tomography to verify the applicability of electric conductivity measurements in Hungarian beech trees,
- Laboratory studies on white and red heart beech samples, using eight sensors, to find the electrode setup most suitable for on-site measurements,
- On-site testing using a 4-sensor setup.

Detailed description of each of the experiments is provided below:

2.1 Impedance tomography measurements

To verify the applicability of electrical conductivity measurements, electrical impedance tomography was used. The Picus Treetronic electrical impedance tomograph (Argus Electronic GmbH) was developed based on methods used for soil and medical investigations. It can be used to gain a high-resolution electrical conductivity map of the tree's cross-section.

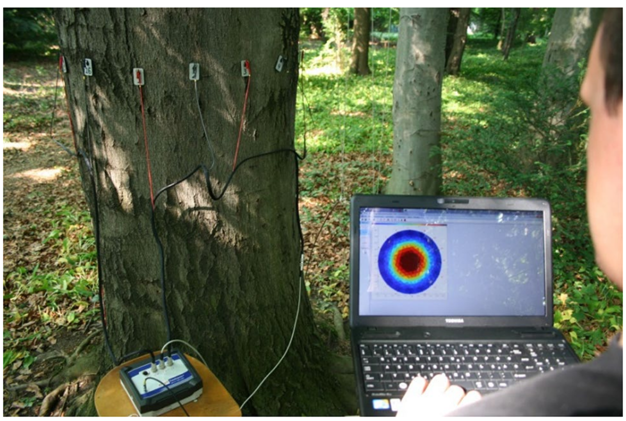

Fig. 2 Impedance tomographic measurement of a live tree

The tomograph introduces an electrical current through two metal electrodes, while it measures the voltage on two other electrodes. This measurement is repeated in a certain number of combinations. The device supports a maximum of 24 sensors, which is the number used in the current tests to provide the most detailed resistance map. In this case, the device takes a total of 253 measurements, which takes about 5 min. Figure 2 shows the impedance tomographic measurement.

Tomographic measurements were carried out during the winter felling period. A total of 30 trees, marked for felling, were examined, so that tomographic results could be compared to the actual cross sections in short order. Measurements were taken between 1 and 1.8 m above ground. The examined specimens showed much variation including small and thin, tall and large diameter, and even forked trees.

2.2 Laboratory resistivity tests

In this investigation, the position of the sensors on the tree trunk was modeled on two beech discs, 40 cm in diameter. One of the discs contained red heart, while the other did not. 8 sensors, used for sending and receiving signals, were driven into the discs around their perimeter (Fig. 3). Simple, commercially available 40 × 2 mm metal nails were used as sensors, and were driven into the discs approximately 15 mm deep (at least 5 mm penetration into the xylem). An EMG 1257 Type TR-0473 function generator was used as a power source. The applied voltage and frequency were 3 V and 4 kHz, respectively.

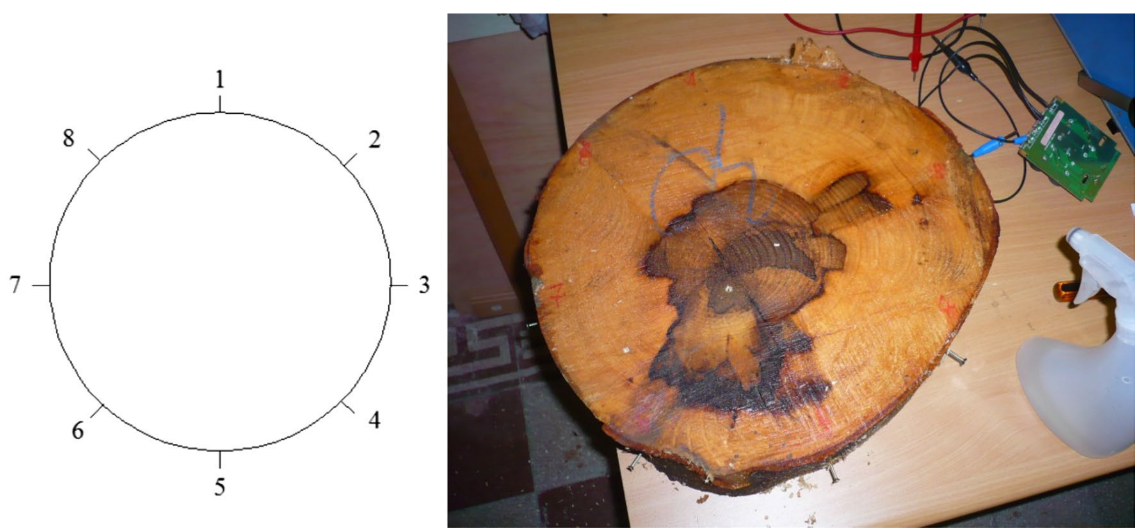

Fig. 3 Location of the eight electrodes along the circumference of a beech disc

The measurement included stimulating the sensor pairs 1–2, 1–3, 1–4, 1–5, 1–6, 1–7 and 1–8 in turn, and, in each case, measuring the voltage using all of the remaining sensor combinations. A total of 27 measurements were taken for each sensor pair, on both discs. After completing the measurement, the ratio of the voltages measured on the white discs to that measured on red heart discs (U_w/U_{rh}) was calculated for all of the combinations. The higher the ratio, the more reliably the given electrode combination can be used to detect red heart. These results were used to develop a simplified method to be used on site.

2.3 On-site measurements

A handheld tool was developed for the on-site measurements, based on the above laboratory tests. The device consists of a 9 V power source, a switch, a standard 3.5 mm jack socket, four metal electrodes (60×2 mm metal nails), a UniVolt DT 890 type voltage meter and a quartz crystal oscillator that provided a 100 Hz AC signal. Figure 4 shows a schematic of the measurement. Electrode locations were determined based on the laboratory measurements. This is a much simpler, faster, and therefore more practical measurement than the currently available methods. Measurements were taken at a height of 1 m, stimulating the 1–2 and the 2–3 electrode pairs in turn, and measuring voltage on the remaining two electrodes in both cases.

Two sets of measurements were taken in the Sopron forests (Hungary). In the first series, 50 trees, approximately 100 years of age, were examined. The diameter of the trees varied between 35 and 75 cm. The tested specimens were selected randomly in the forest plot. After completing the measurements, three specimens were chosen, and increment cores were taken to verify the presence or absence of red heart.

In the second measurement series, 40 trees marked for felling were examined to establish the smallest detectable red heart area by comparing the voltage results to the actual red heart area on the cross section. The examined trees included all forms of red heart, as well as a certain number of unaffected trees.

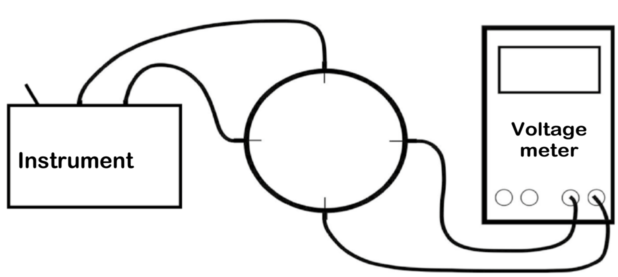

Fig. 4 Schematic of the handheld instrument used for on-site measurements

3 Results and discussion

3.1 Impedance tomography tests

The resistance maps shown in Fig. 5 demonstrate the excellent capabilities of impedance tomography to detect red heart. Dry, low conductivity white material is lighter, while darker areas indicate the higher conductivity red heart material.

Figure 5 shows a close correspondence between the tomograms and the cross-sectional photographs (a white line marks the boundaries of red heart on the latter.) Impedance maps show red heart's resistivity to be a mere third of that of white wood. The exact location within the trunk is also clearly marked by the darker shades. Due to this significant difference, and also to the high resolution of the instrument, the impedance tomograph is capable of detecting not only the presence, but also the size and position within the cross section. On the other hand, it is rather expensive, and setting up and executing the measurement is time-consuming. Therefore, its practical application is limited.

3.2 Laboratory resistance tests

After measuring the voltage values, the combination where the largest difference occurred between white and red heart material was found for each stimulated electrode pair. Table 1 shows the combination with the highest measured U_w/U_{rh} values for each of the stimulated electrode pairs.

According to Table 1, the largest difference of all emerged when stimulating the electrode pair 1–7. In this case, the voltage measured between electrodes 3 and 5 on the red heart disc was only one-fifth of that measured on the unaffected material. This means that it is the best setup for the on-site measurements (i.e. electrodes installed in an orthogonal arrangement, stimulating the material and taking measurements on opposing adjacent electrode pairs). For the analogous 1–3 electrode pair, the most marked voltage difference was, again, found when measuring between sensors 5 and 7. In this case, the difference was less marked, but still very significant. Based on these results, this electrode arrangement was found most expedient and was used for the on-site measurements.

3.3 On-site measurements

In the first measurement series, several results showed strong indication for the presence of red heart. In two cases,

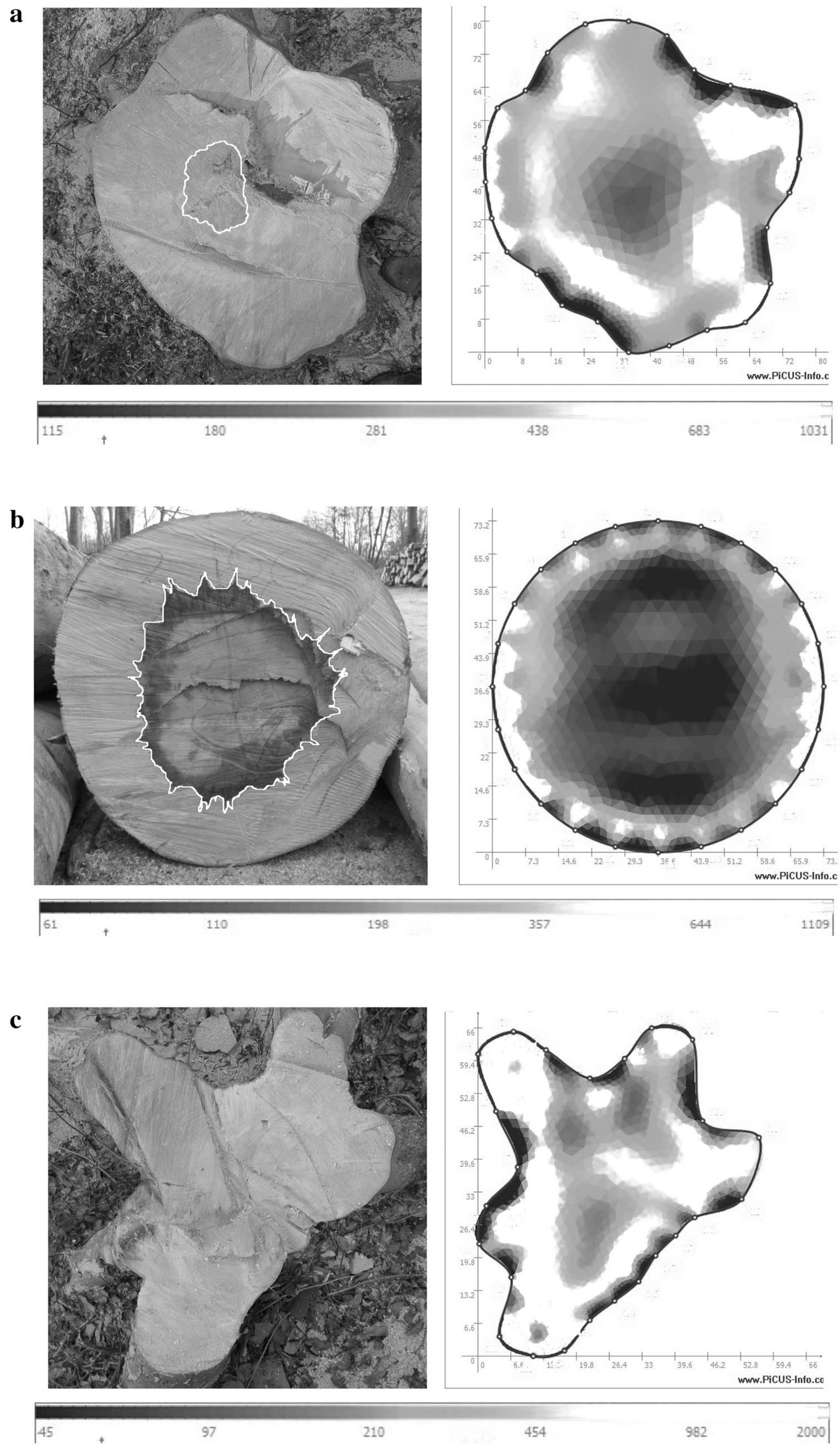

Fig. 5 Photographs vs. impedance tomographic images of beech tree cross sections: **a** small red-heart, **b** large red heart, **c** no red heart

Table 1 Ratio of voltage values measured on white and red heart beech discs (combinations resulting in the most marked differences)

EP_{stim} [a]	EP_{max} [b]	U_w/U_{rh}
1–2	4–8	3.12
1–3	**5–7**	**3.25**
1–4	3–7	3.42
1–5	2–8	1.91
1–6	2–7	3.75
1–7	**3–5**	**4.90**
1–8	2–7	3.30

[a] Stimulated electrode pair

[b] Electrode pair where the greatest difference was found between white and red heart material

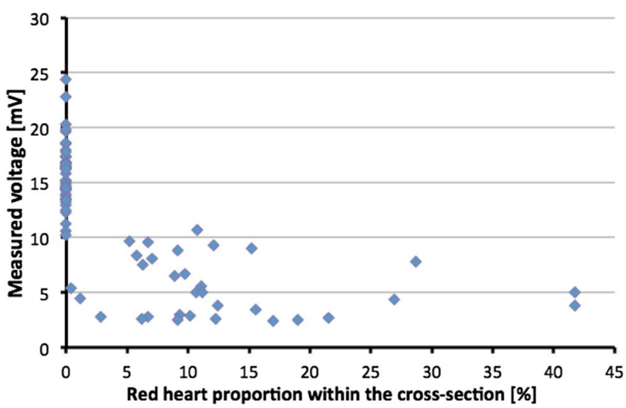

Fig. 6 Relationship between the proportion of red heart in the cross section and the measured voltage values

the voltages were similar to those measured in the laboratory tests. Increment cores were taken from these two trees, as well as from a third tree as control. In all three cases, the predictions were proven correct. The increment cores of the two trees expected to contain red heart were indeed affected. In the third specimen, which was assumed to be white based on the measured voltage values, no red heart was found. While taking localized core samples is not a 100% reliable way of establishing the presence of red heart, this is a good indication of the usefulness of the method.

Subsequent measurements were taken immediately before cutting. After felling, the proportion of red heart was recorded on the cross section. Figure 6 shows the relationship between the proportion of red heart and the measured voltage. There were many forked trees in the examined area, which was a strong indicator of red heart.

Two important conclusions can be drawn from Fig. 6:

- The voltage values can predict the presence of red heart very reliably in the examined diameter range. There was only one case where red heart was found above 10 mV of measured voltage, while below this value, some red heart was always present. The method correctly identified the presence or absence of red heart in 87 of 88 cases. Seven data points (including the one erroneous reading) were very close to the threshold value of 10 mV (in the ±1 mV range). Arguably, these data points represent an area of uncertainty, but even so, the presence or absence of red heart can be predicted with more than 90% confidence.
- Even very small red heart (<5% of the cross section) was reliably predicted. The reason for this may be that, according to practical experience, red heart tends to be more extensively higher up in the stem (e.g. at 1 m height, where electrical conductivity was measured.)
- In the trees that did contain red heart, there was almost no relationship between the measured voltage and the proportion of red heart, except that above 6 mV, and above 8 mV red heart was always below 30 and 15%, respectively. On the other hand, in many cases there was very little red heart found even when the measured voltage was very low (2–3 mV).

The above conclusions imply that the simplified measurement method described in this article is capable of detecting the presence or absence of red heart with a high degree of certainty, but it provides no reliable information about the extent of red heart. These results contradict the earlier findings by Hanskötter (2004), who concluded that only certain types of red heart ('wet heart') are detectable by impedance tomography. The reason for this is unclear. It is possible that wet heart is typical in Hungarian forests, and this is why these measurements were so exceptionally successful.

Measured voltage values depend on the diameter of the tree as well. The higher the diameter, the lower the measured values and vice versa. Based on the results measured on unaffected trees, the typical voltage values corresponding to 40 and 60 cm diameter are 15–20 and 12–17 mV, respectively. Figure 7 shows a very weak relationship between the circumference and the voltage values, with a very significant spread.

The weak negative correlation implies that tree diameter does influence the measurement, but only to a very small extent. In addition, large diameter specimens, where voltage values tend to be somewhat lower, are also more likely to contain red heart. In the examined diameter range, the measurement seems to be reliable enough without diameter correction.

Temperature and seasonality affect the moisture content of trees, and, as a consequence, the electrical conductivity as well. All of the measurements described in the article were taken in the winter felling period, so the threshold value mentioned above is valid in the winter only. Further

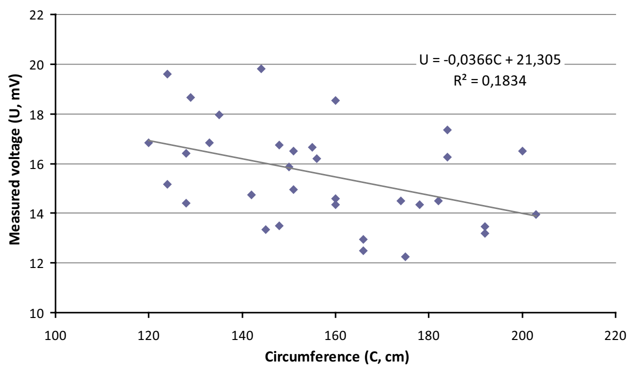

Fig. 7 Dependence of the measured voltage on the diameter in unaffected beech trees

measurements are needed to establish the applicability of the method in other seasons.

4 Conclusion

The experiments were directed at the nondestructive detection of beech red heart based on its electrical conductivity. Based on these results, the following is concluded:

1. Low resistivity areas seen on the cross-sectional impedance maps taken during preliminary impedance tomography measurements correlate well with the red heart seen after felling. There is a marked difference in conductivity, which indicates that resistance measurements have a good potential for detecting red heart.
2. Based on 8-electrode laboratory measurements, it was established that a 4-sensor arrangement, where electrodes are installed in an orthogonal arrangement, is a simple and powerful setup for detecting red heart. When a significant amount of red heart is present, measured voltage values drop to 1/3 to 1/5 of that measured on unaffected wood, when two adjacent electrodes are stimulated, and voltage is measured on the other two.
3. The new measurement setup was capable of detecting the presence of red heart very reliably in the winter felling period in Hungary. In the meantime, no close relationship was found between the extent of red heart and the measured voltage. This implies that this simple setup, while capable of detecting red heart, cannot reliably establish its extent.
4. The weak negative correlation between the measured voltage and the tree diameter does not significantly affect the measurement. The reliability of the test does not depend on the diameter in the examined range (40–60 cm), and there is no need for diameter correction.

The above results show that the method developed is reliable for detecting red heart in the winter, at least in Hungarian forests. Further research, using measurements closer to the ground, or several measurements along the length of the tree trunk, may refine the above conclusions and help in the further development of the new method.

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