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Real-time wood moisture-content determination using dual-energy X-ray computed tomography scanning

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ABSTRACT

The estimation of the pixel-wise distribution of the moisture content (MC) in wood using X-ray computed tomography (CT) requires two scans of the same wood specimen at different MCs, one of which is known. Image-processing algorithms are needed to compensate for the anisotropic distortion that wood undergoes as it dries. An alternative technique based on dual-energy CT (DECT) to determine MC in wood has been suggested by several authors. The purpose of the present study was to evaluate the hypothesis that DECT can be used for the determination of MC in real time. A method based on the use of the quotient between the linear attenuation coefficients ($\mu$) at different acceleration voltages (the so-called quotient method) was used. A statistical model was created to estimate the MC in solid sapwood of Scots pine, Norway spruce and brittle willow. The results show a regression model with $R^2 > 0.97$ that can predict the MC in these species with a RMSE of prediction of 0.07, 0.04 and 0.11 (MC in decimal format) respectively and at MC levels ranging from the green to the totally dry condition. Individual measurements of MC show an uncertainty of up to ±0.4. It is concluded that under the conditions prevailing in this study, and in studies referred to in this paper, it is not possible to measure MC with DECT.

INTRODUCTION

Wood is a biological structure that fulfils its natural function at a high moisture level but in order to be used as a construction material the moisture has to be reduced to a level that is suitable for the intended use. Nearly all wood properties are influenced by the moisture content (MC), which is the ratio of the mass of water in the wood to the dry mass of the wood substance. Being able to determine the MC of wood with high accuracy is thus of great importance for its use. The most widespread and exact method of measuring the MC is the gravimetric method or the oven-dry method, where wood is dried at a temperature of 103 ± 2°C until all the water is removed. Some drawbacks of the gravimetric method are its destructive and time-consuming nature, and the evaporation during the oven-drying process of volatile compounds other than water may cause measurement errors. The method is, however, seen as a reference method for MC determination.

For industrial applications, non-destructive and non-contact methods have been developed for the measurement of the MC in wood (Bucur 2003, Ross 2015, Gonçalves et al. 2018). X-ray computed tomography (CT) scanning technology has recently been developed as an industrial tool for outer geometry assessment and internal feature detection of logs for the optimization of the disjoining processes in the sawmill and veneer industries, and MC detection by the same technology is now of interest. In the present study, the possibility of using dual-energy X-ray CT (DECT) for the real-time measurement of local MC in wood has been evaluated. The study was based on earlier studies related to DECT for MC measurements, and on new measurements performed with the help of a medical CT scanner in an attempt to verify earlier studies.

CT was developed within the medical field during the 1970s. A CT-scanner works by sending an X-ray beam through an object and quantifying the intensity (number of photons per second per unit cross-sectional area) of the X-ray beam after it has passed through the scanned object so that the attenuation of the radiation when interacting with the material can be calculated. In CT scanning, this attenuation is measured in different angular positions, and the data collected in the detector is converted into a two-dimensional image of a spatial cross-section volume of the scanned material (Deans 1993).

When complete continuous X-ray data are available, an attenuation-coefficient function $f(x, y)$ can be constructed exactly using the filtered back-projection formula (Feeman 2015). The linear attenuation coefficient is then the back-projection of the inverse Fourier transform of the product of the absolute value of the wavenumber and the Fourier transform of the Radon transformation of the linear attenuation coefficient, i.e.

$$\mu(x, y, \tilde{E}_i) = \frac{1}{2} \mathcal{B} \{ (\tilde{F} \odot |\tilde{S}| \cdot \tilde{F}(R(x, y))) \},$$

where $\mu(x, y, \tilde{E}_i)$ is the linear attenuation coefficient at coordinates $x$ and $y$ for a given energy spectrum. The Radon
transformation \(\mathbb{R}_{\mu}\) of the linear attenuation coefficient is measured by the CT scanner. Attenuation of X-rays as they pass through matter is determined by interactions like the photoelectric absorption and the Compton effect, but for biological materials, the varying chemical composition and the varying density also influence the attenuation considerably. The measurements by a CT device are also influenced by the type of X-ray tube, the X-ray tube voltages, and X-ray filtration.

The attenuation of the X-ray beam that passes through a homogeneous material depends on the intensity of the incident X-ray beam \(I_0\) and on the linear attenuation coefficient \(\mu\) of the material according to Lambert-Beer’s law:

\[
I = I_0 e^{-\mu d},
\]

where \(I\) is the intensity of the transmitted X-ray beam, and \(d\) is the thickness of the material. The linear attenuation coefficient is material-specific, and it is ultimately dependent on the effective atomic number \(Z_{\text{eff}}\) and on the electron density of the material (see e.g. Hsieh 2009).

A CT image is a grey-scale image in which each pixel has a numerical value that is known as the CT number. CT numbers are measured in Hounsfield units (HU) and are defined as:

\[
\text{CT number} = \frac{1000 (\mu_x - \mu_{\text{water}})}{\mu_{\text{water}}},
\]

where \(\mu_x\) is the attenuation coefficient of the material and \(\mu_{\text{water}}\) is the linear attenuation coefficient of water. Equation (3) defines the CT number at an average photon energy of 73 keV, which corresponds to an X-ray tube voltage of 140 kV (Huda et al. 2000), a usual setting in medical CT scanners. In Equation (3), a CT number of minus 1000 \((-1000)\) corresponds to the linear attenuation coefficient of air while a CT number of zero \((0)\) corresponds to that of water. The CT number in a pixel is the average of a three-dimensional entity known as a voxel, defined by the dimensions of the pixel and the thickness of the scanning X-ray beam (scanning depth).

CT was first used as an analytical tool to study wood during the early 1980s and the first tests were carried out on logs in California at the Imatron Company and later several tests were performed at the Louisiana State University, mostly on hardwood (Giudiceandrea et al. 2012). Lindgren (1985) established the existence of a correlation between the CT number and the density of wood and could thereby describe the density profile for a volume of wood at the voxel level and distinguish different features in wood such as knots, heartwood and sapwood. The application of CT in wood material science has spread since then and CT is now a technology that has developed to the point where industrial CT scanners are being installed in sawmills and veneer production mills around the world.

The methods developed so far to measure MC in wood using X-ray CT require two scans of the same wood region at two different MC levels, of which one is known (Lindgren 1992). As the CT number provides information that can be related to density and the voxel dimensions give information on volume, mass can be calculated from a CT image and the same rationale of the gravimetric method can be applied to two images, one of them being, for practical reasons, of the oven-dry wood specimen (Lindgren 1992). This method of measuring MC has since then been applied and verified in several studies (see e.g. Danvind 2005, Watanabe et al. 2012, Hansson and Fjellner 2013, Couceiro and Elustondo 2015), but a major shortcoming is that the MC can only be determined by this method when the wood piece has been dried to 0% MC and re-scanned which means that real-time measurements of the MC are not possible.

In order to develop a real-time measurement technique for studying the local MC distribution in wood, a DECT approach has been explored. DECT is based on the different degrees of attenuation that X-ray radiation undergoes when travelling through a material based on the different energies of the X-ray spectrum, which means that the attenuation of the X-ray is dependent not only on the material properties but also on the energy spectrum of the X-ray. The different values of the linear attenuation coefficient \(\mu\) which are obtained when two scans are performed at the same place in the wood but with different X-ray energy spectra can theoretically be used for MC calculation. Two scans at different energy levels can easily be obtained with a medical CT scanner within a short time-span.

Jackson and Hawkes (1981) reported that the attenuation that an X-ray undergoes when travelling through a material can be expressed as the gravimetric proportion of the attenuation of each of its component materials. Such a principle can be applied to wood containing moisture if it is considered to be a mixture of only wood and water. Applying the principles that rule the use of DECT that can be found in Hsieh (2009), Kim et al. (2015) expressed the attenuation coefficient of wood containing moisture as:

\[
\mu_{\text{mw}} = a \mu_{\text{water}} + b \mu_{\text{wood}},
\]

where \(\mu_{\text{mw}}\) is the mass attenuation coefficient of wood containing moisture, \(\mu_{\text{water}}\) is the mass attenuation coefficient of water, \(\mu_{\text{wood}}\) is the mass attenuation coefficient of wood and \(a\) and \(b\) are gravimetric proportionality constants for water and wood respectively. The mass attenuation coefficient is the linear attenuation coefficient divided by the density of the material. MC is the ratio of the mass of water to the mass of the absolutely dry wood substance:

\[
\text{MC} = \frac{a}{b}.
\]

Based on the same logic, Kullenberg et al. (2010) defined the parameter \(k\) as the ratio of the linear attenuation coefficients of a material for two different X-ray energy spectra:

\[
k_1 = \frac{\mu_{1A}}{\mu_{2A}},
\]

where \(\mu_{1A}\) and \(\mu_{2A}\) are the attenuation coefficients of a material \(A\) at the low and high X-ray energies, respectively. They performed tests in an X-ray scanner and established the existence of a calibration function between \(k_1\) and MC for wood chips with a standard error of estimate (SEE) between 1.2% and 3.9%. The same method was tested by Hultnäs and Fernandez-Cano (2012) trying to prove the
interspecies applicability of the model developed by Kullenberg et al. (2010), but the statistical analysis showed large errors.

Tanaka and Kawai (2013) tried a different approach to calibrate the grey-scale values in the CT image to the linear attenuation coefficients, using as reference the thickness of a material with known linear attenuation coefficients showing the same grey-scale values as that of X-ray images of the wood at a given MC. The SEE that they obtained was greater than 20 percentage points. Tanaka (2015) reported experiments similar to those by Tanaka and Kawai (2013) but giving a SEE of 2.16 percentage points. This was nevertheless accompanied by a contradicting graph, an issue that, at the time of the writing of this paper, is under discussion between authors.

Kim et al. (2015) used a hand-held radiation measurement instrument to establish a relationship between the grey-scale values in the X-ray images and the intensity of the X-ray through the use of the parameter \(k_1 \) in Equation (6). They established a prediction model with a root-mean-square error (RMSE) of prediction of 3.15%.

Lindgren et al. (2016) used a micro-CT and expressed the linear attenuation coefficient of wood as the volumetric proportion of the linear attenuations of wood and water, respectively. They also developed a sort of theoretical relationship between MC and the parameter \(k_1 \) in Equation (6). Nevertheless, they did not report any development of a model based on experiments, nor any statistical analysis of the results other than theoretical.

Studying the previously mentioned reports, some issues arise:

(1) The physics behind the overall approach may raise doubts because of the limited amount of records available, inconsistent results in different studies, very large errors of estimate, the use of wood chips and bulk material, or the facts that some proposals are only theoretical and are not supported by experiments. Some of the presented models can show values of \(R^2 \) greater than 0.9, but the errors of estimate show poor prediction ability and suggest a great spread in the predictions.

(2) The comparison and evaluation of the results previously published are troublesome because the use of the percentage (%) to describe MC prediction ability of models is generalized in wood science. This can nevertheless be confusing, as it seems obvious that authors often mean percentage points, not actual percentages. When predicting MC, especially with decreasing levels of MC, mistaking percentage for percentage points can be extremely misleading.

(3) An issue that seems to be common in all the reports regarding DECT for measuring MC in wood is the difficulty of determining the actual photon count which provides basic data to apply DECT as expressed in Equation (4). It is suggested that parameter \(k_1 \) in Equation (6) can solve this issue.

Besides the general considerations behind the method and considering each article individually, further doubts appear.

(1) Kullenberg et al. (2010) do not clarify which parameter is obtained from the scanner and is used to calculate the \(k \) value. Most scanners provide not data of attenuation or photon count data, but a grey-scale that must be calibrated somehow. It is not clear whether the relationship between grey-scale and attenuation coefficient is linear or even known. This issue is also present in Hultnäs and Fernandez-Cano (2012).

(2) Tanaka and Kawai (2013) present a SEE of 21.9%. No equation for SEE is presented, so it must be assumed that the authors mean 21.9 percentage points. In such a case, the error of the estimate is much too large to consider the method to be useful. Furthermore, the use of analogical methods that require digitalization likely to generate large errors.

(3) Tanaka (2015) presents the results of a model prediction in an observed-predicted plot that claims a SEE of 2.16%. According to the formula presented in the article, it seems that the author means 2.16 percentage points. Nevertheless, a recalculation of the SEE with data extracted roughly from the graph presented results instead in a SEE of 11.4 percentage points instead.

(4) Kim et al. (2015) also need to de-code the grey-scale in the picture into a parameter that can be connected to the linear attenuation coefficient of the material. This process is susceptible to error. Nevertheless, the prediction ability of the method, with a RMSE of 3.15 percentage points (according to the equation presented), suggests that the method could be useful in research as well as for industrial applications.

(5) Lindgren et al. (2016) present only a theoretical approach, and typical CT-related experimental errors, such as noise and artefact, are not taken into account.

Considering the doubts that both the previous reports present and also the potential that the theory suggests, this work has studied the application of DECT with a medical CT scanner to estimate the MC with a parameter similar to \(k_1 \), obtained solely from the CT numbers instead of from the linear attenuation coefficients.

The purpose of the present study was to evaluate the hypothesis that DECT can be used for the determination of MC in real time with a medical CT scanner or similar X-ray CT scanner.

Compared with the micro-CT technology proposed by Lindgren et al. (2016), medical CT scanning has the advantages of ease of operation, the possibility of scanning large specimens and short scanning times (less than 1s/scan). Medical CT scanners have, however, the disadvantage of providing not attenuation coefficients but CT numbers, and it has also been claimed that medical CT may work in inappropriate ranges of X-ray tube acceleration voltages to give accurate detection differences between wood and water (Hsieh 2009, Lindgren et al. 2016).

Materials and methods

Materials

A total of 12 specimens of sapwood from Scots pine (Pinus sylvestris L.), 6 specimens from Norway spruce (Picea abies L.),
and 4 specimens from brittle willow (Salix fragilis L.) were used for the DECT study. Scots pine and Norway spruce were selected because they are the most extensively used commercial species in Scandinavia, while Brittle willow was chosen because of its low dry density and high MC in the green state compared to the other two species.

The specimens were sawn from green sapwood in order to get the highest possible MC, and avoiding heartwood to reduce disturbances in chemical composition because of extractives. The specimens were free from knots and other visible defects. The dry density was 492, 468, and 339 kg/m³ for Scots pine, Norway spruce and brittle willow, respectively, and the green MC was 1.3, 1.1, and 2.1.

The cross-section dimensions of the specimens were limited to the maximum possible dimension that could be cut from sapwood, approximately 32 × 32 mm² in cross-section area, and 100 mm in length.

Methods

The method used in this study makes use of the parameter k₁ found by Kullenberg et al. (2010), and also used by Hultnäs & Fernandez-Cano (2012), Kim et al. (2015) and Lindgren et al. (2016). The relationship between the linear attenuation coefficient and the CT number is well known, but the value of CT numbers in individual pixels might be misleading in the case of a medical CT scanner. The reason for this is the proprietary software and algorithms that process the data, which may apply different kind of filters to the image. Because those algorithms and filters are unknown, in order to test the feasibility of the method, it must be assumed that a parameter k₂ defined by Equation (7) is valid:

\[ k_2 = \frac{CT_1}{CT_2}, \]

where \( CT_1 \) is the CT number obtained at the lower X-ray tube acceleration voltage, and \( CT_2 \) is the CT number obtained at the high acceleration voltage. Lindgren et al. (2016) studied the relation between \( k_1 \) and the MC, buts in the present project \( k_2 \) is compared to the MC determined by the gravimetric method. One of its reported benefits of DECT would be the possibility to determine the local MC distribution, but in our study only the average of the entire specimen was considered because it would ultimately not be possible to use as reference of local values of MC, obtained with the gravimetric method.

A Siemens Somatom Emotion Duo CT-scanner was used. It allows acceleration voltages in the X-ray tube of 80, 110 and 130 kV, which provide average photon energies of 52, 63 and 70 keV, respectively (Huda et al. 2000).

The specimens were first scanned in the green state using a series of single scans with the scanning plane oriented perpendicular to the longitudinal direction of the specimen. The scans were distributed throughout the length of the specimen so that the whole specimen was scanned with no overlapping of the scanning beam between scans. The process was carried out at two X-ray tube acceleration voltages, 80 and 130 kV, and two sets of data were obtained. The scanner was set with a pixel size of 0.14 × 0.14 mm² and a scanning depth of 10 mm. The scanner was centred at the volume sections so that the 10 mm scanning depth of the scanning beam would cover the whole section of the specimen. After performing the two scans at different energy levels, the scanning position was moved 10 mm in the longitudinal direction of the specimen so that it was centred in the next volume section, and the process was repeated until the whole specimen had been scanned at the two energy levels. Figure 1 shows one of the specimens in which the 10 mm sections corresponding to each single scan are drawn, and their corresponding scanning images are presented. With the information collected through this procedure, the average CT numbers of the entire specimen at the two energy levels were calculated so that \( k_2 \) could be calculated according to Equation (7). Afterwards, the specimen was dried to a lower MC and the process was repeated until the specimen reached 0% MC. The calculations to obtain \( k_2 \) were performed in Matlab (The MathWorks Inc. 2018) by processing the CT images as matrices and computing only those pixels containing CT numbers in the range corresponding to wood.

The weight of the specimens was obtained at the time of each scan so that the MC could be calculated gravimetrically after the specimen had reached zero MC. Finally, for each specimen a dataset was obtained consisting of a series of different MC values ranging from green to completely dry, and the corresponding \( k_2 \) values.

For the statistical study, each specimen at a given MC was considered as an independent observation. For instance, the brittle willow specimens were scanned at ten different MCs, and each specimen thus gave ten independent observations. For each of four specimens of brittle willow, which makes a total of 40 independent observations. For each species, a regression equation with all the independent observations was drawn to create a model to predict moisture content from \( k_2 \). The MC value of each specimen was then predicted with the model created and compared with the gravimetric MC. The prediction ability of the model was evaluated with the root-mean-square error (RMSE):

\[ \text{RMSE} = \sqrt{\frac{\sum (\text{MC}_g - \text{MC}_{CT})^2}{n}}, \]

where \( n \) is the total number of observations, \( \text{MC}_g \) is the MC obtained gravimetrically and \( \text{MC}_{CT} \) is the MC obtained from the CT data.

For Scots pine, there were 12 specimens, and the MC and \( k_2 \) values were obtained at 5 times for 6 of the specimens and at 7 times for the other 6. For Norway spruce 6 specimens were studied at 7 different times and for brittle willow, 4 specimens were studied at 10 different times. Defining what constitutes an independent observation as explained earlier, Scots pine provided 72 observations, Norway spruce 42 observations and brittle willow 40 observations. The reason behind this difference in number and spread in the measurements is that the experiments were not performed simultaneously and the next experiment was designed according to the results obtained in the previous ones, trying to collect data for those MC levels that seemed to be the most
relevant. Nevertheless, in the statistical analysis, all observations were considered.

To avoid confusion, MC is expressed in this paper in the decimal format.

The drying equipment was chosen based only on practical reasons because the research aims to measure the MC at different levels and not to study the drying procedure. The specimens were dried in an ordinary microwave oven to approximately the fibre-saturation point (FSP) because this gives faster drying than any other available method. Drying wood in a microwave oven below FSP can cause internal combustion, so below FSP the specimens were conditioned in a climate chamber. The final drying to 0% MC was performed in an oven at a temperature of 103°C.

Results

Figure 2 shows the results of the MC gravimetric measurements plotted against $k_2$, differentiated into specimen and species.

Analysis and discussion

The values plotted in the graphs in Figure 2 were fitted with third-order polynomials:

\[
MC_{\text{pine}} = 2e^6k_2^3 - 7e^6k_2^2 + 7e^6k_2 - 2e^6,
\]

(9)

\[
MC_{\text{spruce}} = 2e^6k_2^3 - 6e^6k_2^2 + 5e^6k_2 - 2e^6,
\]

(10)

\[
MC_{\text{willow}} = 7e^6k_2^3 - 2e^7k_2^2 + 2e^7k_2 - 6e^6.
\]

(11)

The choice of a third-order polynomial to establish the models was conditioned by the pattern followed by the data for brittle willow, and it was then decided to use third-order polynomials also for Scots pine and Norway spruce in order to maintain consistency. From the model for the prediction of MC from $k_2$ the graphs shown in Figure 3 were obtained.

A relationship between MC and $k_2$ is obvious for Scots pine and Norway spruce, but in the case of brittle willow, there is a clear anomaly at around 0.2 MC, where the increase in $k_2$ with increasing MC does not follow the general trend (Figure 2). After a thorough inspection of the results and repetition of the experiments, no experimental errors were found to be the cause of the anomaly. A reason could be in the reconstruction process and the filters that may be built into the software, which are unknown because they are proprietary. This anomaly affected the choice of a third-order polynomial for the model equation. The coefficient of determination for the fitted cubic function is 0.97 for Scots pine and brittle willow, and 0.98 for Norway spruce. The root mean square error (RMSE) of prediction of MC is 0.11 for brittle willow, 0.04 for Norway spruce and 0.07 for Scots pine. Such a prediction ability is however too weak for most potential applications of the method, such as measuring the MC in real time during drying under laboratory conditions. A much higher precision is usually required.

Even though the observed-predicted plot shown in Figure 3 suggests a great prediction ability, the RMSE and further analysis of the residuals plots show otherwise. The
distribution of the residuals is not symmetrical in relation to the zero line, nor is it constant along the horizontal axis. In the three species, the residuals seem to be larger of higher MC, and the distribution of the residuals seems to follow a similar pattern in all three species, which suggests that there could be a missing variable or group of variables that hinder the prediction, or even that the relationship between $k_2$ and MC could be a rational function. The value of $k_2$ seems being highly uncertain, and small variations in $k_2$ would cause large inaccuracies in the prediction of MC. CT images show noise that is dependent on the reconstruction kernel used and on the energy level, but there is always a certain amount of noise, which greatly affects the value of $k_2$.

The uncertainty of the calculation of $k_2$ and MC can be studied using Equations (12) and (13) based on examples of theoretical CT numbers that fit the model in the interval of $k_2$ values that are relevant.

$$\Delta k_2^2 = (\Delta CT_1)^2 \left( \frac{\partial k}{\partial CT_1} \right)^2 + (\Delta CT_2)^2 \left( \frac{\partial k}{\partial CT_2} \right)^2,$$  \hspace{1cm} (12)

$$\Delta MC^2 = (\Delta k_2)^2 \left( \frac{\partial MC}{\partial k_2} \right)^2.$$  \hspace{1cm} (13)

Based on MC predictions from Equations (9), (10) and (11), this results in an uncertainty of prediction for Scots pine, Norway spruce and brittle willow with CT1 = 500 ± 2 and CT2 = 506 ± 2 as shown in the equations:

$$MC_{\text{pine}} = 0.2022 \pm 0.1011,$$  \hspace{1cm} (14)

$$MC_{\text{spruce}} = 0.1054 \pm 0.4353,$$  \hspace{1cm} (15)

$$MC_{\text{willow}} = 0.1107 \pm 0.3765.$$  \hspace{1cm} (16)

The models show very poor prediction ability for pixel-wise estimations of MC, even though the results as average values for the entire wood specimens show a good correlation. An error of ±2 in the measurement of a CT number is relatively low considering that the noise in the image results in standard deviations of 4.1 and 2.5 for CT1 and CT2, respectively, when measuring a water phantom. When performing pixel-wise calculations it must also be noticed that the sharpness of the CT image varies with the energy spectra of the X-ray beam, and this may introduce anomalies and reveal patterns that respond to anatomical features such as the earlywood/late-wood transition, and not to actual differences in MC.

The uncertainties in earlier studies of MC measurements by DECT, and the poor prediction ability of our measurements indicate some major flaw in the suggested theory for the so-called quotient method, and we therefore suggest the following theoretical approach.

Figure 4 represents the assumption that wood is scanned at two different X-ray tube voltages, e.g. 50 and 150 kVp, representing two energy spectra $E_1$ and $E_2$. 

Figure 3. Observed-predicted plots (top), residuals in relation to predicted MC (middle) and residuals in relation to gravimetric MC (bottom) for Scots pine (left), Norway spruce (middle) and brittle willow (right).
The linear attenuation coefficient ($\mu$) of a material (in a voxel) consisting of different atoms, $i$, is given by:

$$\mu = \sum_i N_A \frac{1}{M_i} \rho_i \sigma_i$$

where $N_A$ is the Avogadro number, $M_i$ is the atomic weight for the atomic species $i$, $\rho_i$ is the density, and $\sigma_i$ is the microscopic cross-section for atom $i$.

If wood is regarded as a compound of wood substance and water, where wood is mainly regarded as consisting of oxygen, hydrogen, and carbon atoms in the form of carbohydrate [CH$_2$O], the linear attenuation coefficient ($\mu$) can be expressed as:

$$\mu = \rho_{\text{water}} N_A \sum_i \frac{1}{M_i} \rho_i \sigma_i + \rho_{\text{wood}} N_A \sum_i \frac{1}{M_i} \rho_i \sigma_i$$

where $\rho$ is the density and $\rho_i$ is the number portion of the atoms in water and wood, respectively.

The linear mass attenuation coefficient ($\mu$) at the two different X-ray tube voltages can then be expressed as:

$$\begin{align*}
\{ \mu_1 &= a_1 \rho_{\text{water}} + b_1 \rho_{\text{wood}} \\
\mu_2 &= a_2 \rho_{\text{water}} + b_2 \rho_{\text{wood}} \}
\end{align*}$$

where $a_1$ and $b_1$ are constants based on Equation (18).

From Equation (19), $\rho_{\text{water}}$ and $\rho_{\text{wood}}$ can be solved and the moisture content $\rho_{\text{water}}/\rho_{\text{wood}}$ can be calculated. However, earlier authors have preferred to study the quotient $\mu_1$ and $\mu_2$ as:

$$k = \frac{\mu_1}{\mu_2} = \frac{a_1 \rho_{\text{water}} + b_1 \rho_{\text{wood}}}{a_2 \rho_{\text{water}} + b_2 \rho_{\text{wood}}}$$

If the X-ray tube voltages are in the range of 50–150 kV$_p$, the wavelength of the X-ray radiation is between 0.02 and 0.003 nm, i.e. the attenuation of the beam takes place in the electron shells with the atomic numbers $Z$ for the different atoms. There are three processes:

1. The photoelectric absorption ($\rho$), where the microscopic cross-section of atoms is $\sigma_i \sim Z^n / E^l$, where $n$ and $l$ are positive constants.
2. The Compton effect where $\sigma_i \sim Z \cdot f(E/m_ec^2)$ according to Klein-Nishina, where $m_ec^2 = 511$ keV is the electron mass in energy units.
3. Electron pair production only exists at energies greater than $2m_ec^2$, and is of interest when only X-ray is concerned.

Figure 4. Graphs showing the two energy spectra $E_1$ and $E_2$, assuming that wood is scanned at two different X-ray tube voltages $V_1$ and $V_2$.

In the present energy range, it is contended that the Compton effect is the most important factor in this energy range (see e.g. Sedlmair 2009, Equation (12) and p. 21). The function $f(E/m_ec^2)$ is the same for each atom.

$$a_k = \frac{\int \frac{E_k}{m_ec^2} \sum_i \alpha_i(z) \rho_i}{\sum_i \alpha_i(z) \rho_i} = \frac{\int \frac{E_k}{m_ec^2}}{\sum_i \rho_i} \alpha_k, \text{tot} \quad k \in 1, 2,$$

where $i$ is the water components (atoms), and

$$b_k = \frac{\int \frac{E_k}{m_ec^2} \sum_i \beta_i(z) \rho_i}{\sum_i \rho_i} \beta_k, \text{tot} \quad k \in 1, 2,$$

where $m$ is the wood components (atoms).

The total dependence of the different energy spectra is in the factor $f(E/m_ec^2)$, which gives that $\alpha_{1, \text{tot}} = \sum_i \alpha_i = \alpha_{2, \text{tot}} = \alpha_{\text{tot}}$ and $\beta_{1, \text{tot}} = \sum_i \beta_i = \beta_{2, \text{tot}} = \beta_{\text{tot}}$. This means that:

$$\begin{align*}
\mu_1 &= \alpha_{\text{tot}} \int \frac{E_1}{m_ec^2} \rho_{\text{water}} + \beta_{\text{tot}} \int \frac{E_1}{m_ec^2} \rho_{\text{wood}} \\
\mu_2 &= \alpha_{\text{tot}} \int \frac{E_2}{m_ec^2} \rho_{\text{water}} + \beta_{\text{tot}} \int \frac{E_2}{m_ec^2} \rho_{\text{wood}}
\end{align*}$$

and that

$$\begin{align*}
\mu_1 &= \frac{\int \frac{E_1}{m_ec^2} \rho_{\text{water}} + \beta_{\text{tot}} \rho_{\text{wood}}}{\alpha_{\text{tot}} \rho_{\text{water}} + \beta_{\text{tot}} \rho_{\text{wood}}} = \frac{\int \frac{E_1}{m_ec^2}}{\alpha_{\text{tot}} \rho_{\text{water}} + \beta_{\text{tot}} \rho_{\text{wood}}}, \\
\mu_2 &= \frac{\int \frac{E_2}{m_ec^2} \rho_{\text{water}} + \beta_{\text{tot}} \rho_{\text{wood}}}{\alpha_{\text{tot}} \rho_{\text{water}} + \beta_{\text{tot}} \rho_{\text{wood}}} = \frac{\int \frac{E_2}{m_ec^2}}{\alpha_{\text{tot}} \rho_{\text{water}} + \beta_{\text{tot}} \rho_{\text{wood}}},
\end{align*}$$

i.e. the quotient is independent of $\rho_{\text{water}}$ and $\rho_{\text{wood}}$ and the moisture content cannot be determined.

**Conclusions**

The purpose of this study was to evaluate the hypothesis that dual-energy CT (DECT) can be used for the determination of moisture content (MC) in real time with a medical CT scanner or similar X-ray scanners. A medical X-ray CT scanner was used to measure the density profile of wood X-ray tube acceleration voltages of 80 and 130 kV and the quotient of the CT-numbers at different X-ray tube voltages can then be expressed as:

$$\begin{align*}
\mu_1 &= \alpha_{\text{tot}} \int \frac{E_1}{m_ec^2} \rho_{\text{water}} + \beta_{\text{tot}} \int \frac{E_1}{m_ec^2} \rho_{\text{wood}} \\
\mu_2 &= \alpha_{\text{tot}} \int \frac{E_2}{m_ec^2} \rho_{\text{water}} + \beta_{\text{tot}} \int \frac{E_2}{m_ec^2} \rho_{\text{wood}}
\end{align*}$$

and that

$$\begin{align*}
\mu_1 &= \frac{\int \frac{E_1}{m_ec^2} \rho_{\text{water}} + \beta_{\text{tot}} \rho_{\text{wood}}}{\alpha_{\text{tot}} \rho_{\text{water}} + \beta_{\text{tot}} \rho_{\text{wood}}} = \frac{\int \frac{E_1}{m_ec^2}}{\alpha_{\text{tot}} \rho_{\text{water}} + \beta_{\text{tot}} \rho_{\text{wood}}}, \\
\mu_2 &= \frac{\int \frac{E_2}{m_ec^2} \rho_{\text{water}} + \beta_{\text{tot}} \rho_{\text{wood}}}{\alpha_{\text{tot}} \rho_{\text{water}} + \beta_{\text{tot}} \rho_{\text{wood}}} = \frac{\int \frac{E_2}{m_ec^2}}{\alpha_{\text{tot}} \rho_{\text{water}} + \beta_{\text{tot}} \rho_{\text{wood}}},
\end{align*}$$

i.e. the quotient is independent of $\rho_{\text{water}}$ and $\rho_{\text{wood}}$ and the moisture content cannot be determined.
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Disclosure statement

No potential conflict of interest was reported by the authors.

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