Taylor & Francis
Taylor & Francis Group

Arboricultural Journal
The International Journal of Urban Forestry

ISSN: 0307-1375 (Print) 2168-1074 (Online) Journal homepage: http://www.tandfonline.com/loi/tarb20

Intact-decay transitions in profiles of density-calibratable resistance drilling devices using long thin needles

Frank Rinn

To cite this article: Frank Rinn (2016): Intact-decay transitions in profiles of density-calibratable resistance drilling devices using long thin needles, Arboricultural Journal, DOI: 10.1080/03071375.2016.1228336

To link to this article: http://dx.doi.org/10.1080/03071375.2016.1228336

Arboricultural Journal, 2016
http://dx.doi.org/10.1080/03071375.2016.1228336

Taylor & Francis
Taylor & Francis Group

Intact-decay transitions in profiles of density-calibratable resistance drilling devices using long thin needles

Frank Rinn*

In 1986, two German universities started developing resistance drilling for tree-ring analysis in a joint physics–botany project. In order to differentiate between early wood and late wood zones of tree-rings, the system had to provide a minimum spatial (>10 points per mm) and signal (>10 Bit) resolution combined with a high (preferably linear) correlation to wood density ($r^2 > 0.8$). The same conditions have to be fulfilled when decay in trees and timber should be identified reliably because the stages of decomposition by fungal decay are largely characterised and differentiated by the corresponding loss in density. Experiences from thousands of drillings in trees since 1986 suggest that the profile trend in the transition zone from intact to decayed wood seems to indicate the speed of radial extension of the decomposition. For a few of the various types of resistance drills used on the market, a sufficient resolution and precision in combination with a high correlation to wood density was already shown. Consequently, these device types deliver correspondingly reliable profiles enabling experts to estimate trends in future radial increments as well as in radial spread of decay.

Keywords: resistance drilling; wood decay; decay extension rate; resolution; precision; density correlation

Introduction

When significant decay is detected in mature urban trees, pruning, cabling or other action is often recommended in order to make the tree safer again. Depending on age and vitality of the tree and the amount of decay, the question arises if the investment in mitigation action is worth spending in terms of the expected remaining lifetime of the tree. In order to answer this question, it is necessary not only to take into account site conditions, tree age, shoot growth and other aspects of vitality, but also to know whether the tree is able to compartmentalise the decay and to build up sufficient compensatory radial increments.

Static load tests (as scientifically described by Nielsen, 1990) and sonic (stress wave) tomography, patented by Rinn (1999), provide similar values on loss of load carrying capacity due to decay (Figure 1) but give no information on future development of the strength loss (due to deterioration and compensatory increment growth).

Increment coring was largely used in the past for evaluating decay in trees but identification and efficiency of compartmentalisation is difficult to determine this way. One of the reasons for this is that intensity of discolouration is commonly not proportional to the degree of decomposition (Råberg, 2006). In addition, densified lines around decayed areas, interpreted as a special kind of barrier zone (Eckstein & Saß, 1994) may

---

*Email: frank.rinn@rinntech.com, www.rinntech.com

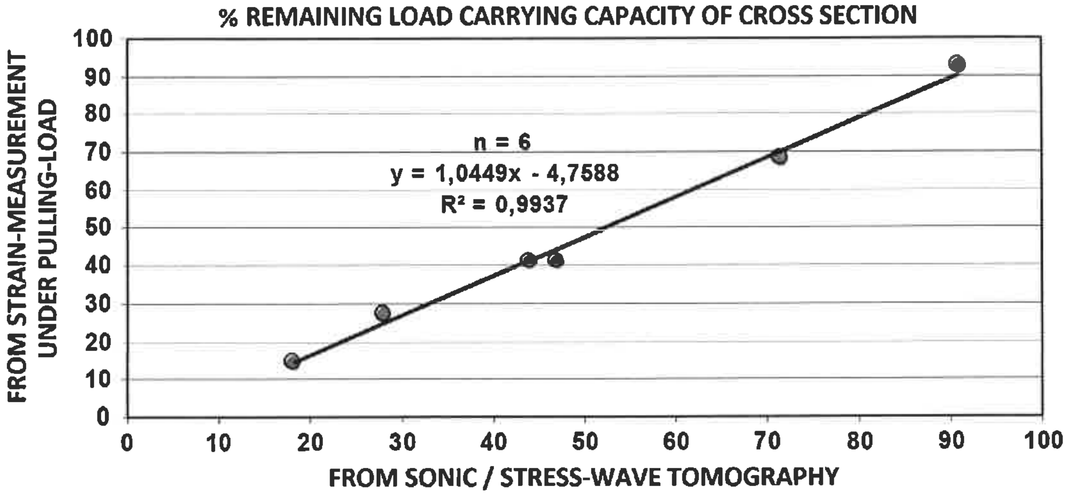

Figure 1. Using calculations by L. Wessolly, Lesnino compared remaining load-carrying capacity of defected cross-sections as estimated by pull-tests and sonic tomography (Lesnino, 2009) and found a surprisingly high correlation when compiling the results of six measured trees.

not be indicated by discolouration (Figure 2) and thus can only be detected by technical measurements of density. In addition, in decayed areas it is often difficult to get out cores with sufficient quality for microscopy. Furthermore, many arborists avoid increment coring because of the potential damage to the tree by the auguring (Norton, 1998).

Consequently, it is interesting to know whether resistance drilling, the most frequently used diagnostic technology in urban tree risk assessment, is able to provide information helping experts to predict decay spread and radial (compensatory) increment growth rates.

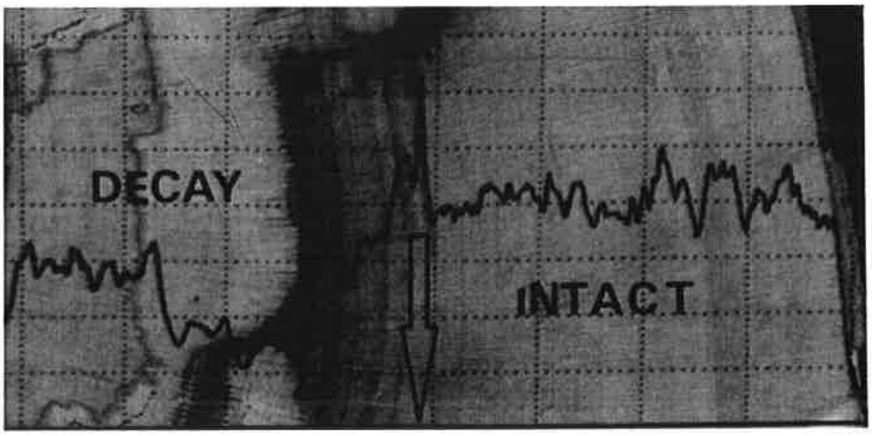

Figure 2. Profile of a resistance drilling with a real RESISTOGRAPH® in *Platanus* (*acerifolia*), showing bark on the right, then intact sapwood and white rot decay in the centre part. The abscissa axis equals the path of the drilling needle. Approx. 1 cm outside the decayed area, the peak (*) indicates an extremely high density. Eckstein and Saß (1994) analysed the wood in such peak areas and found that the lumen of the cells were plugged by suberines and phenols, leading to a significant higher density and building a special kind of barrier zone. As visible by the profile shown here, the colour of wood in the area of the peak was not altered, thus this special kind of barrier zone cannot be detected visually.

Method

The original concepts of most resistance drilling devices currently used on the market for inspecting trees and timber were developed in the 1980s in Germany. Capabilities and limitations of this method in arboriculture can only be verified when knowing the basic principles of this technique. These principles can best be understood when reviewing the historical development of this method from the early ideas to the proof of exactness and reliability.

In the 1970s, German company WESERHÜTTE AG worked on a method for improving the penetration of preservatives into the wood of utility poles by pushing in thin needles. The engineer in charge (T. Kipp) realised that some needles break, while others penetrate easily and concluded that the penetration resistance could probably show wood quality. Timber inspection methods using pin penetration were already used in the 1960s and 1970s (further details see www.resistograph.com). For example, in 1967, HILTI applied for a patent later realised in the so-called PYLODYN (Fink, 1971). These methods delivered one value per penetration, representing a measure for the average density. Paulitsch and Mehlhorn (1973) presented a machine driving a conventional drill bit into particleboards, delivering a penetration resistance profile by measuring torque, highly correlated to wood density. At WESERHÜTTE, Kipp and colleagues intended to use thin pointed needles in order to create a profile along the drilling path. Unfortunately, the company had no interest in developing such a device. When two leading engineers (Kamm and Voss) of WESERHÜTTE retired, the board allowed them to apply for a patent on the idea of timber inspection based on needle penetration resistance.

Kamm and Voss started with an electric motor driving a thin needle into wood. A spring-loaded recording mechanism created a penetration resistance profile in 1:1 scale by moving a scratch pin (attached to the gearbox between motor and needle) over a sheet of pressure sensitive wax paper in the device. Despite years of developmental work, unavoidable properties of mechanical spring-loaded recording made it systematically impossible to evaluate wood conditions correctly and reliably: spring resonance effects caused fluctuations in the profiles, not correlated to real wood condition (Figure 3). Damping such misleading resonance effects by adding counter springs induces plateau effects in the profiles making it even worse (Figure 4). Misinterpretations of profiles with significant consequences, such as unnecessary felling of trees or unnecessary replacements of utility poles or beams in timber structures had been inevitable when using such kinds of mechanically (spring-driven) recording resistance drilling.

Kamm and Voss realised why scientists and experts did not accept such resistance drills because of these systematic errors (due to the spring-loaded recording) and that it would be irresponsible to market such a device (knowing about systematically incorrect results and having no scientific proof of accuracy and reliability). In addition, selling such devices would have exposed experts to the risk of being held responsible for consequences of incorrect decisions regarding tree or timber safety due to inaccurate profiles. Although Kamm and Voss did not understand the main reason behind these problems (a missing clear correlation between the recorded profiles and the wood density along the drilling path), they adopted an approach from Japan which proved to be appropriate.

The two engineers abandoned spring-loaded mechanical recording and developed an electrically recording resistance drill by encountering the power consumption of the motor via loudspeaker in the power cord. In the corresponding patent of 1985,

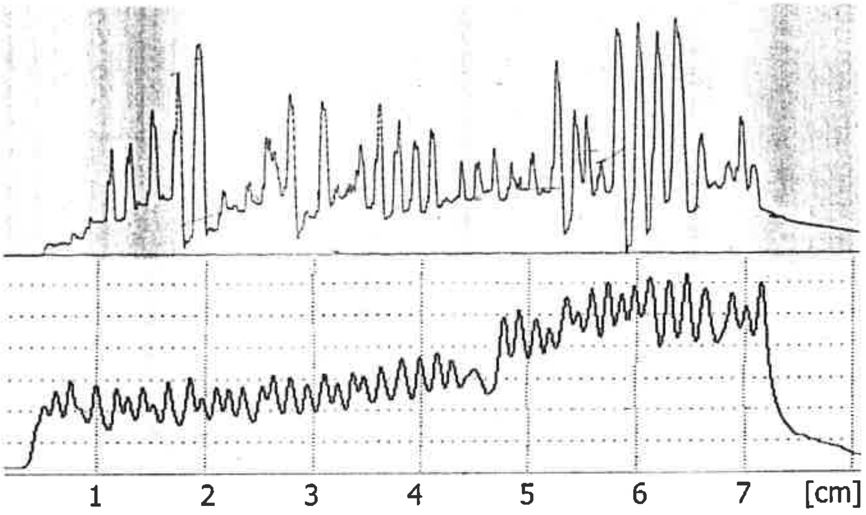

Figure 3. Profiles of two resistance drillings obtained at the same position of an intact (dry) conifer wood sample. The bottom profile was measured by a "real" RESISTOGRAPH®, clearly revealing the density of the intact structure. The top profile was measured by a drill with a mechanical recording mechanism similar to the original prototypes abandoned by Kamm and Voss (1985): as a consequence of unavoidable spring-resonances in the recording mechanism, it drops down to zero several times suggesting local defects (by fungal decay or insects) although the wood is totally intact. Such profiles cannot show real wood condition and thus inhibit a correct interpretation and evaluation. This and all subsequent measurement profiles show drilling depth on the abscissa and drilling resistance on the ordinate axis (while the relatively scaled "drilling resistance" is proportional to density of the penetrated wood along the path of penetration).

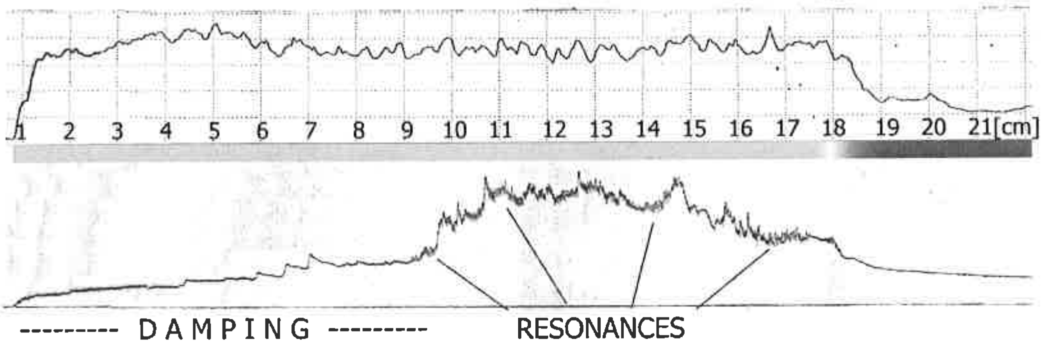

Figure 4. When drilling soft diffuse porous species, such as *Tilia cordata*, the difference between the real density profile and mechanically recorded resistance drills (as used by Kamm and Voss until 1985), is obvious. The top profile, which came from an electronically regulating and recording drill, clearly and reliably reveals the intact structure of the outer wood (marked green) to the point where the profile begins to drop in density (yellow) into the decayed area (red). The bottom profile shows both plateau and resonance effects, typical for spring-driven mechanically recording drilling devices (as used by Kamm and Voss until 1985). In the outer section, this mechanically recorded profile stays on the same low level as the profile does in the central part (with totally rotten wood). Consequently, it is inherently impossible to interpret such profiles correctly. Incorrect identification of sapwood decay has frequently led to trees being felled or topped, even though the wood was intact, only soft.

Kamm and Voss stated (about previous ideas with mechanical recording): "results obtained with this method are quite inaccurate and allow only a rough conjecture about the internal condition of the tested sample". German company FEIN of Stuttgart was interested in buying the KAMM-VOSS-patent application but, due to the lack of proof, asked the tree-ring lab of Hohenheim University for a test of usefulness. In cooperation with the Environmental Physics Institute of Heidelberg University, the Kamm-Voss-idea was scientifically checked, starting in 1986. The original goal of the scientists was to develop a resistance recording drill delivering information on latewood density of oak tree-rings (Rinn, 1988). This goal-setting is the major key for understanding this method up to today.

In 1987, FEIN transformed the first RINN-laboratory-prototype into an electrically recording mobile resistance drill (Figure 5). These devices were named "DENSITOMAT" by Rinn and sold to scientists and experts worldwide for an independent neutral check of reliability. 1988, Görlacher determined a linear correlation coefficient of $r > 0.9$ between DENSITOMAT profiles and the average gross density of dry timber (Görlacher & Hättich, 1990), showing the method's potential for wood quality analysis as well as for decay detection (Rinn, 1993, 1994). However, the technical resolution of these drills was not sufficient for assessing intra-annual density profiles of narrow tree-rings (Rinn, Becker, & Kromer, 1990). Consequently, these machines were limited in detecting incipient decay, fine cracks or ring-checks (Rinn, Schweingruber, & Schär, 1996; Rinn, 2015a), too. How important this is, becomes clear when understanding the impact of incipient decay in trees.

Figure 5. Frank Rinn using the first kind of mobile resistance drills ("DENSITOMAT") for tree-ring analysis of a *Metasequoia glyptostroboides* in Heidelberg Botanical Garden (1987). Providing constant supply voltage, the power consumption of the drill was electrically measured, recorded and plotted on paper in 1:1 scale.

How density and decay influence strength

Density is one of the most important material properties of wood because many other properties, such as strength and stiffness, depend on density (FPS, 1987). In addition, decomposition of wood due to fungal decay is mostly described by weight-loss of the material, equalling changes in density (Means, Cromack, & MacMillan, 1985). How important it is to assess density precisely and reliably becomes clear when realising that 10% loss in density due to (incipient) decay can result in more than 80% loss of wood strength (Wilcox, 1978).

Unfortunately, strength values of wood can be measured directly only by loading until failure (FPS, 1987). As this is not practicable for tree risk assessment or timber inspection, non- or semi-destructive measurements are usually carried out and strength or load-carrying capacity is estimated from the test results. This estimation is commonly based on correlations. Quality and precision of such a correlation is usually characterised by the coefficient of determination (r^2). For linear cases, $r^2 = 1$ means a perfect correlation, $r^2 \sim 0.5$ poor and 0 indicates no correlation.

In order to be able to determine late wood zones of tree-rings, special electronics and new needles were developed for resistance drilling (Rinn, 1990) providing a high spatial and signal resolution (Rinn et al., 1996) and finally resulting in a correlation with $r^2 > 0.9$ between the profiles and wood density (even for green timber in standing trees as shown for real RESISTOGRAPH®-devices by Brashaw, 2013). Fortunately, for tree-risk inspection, this achievement at the same time enables the user to identify incipient decay by relatively small changes in the intra-annual density fluctuations (Rinn, 2015b). That means, this combination of high resolution with high correlation to wood density is the most important property a resistance drill has to fulfil in order to provide the information required for a reliable evaluation of wood condition as part of tree-risk assessments. Because this became fairly clear early on in the development of the method, these conditions, namely precision, resolution and correlation to wood density were declared as prerequisites to be fulfilled by a resistance drill before applying for a licence on the internationally registered trademark IR#646811 (“RESISTOGRAPH®”) in order to differentiate these from other types of resistance drills.

The original drill label “DENSITOMAT” was not protected by a trademark registration and became misused by competitors. As a consequence, the name “RESISTOGRAPH” was coined and registered as a trademark (WIPO, 1993) for exclusively labelling resistance drills that provide high-resolution profiles with high correlation to wood density (because this is required for differentiating between tree-ring density structures and between intact and decayed wood). That means, all resistance drills (as listed on www.resistograph.com) legally marked with this trademark RESISTOGRAPH® provide a certain level of correlation to wood density and resolution, as required for a correspondingly accurate and reliable interpretation.

The importance of accurate representations of wood density becomes clearer when realising that identification of decay in resistance drilling profiles is commonly done by comparing with profiles from intact wood (Rinn, 2015b). In addition to the technical properties of the drill (electronic regulation and recording, high-resolution), this requires a basic understanding of the species-specific typical (radial) density profiles (Rinn, 2013).

Consequently, wood density is the key parameter for this method in many different ways (wood anatomically, biomechanically and technically):

- Density influences many other wood material properties (such as strength).
- Even slight alterations in density due to decay can result in significant strength loss – consequently, resistance drills have to be able to measure density very precisely and in high resolution to be able to recognise such small but potentially dangerous density changes.
- The spatial and signal resolution of the measured radial resistance drilling profile need to be sufficiently high (>8 Bit and at least 10 points per mm) for identifying even narrow tree-rings by changes in density.
- The correlation of the measured value to density has to provide a significant precision and reliability ($r^2 > 0.8$, better $r^2 > 0.9$) because only then can the profiles be interpreted correctly and reliably.
- Species-specific typical radial density profiles need to be known and understood before applying resistance drilling on trees and timber. This is the base for being able to interpret the profiles correctly and to differentiate between intact and decayed sections.

Transitions

When the tip of the drilling needle provides the required shape (Figure 6) for high spatial resolution and the device guarantees a high electronical signal resolution (Rinn, 2012a, 2015b), the profiles clearly reflect the local changes in density along the drilling path (Rinn, 1994). As soon as there is decay with a (locally) lower density, the profile shows smaller intra-annual fluctuations and subsequently a lower average level (Rinn et al., 1996). This means, the higher the spatial and signal resolution of the drilling device, the better and more precise even slight changes in density due to decomposition by fungi can be detected.

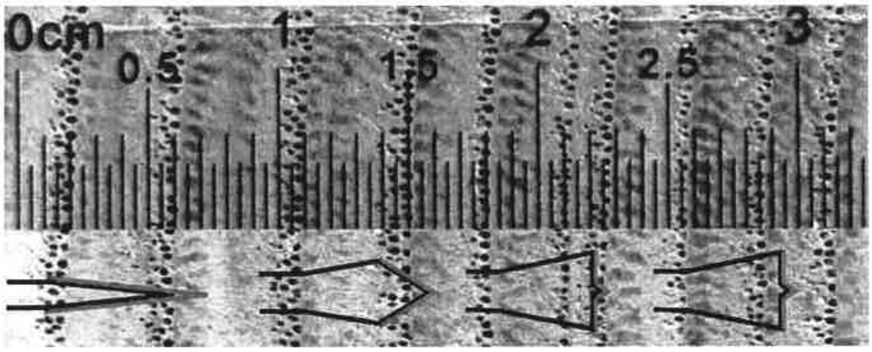

Figure 6. The original needle used for pole inspection by Kipp, Kamm and Voss in 1980 was pointed and ~1 mm in diameter (left). The version of 1985 changed in tip geometry (shaft 1.5 mm, tip 2.5 mm) for getting higher resolution (and better correlation to wood density). For achieving maximum possible spatial resolution and highest possible correlation to wood density, a flat tip geometry was later introduced (tip ~3 mm, shaft 1.5 mm; Rinn, 1990). The red lines indicate the area of maximum penetration resistance while drilling (measured as motor power consumption). The shorter the extension of the red line in drilling direction, the higher the spatial resolution of the profile in this dimension and thus the smaller rings and cracks/defects can be detected (Rinn, 2015c).

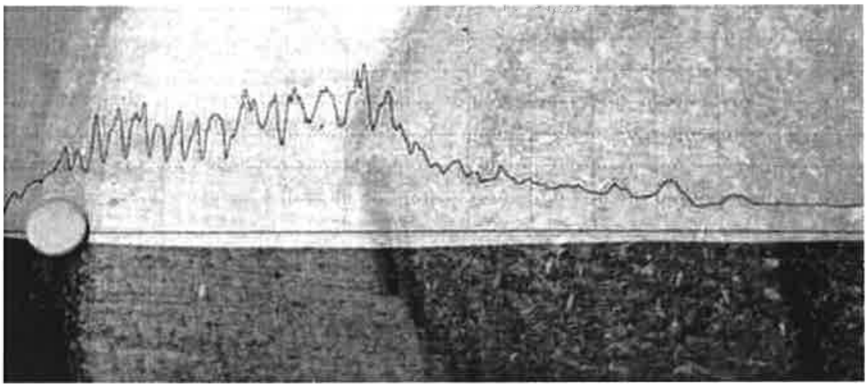

Figure 7. In this profile (*Sophora japonica*), the drilling resistance drops down step-by-step from intact into the decayed area. Due to the loss in density caused by the fungus, this kind of slow transition indicates the presence of wood in many different stages of decomposition, starting with early stages of (incipient) decay (leading to a correspondingly small change in density) and ending in an area with nearly no drilling resistance in a completely destroyed wood structure. By experience, such kinds of profile transitions were correlated to a comparatively fast future radial extension of the decay.

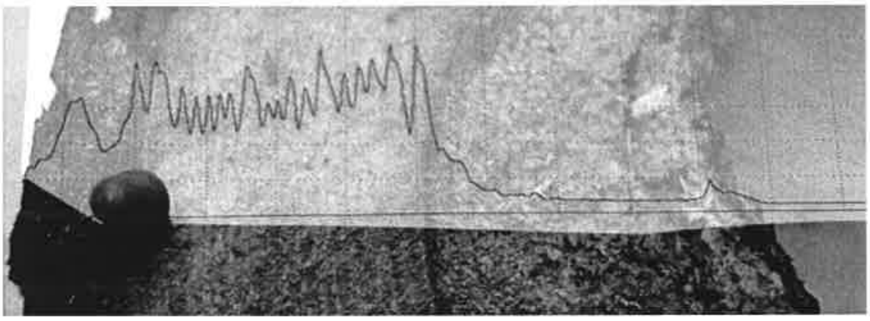

Figure 8. This resistance drilling profile (*Sophora japonica*) first shows the bark followed by the soft secondary phloem, then rises up and clearly reveals the tree-rings by density changes from early wood to late wood zones. After a few centimetres, the profile drops down with a steep slope clearly reflecting a sharp drop in density due to advanced (white-rot) decay. This means that there are not many different stages of decomposition. By experience, this seems to indicate a relatively slow radial extension rate of the fungal decay.

Because the species of the wood, the type of fungal decay and the stage of decomposition all influence density, the transition of the resistance profile from intact to decay can vary strongly (Means et al., 1985). Aside from all the species- and fungi-specific properties, the way that the profiles change from intact to decay have some common aspects and allow for similar conclusions (Figures 7–9).

When the drilling profile drops down slowly step-by-step from high resistance in intact wood to a much lower level of resistance in decayed wood, this indicates the presence of many different stages of decomposition (Figure 7). Through experience with the thousands of resistance drillings since 1986, this kind of slope from intact into decayed sections correlates to a significant radial extension of the decay (Figure 12), by often about 1–2 cm annually. In contrast, when the profile drops down straight from high resistance in intact wood to a much lower level of resistance in decayed wood, this usually correlates to a slow radial extension or even a steady situation as commonly

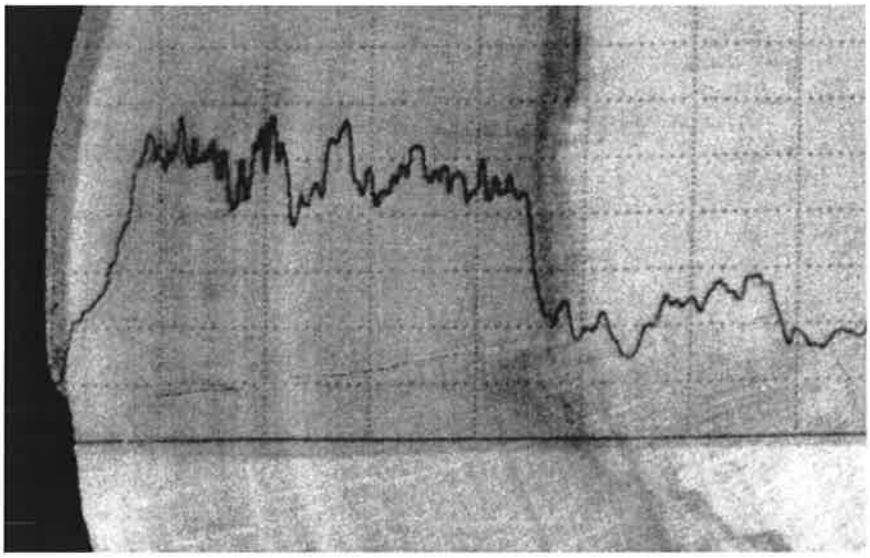

Figure 9. This profile (of a measurement in *Platanus x acerifolia*) shows a straight drop of the drilling resistance values from the intact tree-ring structure down into the area with strongly decayed wood – without any intermediate stages of decomposition. As a result of many observations, this seems to indicate that the compartmentalisation successfully stopped the fungal decay from spreading further radially (at this time and at this point).

described by "compartmentalized decay" (Figure 9). However, as long as there is no scientific proof published confirming these findings in detail for many tree and fungi species, they are just a plausible explanation of the many observations in practical application of high-resolution resistance drills since 1986.

In this context, it is important to know, that more than 10 kinds of resistance drills from at least 5 manufacturers are used on the market and that these drills differ widely in resolution and precision (Dolwin, 2001; Rinn, 2012b; Seaby, 1990; UK Patent 1990). When the same sample is drilled with different kinds of resistance drills, it becomes obvious that the information provided may not be the same and can even lead to contradictory conclusions (Figure 3, 4, 10, and 11). For very few drill types, a high (linear) correlation to wood density ($r^2 > 0.8$) and sufficient spatial and signal resolution (required for a correct representation of the transition from intact to decayed areas in wood) have been proven (Brashaw, 2013; Görlacher & Hättich, 1990; Rinn et al., 1996).

Practical consequences

Before purchasing and using a resistance-drilling machine without knowing about proof of sufficient accuracy, reproducibility and reliability, the manufacturer should be asked to supply the corresponding data and documents. Such proofs of exactness and reliability are not only mandatorily required for scientific applications but for safety-related inspections by experts, too, as clearly described in national and international standards, such as ISO/IEC 17025, ISO 5725, US-ANSI/NCSL Z540–2-1997 and German DIN 1319. The German Standard for technical tree inspection (FLL, 2013) clearly specifies these requirements for all technical tree-diagnostic equipment and lists the conditions to be fulfilled by resistance drills, too. The major condition is a sufficient resolution and a

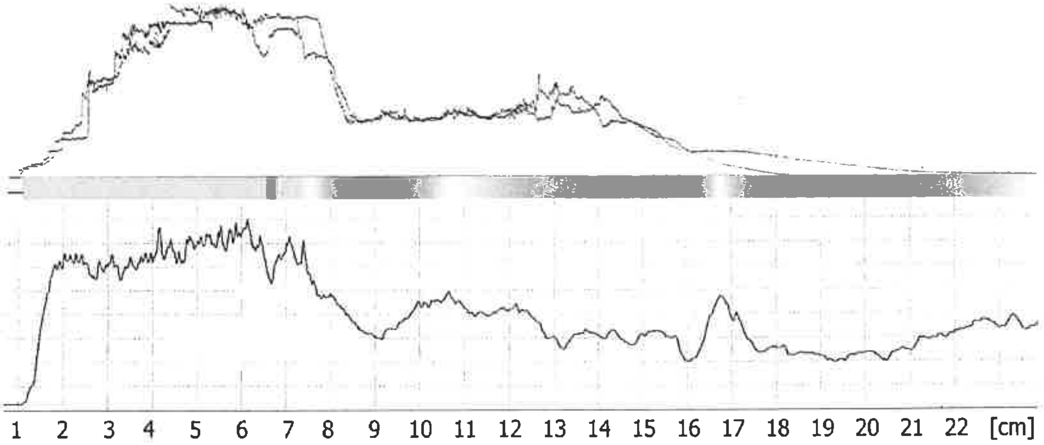

Figure 10. Comparison of resistance drilling profiles by mechanical recording (similar to the Kamm and Voss-drill of 1985) with an electronically recorded measurement, all made in the same transect of a partially decayed sample. The electronically recorded profile (bottom) can be used as a reference because it correctly represents density based on high resolution and high correlation ($r^2 > 0.8$). This profile transition from intact to decay clearly indicates a significant extension rate of the decay. The two mechanically recorded profiles (top) indicate the opposite of the real situation: the sharp drop from intact to decay suggest the presence of a good compartmentalisation. This confirms that the profiles of these resistance drills (using mechanically spring-driven recording) are systematically incorrect and thus do not allow a correct interpretation of wood condition (like Kamm and Voss already published in 1985). In this case, the real situation is the opposite of what seems obvious in the spring-driven mechanically recorded profiles.

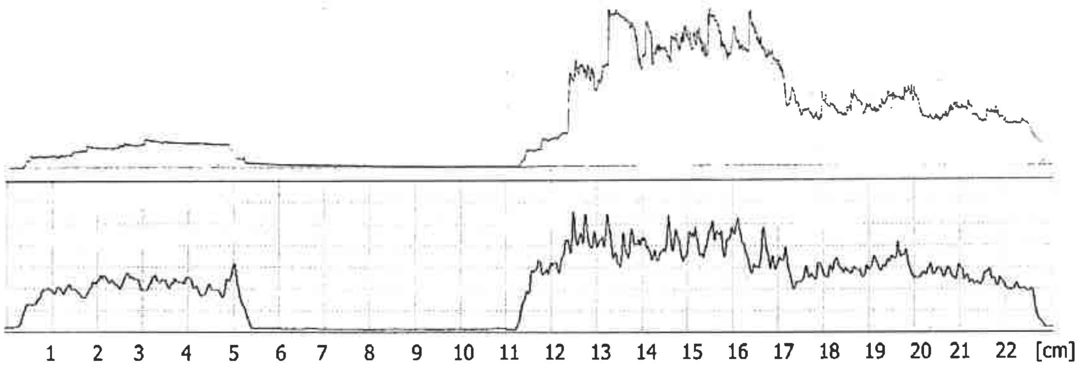

Figure 11. Confirming the findings described in Figure 10, this comparison visualises how strong the profiles of a mechanically recording resistance drill can differ from the real wood condition as represented by the electronically recorded measurement with high resolution and high correlation to wood density. In the outer section of this sample, the electronically recorded profile (bottom) clearly reveals the intact tree-ring structure. The mechanically recorded profile (top) suggests the opposite. Because of such systematically wrong profiles, Kamm and Voss abandoned the spring-driven mechanically recording principle and stepped to electric recording in 1985. They decided that it was irresponsible to sell such devices while knowing about the systematically erroneous results.

clear correlation between the resistance drilling profile and the wood density because a technical diagnostic system makes sense only when it is clear what the results mean. This is one of the main consequences of the standards mentioned above: any material

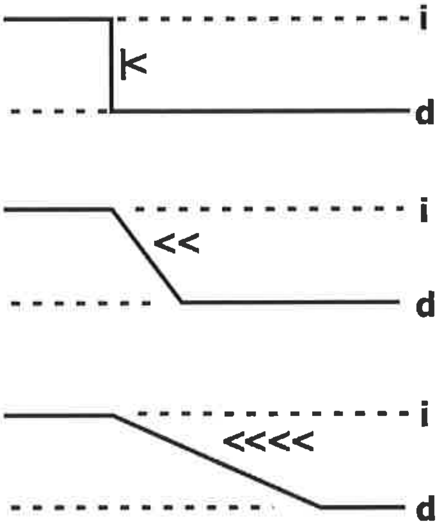

Figure 12. Observations from radial resistance drillings in decayed trees since 1986 suggest that the slope of the profile from intact (level "i") to decay (level "d") indicates the future radial extension rate of the decay: efficient compartmentalisation is represented by a steep step ("|<"). The less inclined the transition, the more different stages of decay are present and the faster (<<<<) the radial extension rate of the decomposition. It has to be taken into account that this "connection" between the profile slope and decay extension rate can only exist when the profile represents wood density along the needle's path correctly. This requires a high resolution and high correlation of the recorded value to wood density $r^2 > 0.8$ as proven for real RESISTOGRAPH® devices and impossible for the spring-driven mechanical recording drills used by Kamm and Voss until 1985.

testing device has to provide information about what the measured values mean in terms of material properties, how precise and how reproducible they are.

In some way, the profiles of all resistance drills reveal aspects of "wood condition" in a more or less clear way. But, the term "wood condition" is not a defined material property and can have largely different meanings. Comparing profiles of different kinds of resistance drills obtained at the same spot of wood makes clear that such measurement results can look quite different, suggesting even contradictory interpretations about wood condition that may lead to opposite evaluations of the corresponding tree or timber (see Figures 4, 10, and 11). Consequently, it is critical to have a clear set of standards: there has to be a definite description (provided by the manufacturer/distributor) about what the measured value or profile means and what material property is revealed – including information on precision and resolution. By following the standards, a material testing system should not be used if this information is not provided, especially not for safety-related inspections.

Correlating drilling resistance to wood density proved to provide a reliable connection to a clearly defined wood material property (Rinn, 2015b) that is important in terms of safety aspects. However, as already described for several tree species (Rinn, 2012a, 2012b, 2013, 2015b), there are significant changes in density (and thus drilling resistance) even in intact parts of wood: in many species, slightly decayed wood can have higher density than intact but soft wood and differs only in local density changes. Consequently, this kind of incipient decay cannot be detected by observing the average level of resistance. It requires a high spatial resolution of the drilling profiles (>10 points per mm) and at the same time a high correlation of the profile to the local density at the point of the needle's tip while penetrating the wood ($r^2 > 0.8$). The same conditions have to be fulfilled when the rate of radial extension is to be estimated because mean and incipient stages have to be revealed and identified. Similarly, without increment coring, radial incremental compensatory growth rates can be identified practically exclusively by changes in density (Schweingruber, Fritts, Bräker, Drew, & Schär, 1978). Consequently, resistance drills have to provide high resolution and correlation to wood density thus enabling the arborist expert to evaluate this aspect as well.

Summary and conclusion

Reliable decay detection in wood mandatorily requires a high spatial and signal resolution in combination with a high correlation ($r^2 > 0.8$) of the resistance drilling profile to average and local wood density along the path of penetration. Only then can the transitions from intact wood to areas of decay be identified correctly in the profiles. Also, only then can the evaluations and conclusions be correspondingly reliable, and defensible, especially in terms of estimation of future decay extension rates, effectiveness of compartmentalisation and compensatory incremental growth rates. The same conditions have to be fulfilled in order to differentiate between intact-but-soft and slightly decayed wood.

Following the ISO/ANSI/DIN standards cited here, experts should only use resistance drills which reliably fulfil the conditions specified above for safety-related inspections. Because of this, licences on the registered trademark RESISTOGRAPH® until now were only granted to very few resistance drills, fulfilling these requirements.

Disclosure statement

No potential conflict of interest was reported by the author.

Notes on contributor

Frank Rinn studied physics at Heidelberg University and later developed different methods, measuring devices and computer programs for various purposes in tree-ring analysis, dendrochronology, tree and timber inspection. For several of his inventions (resistance drilling, sonic tree tomography) he was granted national and international patents and trademarks (RESISTOGRAPH®, Arbotom®, ...) as well as research and innovation awards.

References

Brashaw, B.-K. (2013). *Nondestructive testing and evaluation of wood-research and technology transfer in North America*. Proceedings of the 18th international nondestructive testing and evaluation of wood symposium, Madison, September 2013.

Dolwin, J. D. (2001). *Detection of decay in trees and wood* (PhD thesis). University of Reading, 211.

Eckstein, D., & Saß, U. (1994). Bohrwiderstandsmessungen an Laubbäumen und ihre holzanatomische interpretation [Wood anatomical interpretation of resistance drilling profiles from broad leaf trees]. *Holz als Roh-und Werkstoff, 52*, 279–286.

Fink, H. (1971). Verfahren zum Prüfen der Standfestigkeit von Holzmasten und Vorrichtung zur Durchführung des Verfahrens [Method and device for inspecting the stability of wooden poles. German Patent]. DPMA DE1648513A1. Deutschen Patentamt 1. April 1971. Hilti AG, Liechtenstein. 14 July 1967.

FLL. (2013). *Richtlinie zur Untersuchung von Bäumen im Rahmen der Verkehrssicherungspflicht* [Guideline for examination of trees as part of the traffic safety standards]. Bonn: Baumuntersuchungsrichtlinie.

FPS. (1987). *Wood handbook. Wood as an engineering material. Agricultural handbook No. 72.* Washington, DC: U.S. Forest-Products-Laboratory. U.S. Department of Agriculture.

Görlacher, R., & Hättich, R. (1990). Untersuchung von altem Konstruktionsholz. Die Bohrwiderstandsmethode [Examinations of historic timber. The drilling resistance method]. *Bauen mit Holz, Juni 1990*. Erneuerte Auflage: 1992, Holzbaustatik-Aktuell Juli 1992/2.

Kamm, W., & Voss, S. (1985). Drill resistance method and machine. German and international patent application (DE3501841A1). [This patent was later declared invalid because of previous publications from Japan, USA, and Germany].

Lesnino, G. (2009). *Vergleichsuntersuchungen zur Sicherheitsermittlung an Bäumen – Schalltomografie und Zugversuche* [Comparative analysis for safety analysis of trees: Sonic tomography and pull tests]. Böblingen: Baumtage-Süd.

Means, J.-E., Cromack, K., Jr., & MacMillan, P.-C. (1985). Comparison of decomposition models using wood density of Douglas-fir logs. *Canadian Journal of Forest Research, 15*, 1092–1098. doi:10.1139/x85-178

Nielsen, C. C. N. (1990). Einflüsse von Pflanzenabstand und Stammzahlhaltung auf Wurzelform, Wurzelbiomasse, Verankerung sowie auf die Biomassenverteilung im *Hinblick auf die Sturmfestigkeit der Fichte* [Impact of planting distance and number of trees on root structure, root biomass and stability in terms of stability of spruce trees]. Frankfurt am Main; Sauerländer, 279. Dissertation Kopenhagen University. ISBN 3-7939-5100-6.

Norton, D. A. (1998). *Impacts of tree coring on indigenous trees*. Private Bag 4800, Christchurch. Conservation Research Group, School of Forestry, University of Canterbury. Published by Department of Conservation, Head Office, PO Box 10-420, Wellington, New Zealand. ISSN 1171-9834.

Paulitsch, M., & Mehlhorn, L. (1973). Neues Verfahren zur Bestimmung des Rohdichteprofils von Holzspanplatten [New method for determining the density profile of wooden particle boards]. Holz als Roh-und Werkstoff, *31*, Seite, 393–697.

Råberg, U. (2006). Fungal degradation and discolouration of Scots pine. Diss. Uppsala: Sveriges lantbruksuniv, *Acta Universitatis agriculturae Sueciae, 1652-6880, 2006*, 107. ISBN 91-576-7256-3.

Rinn, F. (1988). *A new method for measuring tree-ring density parameters* (Physics diploma thesis). Institute for Environmental Physics, Heidelberg University, 85.

Rinn, F. (1990). Device for material testing, especially wood, by drill resistance measurements. German Patent 4122494; Publication-No. DE4122494 B4. Application 03 Septemper 1990. pp. 10.

Rinn, F., Becker, B., & Kromer, B. (1990). *Density profiles of conifers and deciduous trees.* Proceedings Lund-symposium on tree rings and environment, Lund University.

Rinn, F. (1993). *Catalogue of relative density profiles of trees, poles and timber derived from RESISTOGRAPH micro-drillings*. Proc. 9th int. meeting non-destructive testing, Madison 1993.

Rinn, F. (1994). Resistographic visualization of tree-ring density variations. International conference tree rings and environment, Tucson, AZ, 1994. *Radiocarbon, 1996*, 871–878.

Rinn, F., Schweingruber, F.-H., & Schär, E. (1996). Resistograph and X-ray density charts of wood. comparative evaluation of drill resistance profiles and X-ray density charts of different wood species. *Holzforschung, 50*, 303–311.

Rinn, F. (1999). Device for investigation materials. US-Patent US6813948; international Patent PCT/DE00/01467 (1999.05.11).

Rinn, F. (2012). Basics of typical resistance-drilling profiles. *Western Arborist Winter, 2012*, 30–36.

Rinn, F. (2012b). Basics of micro-resistance drilling for timber inspection. *Holztechnologie, 53* (2012) 3, 24–29.

Rinn, F. (2013, February). Typical trends in resistance drilling profiles of trees. *ArboristNews*, 42–47.

Rinn, F. (2015). Central defects in sonic tomography. *Western Arborist Spring, 2015*, 38–41.

Rinn, F. (2015). Key to evaluating drilling resistance profiles. *Western Arborist Fall, 2015*, 14–19.

Rinn, F. (2015c). Risserkennung mittels Bohrwiderstandsmessungen [Crack detection with resistance drilling]. *Holztechnologie, 56*, 62–63.

Schweingruber, F. H., Fritts, H. C., Bräker, O. U., Drew, L. G., & Schär, E. (1978). The X-ray technique as applied to dendrochronology. *Tree-Ring Bulletin, 38*, 61–91.

Seaby, D. A. (1990). Recent advances in detection of wood decay. Paper No. 21. In Research for practical arboriculture (S. J. Hodge Ed.). *Forestry Commission Bulletin, 97*, 168–176.

UK Patent GB/2/242/09/A. Application No. 900.6090.6, filed 17-03-1990. D. A. Seaby, Wood Decay Detecting Drill.

Wilcox, W. W. (1978). Review of literature on the effects of early stages of decay on wood strength. *Wood and Fiber, 9*, 252–257.

WIPO. (1993). Trademark registration IR#646811 "Resistograph" by and for Frank Rinn, Heidelberg, Germany.