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Frequency dependent mechanical properties of violin varnishes and their impact on vibro-mechanical tonewood properties

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ABSTRACT

Violin varnishes influence the vibrational properties of tonewood. However, the frequency dependence of the varnish influence and mechanical properties of typical varnishes has received little attention. The viscoelastic properties of various violin varnish materials over the audible frequency range were characterized by dynamic mechanical analysis. The properties of the studied varnishes showed comparable frequency dependencies. For all varnishes, E increased and tan(δ) decreased with increasing frequency. The results were in good agreement with an analytical mechanical model, which was used for additional numerical FEM calculations. The approach of numerically determining varnish-induced changes in the vibrational properties on basis of the individual wood and varnish properties was confirmed through comparison with experimental results obtained in an earlier study. The latter procedure was subsequently used to analyse varnish-induced changes in the eigenfrequencies of a violin soundboard. The results revealed that the frequency dependence of the varnish properties determined the specific influence of varnishes on the vibrational properties of tonewood, which should be taken into account when assessing the impact of varnishes.

1. Introduction

Varnishes are applied to protect violins against external hazards, such as from general wear-and-tear and moisture, as well as to enhance the instrument's appearance. The varnish application, however, induces changes in the vibro-mechanical properties of wood and the instrument's timbre. The influence of varnish on the vibro-mechanical properties was evaluated on wooden sample strips [1–4], wooden sample plates [5–7], top and bottom plates of instruments [1,8], and on complete violins [1, 9–11]. The recorded changes originate from an additional mass load by the varnish and different dynamic mechanical properties (i.e. complex tensile modulus E and loss tangent tan(δ)) of wood and varnish.

The vibrational properties of the finished instrument determine the sound quality of the violin. In contrast to studies on varnish induced changes of the vibro-mechanical properties of wood, the actual viscoelastic properties of the pure varnishes have received far less attention. In particular, the frequency dependency of the mechanical properties of varnishes has rarely been investigated. However, this dependency determines E and tan(δ) and thus their actual influence on the vibrational and acoustic wood properties over the relevant hearing range of humans, ranging from 20 to 20′000 Hz. If the varnish properties show a pronounced frequency dependence, their influence on the vibrational properties at low and high frequencies will differ. In a study on the influence of varnish on the properties of wood, Ono [6] studied a copal and toluene based resin and a nitrocellulose sealing. Based on the 1st flexural vibration mode of dried samples, Ono [6] determined E (3.6 GPa and 2.1 GPa) and tan(δ) (0.053 and 0.057) of the varnish and sealing respectively, for frequencies in the range of 100–270 Hz. Similarly, Gunji et al. [12] investigated the properties of a polyurethane lacquer and reported single values for E (2.5 GPa) and tan(δ) (0.050) in a frequency range of 50–300 Hz for the 1st mode. In reference to cross-linked polymers, Simonnet et al. [13] discussed the general viscoelastic properties for alcohol and oil varnishes, mainly regarding their temperature dependency, but also by reflecting on the influence of frequency. Moreover, changes in mechanical properties during the drying of linseed oil and a standard oil varnish were measured by dynamic mechanical analysis

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(DMA) as a function of time; however, the mechanical properties were only assigned with arbitrary units [13]. In contrast to the latter studies, Obataya et al. [3] performed more detailed investigations into the frequency dependency of the viscoelastic properties of Oriental (urushi), clear and natural oil-based lacquers. A viscoelastometer was used in the investigations to isothermally measure E and the inverse quality factor Q^{-1}(=tan(δ)) values of the lacquers for a frequency range of 1–100 Hz at different temperatures. As E and Q^{-1} of most lacquers showed a linear (log-) frequency dependence and no relaxation at low temperatures, straight lines were fitted to the results at low frequency and used as extrapolations for the values of E (ranging from 2.1 to 2.6 GPa) and Q^{-1} (ranging from 0.015 to 0.050) at 550 and 750 Hz (the average frequencies of evaluated wood samples). For the exceptional case of clear lacquer, the time-temperature superposition (TTS) principle [14] was applied to determine E (1.4 and 1.3 GPa) and tan(δ) (0.250 and 0.260) at 550 Hz and 750 Hz, respectively. For the latter, the results were further presented over a frequency range of 1–10000 Hz, showing an increase in E and a decrease for Q^{-1} with increasing frequency. All outlined references applied mechanical models to compare the numerical results of E and tan(δ) (based on separate wood and varnish properties) with measurements of varnished wooden samples. Moreover, the influence of different parameters such as thickness and amount applied (mass) was evaluated. However, the investigations were performed at specific frequencies, which were observed for the varnish and wood samples. The influence of varnishes on the vibro-mechanical properties of wood over the entire audible range, being determined by the frequency dependence of the wood and varnish properties, has not been studied. Moreover, the actual values provided, refer to lacquers and synthetic varnishes that are commonly used for pianos and harps. Investigations into frequency dependent viscoelastic varnish properties of common violin varnish materials, for which explicit values were recorded, could not be found.

Our study focusses on typical traditional violin varnishes. The viscoelastic properties of three representative varnish materials, comprising a particulated grounding, a shellac alcohol and a copal oil varnish, were investigated by testing thin varnish films. The focus was laid on the frequency dependent characterization of the varnishes by studying their dynamic mechanical properties. The varnish films were investigated by DMA and applying the time-temperature superposition (TTS) principle, which allowed an extension of the frequency range [15,16]. For further numerical analyses, a mechanical model was used to describe E and tan(δ) as a function of frequency, which allows to investigate the influence of the varnish on the vibrational behaviour of wood over a wide frequency range. The applicability of the latter approach was validated by a comparison of numerical finite element method (FEM) calculations to experimental measurements of varnish-induced changes on the behaviour of wooden plates as published previously [5]. The results are discussed in the context of numerically determined frequency changes of a violin soundboard induced by different varnish properties.

2. Materials and methods

The varnishes comprised different typical varnish materials based on the suggestions of Baese [17] for traditional varnishing according to the Cremonese varnish procedure. The following varnishes were used for the preparation of thin films:

- A grounding (G), which was composed of a clear oil varnish (Old-Wood classical amber) in combination with 29 wt% pumice powder (Pumice Powder 6/0 from Kremer Pigmente)
- An alcohol varnish (A) consisting of shellac (Shellac Orange from Kremer Pigmente), gum elemi (from Hammerl) and spike oil (Spike-Lavender Oil from Kremer Pigmente) dissolved in ethanol. The alcohol varnish is also known as "1704 varnish".
- An oil varnish (O) (standard quality oil varnish golden brown from Hammerl)

The thin films were obtained by applying the varnishes with a bar coater (gap thickness between 300 μm and 500 μm) on a polypropylene (PP) foil. To avoid possible deformations of the PP foil thus inducing an inhomogeneous varnish distribution, the PP foil was fixed with a double-sided adhesive foil to a stiff plate. The freshly applied films were dried in a conditioned room at 20 °C and 65% RH. When the films were no longer sticky, they were removed from the foil and conditioned in a climate chamber at 20 °C and 35% RH for a minimum of three months.

Samples with dimensions of 6 mm × 50 mm and 4 mm × 30 mm were cut from dried varnish films for the dynamic and static tests, respectively. The final thicknesses ranged between 85 μm (for the alcohol varnish) to 255 μm (for the grounding).

The densities of the varnishes after conditioning at 20 °C and 35% RH were determined by weighing samples that were prepared for DMA measurements (Table 1).

2.1. Static tensile tests

The aim of the static tensile measurements was to receive a higher precision for the static tensile modulus (E_0), i.e. one of the input parameters for the mechanical model used to describe the dynamic behaviour of the varnishes (see '2.2 Dynamic mechanical analysis (DMA)' below).

A micro tensile testing setup with a 5 N load cell, as described in Burgert et al. [18], was used to mechanically test the varnish materials. The samples were clamped at a length of 11 mm and measured with a displacement rate of 3 μm/s (displacement controlled). For each varnish material, at least three samples were measured. The tests were performed with equilibrated samples at 65% RH and 20 °C. For each sample, three E_0-moduli were determined out of linear regressions to the initial part with a minimum of 10 measuring points and $r^2>0.95$, $r^2>0.975$ and $r^2>0.99$ respectively.

2.2. Dynamic mechanical analysis (DMA)

The viscoelastic properties of the varnishes were measured with a DMA RSA III (TA Instruments, New Castle, USA) in the tensile mode at a 0.03% strain level. Isothermal logarithmic frequency sweeps in the range of 0.1 Hz–30 Hz with 10 points per decade were performed at 5 °C steps from −10 °C (occasionally −15 °C) to 30 °C (occasionally 35 °C). The determined dynamic modulus $E = E' + i\,E''$ separates into the storage modulus E', representing the elastic behaviour, and the loss modulus E'', representing the viscous part. The loss tangent, depicting a measure for the damping of the material, is defined as the ratio: $\tan(\delta) = E''/E'$. For each varnish material, two samples were measured.

'Modified' Cole-Cole (log(E'') vs. log(E')) [19,20] and van Gurp-Palmen plots (tan(δ) vs. log(E)) [15,16] were used to check the applicability of the time-temperature superposition (TTS) and to remove outliers. Measurements at temperatures where a vertical shift would have been required to obtain overlapping curves in these plots, were not taken into account for TTS. For the master curves, all measurements were shifted to a reference temperature of 20 °C. The shifting values were determined by minimizing the sum of the relative root-mean-square errors for E', E'' and tan(δ). For the individual varnish sample, the shifting of the different viscoelastic measures was performed with the same parameters. The profile of the shifting values was in good agreement with

Table 1
Average densities and their standard deviation (std) of the selected varnish materials, measured on dried samples with dimension 6 mm × 50 mm.

	Grounding Ø (std)	Alcohol varnish Ø (std)	Oil varnish Ø (std)
Density (kg m^{-3})	1155 (30)	984 (30)	1097 (26)
# samples	4	7	5

the William-Landel-Ferry (WLF) ($r^2 > 0.993$) and to the Arrhenius model ($r^2 > 0.980$), thus a further indication that TTS can be applied [14].

The use of a mechanical model representing the viscoelastic varnish properties, facilitated further numerical analyses. The five-parameter fractional derivative model [21] was used to describe the mechanical behaviour of the varnishes. In contrast to well-known standard models, such as Maxwell, Kelvin-Voigt and Zener models, the five-parameter fractional derivate model showed good agreement over a wide frequency range. Adapted from the complex shear modulus, E', E'' and $\tan(\delta)$ are described with five parameters: the static modulus E_0, a modulus E_∞ being related to the high-frequency dynamic modulus, the fractional derivatives governing the low and high frequency behaviour α and β and the relaxation time t by Ref. [21]:

$$E' = E_0 + E_0(d-1)\frac{\cos\left(\frac{\alpha\pi}{2}\right)\omega_n^\alpha + \cos\left((\alpha-\beta)\frac{\pi}{2}\right)\omega_n^{\alpha+\beta}}{1 + 2\cos\left(\frac{\beta\pi}{2}\right)\omega_n^\beta + \omega_n^{2\beta}} \tag{1}$$

$$E'' = E_0(d-1)\frac{\sin\left(\frac{\alpha\pi}{2}\right)\omega_n^\alpha + \sin\left((\alpha-\beta)\frac{\pi}{2}\right)\omega_n^{\alpha+\beta}}{1 + 2\cos\left(\frac{\beta\pi}{2}\right)\omega_n^\beta + \omega_n^{2\beta}} \tag{2}$$

$$\tan(\delta) = \frac{E''}{E'} = \frac{(d-1)\left(\sin\left(\frac{\alpha\pi}{2}\right)\omega_n^\alpha + \sin\left((\alpha-\beta)\frac{\pi}{2}\right)\omega_n^{\alpha+\beta}\right)}{1 + 2\cos\left(\frac{\beta\pi}{2}\right)\omega_n^\beta + \omega_n^{2\beta} + (d-1)\left(\cos\left(\frac{\alpha\pi}{2}\right)\omega_n^\alpha + \cos\left((\alpha-\beta)\frac{\pi}{2}\right)\omega_n^{\alpha+\beta}\right)} \tag{3}$$

where $d = \frac{E_\infty}{E_0}$, $\omega_n = 2\pi f\tau$ and f the frequency.

2.3. Numerical studies on the vibrational and mechanical properties of varnished wood

Two comparisons of the obtained varnish properties and their influence on the vibrational properties of wood to experimentally measured varnish induced changes as given in Ref. [5] were conducted. The same varnish materials were used in both the latter and current study. Since in Ref. [5] only the oil and alcohol varnishes were studied individually in different multi-layer varnish systems, the comparison could only be made for the two varnishes. A comparison to experimental measurements of varnished wooden plates for the properties of the grounding was not possible. Furthermore, the influence of the varnish on the damping properties of tonewood and the varnish induced shifts of the eigenfrequencies of a violin soundboard were numerically investigated as described in the following paragraphs.

2.3.1. Comparison of dynamic mechanical properties (case 1)

The obtained complex moduli of the pure varnishes were compared to an inverse determination of E on the basis of a two-layer finite element method (FEM) model and the measured frequency changes in Ref. [5]. In the FEM model, the varnish was modelled as a continuous and non-penetrating layer on top of the wood plates. The plate dimensions and wood properties were taken from Ref. [5]. The varnish thicknesses were determined on the basis of the given varnish induced mass changes and their densities (cf. Table 1). E was then determined from an optimization by minimizing the objective function:

$$g = \sum_i \sqrt{\left(\frac{\Delta f_{i,num} - \Delta f_{i,exp}}{f_{i,num,unvarnished}}\right)^2} \tag{4}$$

Where $\Delta f = f_{varnished} - f_{unvarnished}$ is the frequency difference between the varnished and unvarnished plate (induced by the varnish application) for mode i. Referring to Ref. [5], the first radial and longitudinal as well as the first and second torsional bending modes were considered. The subscripts *num* and *exp* correspond to the frequencies being determined numerically and experimentally.

2.3.2. Comparison of eigenfrequencies (case 2)

The influence of the obtained mechanical varnish properties on the eigenfrequencies of the wood plates was determined by FEM simulations (same FEM model as for case 1) and compared to the experimentally observed changes.

2.3.3. Influence of the varnish on damping properties of tonewood (case 3)

The effect of the varnishes on the damping properties of wood was evaluated following the general formulation for multi-layered build-ups as carried out for the loss tangent by Ref. [12]:

$$\tan(\delta) = \frac{\sum (EI\tan(\delta))_j}{\sum (EI)_j} \tag{5}$$

where I is the second moment of area and j refers to the different layers of the build-up (i.e. wood and varnish). For this analysis, the obtained varnish properties with a varnish thickness of 100 μm were investigated in combination with common Norway spruce tonewood properties (r = 460 kgm^{-3}, E_L = 15 GPa, E_R = 0.8 GPa, $\tan(\delta)_L$ = 0.007, $\tan d(\delta)_R$ = 0.020) at low frequencies from Ref. [22] and a wood thickness of 3 mm.

2.3.4. Eigenfrequencies of a varnished violin soundboard (case 4)

The potential influences of encountered differences in E of various varnish materials and the frequency dependence of the varnish properties on the eigenfrequencies of a violin soundboard were investigated by FEM calculations. For this analysis, the moduli of wood and varnish were

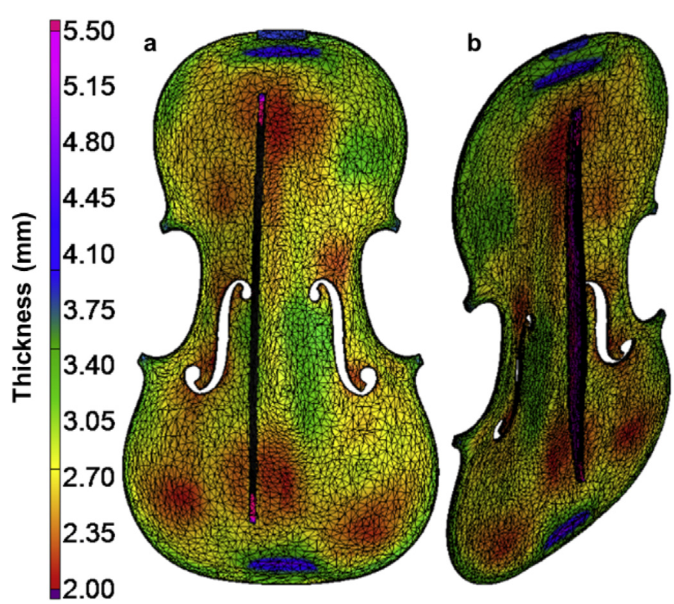


Fig. 1. Wall thickness distribution of the studied violin soundboard.

assumed as constant (i.e. independent of frequency). Inter-varnish variations and frequency dependences of the varnish properties were taken into account in so far, as two varnishes with different complex moduli were considered. In order to highlight differences, slightly exaggerated values of the DMA measurements were used. The influence of a 'compliant', referring to a relatively low E (E_v = 1 GPa) and a 'stiff' varnish (E_v = 3 GPa), on the eigenfrequencies of a violin soundboard made of rather 'compliant' (E_L = 12 GPa, E_R = 800 MPa, G_{LR} = 700 MPa) and 'stiff' (E_L = 15 GPa, E_R = 1000 MPa, G_{LR} = 900 MPa) Norway spruce wood were evaluated. The calculations were performed using Abaqus with a CAD model on basis of an X-ray tomography of a real instrument. The wall thickness distribution of the soundboard is shown in Fig. 1. Varnish thicknesses of 50 µm, 100 µm and 150 µm were considered for the study. The densities of Norway spruce and varnish were selected as 430 kgm^{-3} and 1100 kgm^{-3} respectively.

3. Results and discussion

3.1. Results of the static tensile tests

Even though variations between samples of the same varnish material were apparent, there were clear differences between the different varnish materials. While the alcohol and oil varnish did not show any fracture up to the maximum applied strains (one oil varnish sample was strained up to 64% for testing purposes), the grounding had a consistent ultimate strain of 1.446(±0.009)%.

From the three varnishes tested, the grounding clearly showed the highest static tensile modulus with 497(±92) MPa, roughly seven times (based on the averaged values) greater than the modulus of the alcohol varnish reaching 69(±16) MPa. However, the latter was again (based on the averaged values) around 3.7 times greater than the static tensile modulus of the oil varnish, for which only two values could be obtained by the applied method (11 and 23 MPa).

The detailed results of the static tensile tests are provided in the supplementary materials. The values reported here refer to the values obtained for r^2>0.975.

3.2. Results of the dynamic mechanical analysis

Fig. 2 exemplarily visualizes the TTS working principle for one grounding sample. The original measured data for E', E'' and tan(δ), as shown in Fig. 2 a, were shifted to form continuous master curves over a wide frequency range (Fig. 2 b). The corresponding shifting values are shown in the figure legend.

Different fits of the five-parameter fractional derivative model (equation (1) to (3)) to the obtained master curves based on the experimental measurements, varying with handling of E_0, were determined. The values were obtained by minimizing the sum of the root-mean-square errors of E, E', E'' and tan(δ). Fig. 3 shows four different fits to the master curve in the frequency range of 0.1 Hz–100000 Hz for the same grounding sample as before (cf. Fig. 2). For the first three curves, the fitting was reduced to a four parameter problem by using the mean value ($E_{0,\ stat.\ ø}$ = 497 MPa), the lowest ($E_{0,\ stat.\ low}$ = 393 MPa) and the highest ($E_{0,\ stat.\ up}$ = 677 MPa) value for E_0 from the static measurements (cf. supplementary materials). In contrast, the fourth curve ($E_{0,\ opti}$), shows the fitting result without predetermined E_0. For the complex modulus, all regressions showed a good agreement over the frequency range considered. For low frequencies values, where E approaches the different E_0, major differences became apparent. Besides this, strong deviations to the master curve for low frequencies (f<1 Hz) emerged for tan(δ) when using the measured static $E_{0,\ stat}$. The results illustrate that the influence of E_0 was restricted to the low frequency range (f<1 Hz), a region that is not relevant for the study of musical instruments. In the frequency range of 1 Hz–100000 Hz, all regressions show a good agreement for the viscoelastic measures, irrespective of E_0. Regarding violins, the frequency range of interest can reasonably be assumed to be greater than 20 Hz. Thus, for further numerical evaluations of the varnish impact on the vibrational behaviour at different frequencies, the actual choice of E_0 plays a minor role.

A comparison of the master curves of all samples is provided in Fig. 4 a and b. Fig. 4 c and d show the corresponding fits on basis of the five-parameter fractional derivative model obtained for regressions in the range of 0.1 Hz–100000 Hz and taking the mean value of E_0 from the static tensile measurements. The selected E_0 and the obtained parameters are summarized in Table 2. For all varnishes, E increased with increasing frequency while tan(δ) decreased. The values of tan(δ) are thereby strongly negatively related to log(E'/r), irrespective of the varnish materials (Fig. 5). As previously for the static tensile measurements, the grounding showed the highest while the oil varnish showed the lowest E for the entire frequency range. At the same time, tan(δ) was highest for the oil varnish and lowest for the grounding.

In case of tan(δ), the main deviations between the different varnish materials occurred at low frequencies while differences at higher frequencies were smaller. Overall, the complex modulus and tan(δ) of the

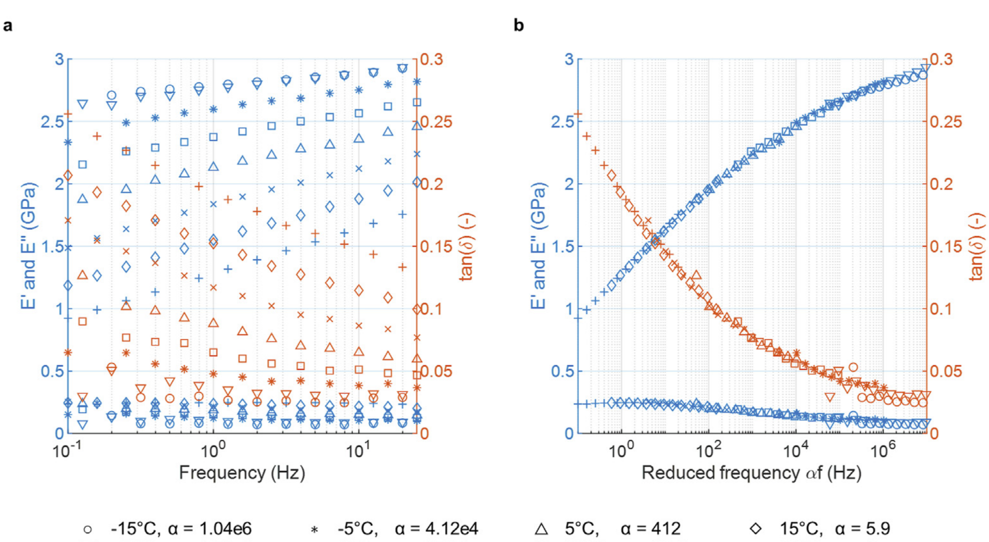


Fig. 2. **a** Storage modulus E′, loss modulus E'' and loss tangent tan(δ) for one grounding sample at various temperatures and **b** the corresponding shifted master curves for E′, E'' and tan(δ) at 20 °C. To increase clarity, only every second measuring point is shown.

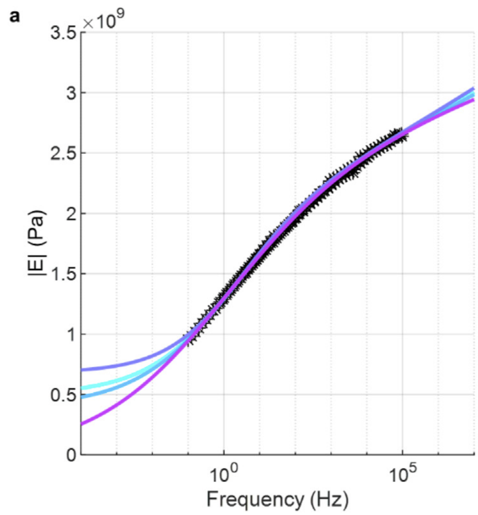


Fig. 3. Comparison of the DMA master curve (*) to the regressions for the five-parameter fractional derivative model on basis of the average ($E_{0,\ stat.\ Ø}$ = 497 MPa), the lowest ($E_{0,\ stat.\ low}$ = 393 MPa) and the highest ($E_{0,\ stat.\ up}$ = 677 MPa) observed static tensile moduli as well as without E_0 ($E_{0,\ opti}$) for **a** the complex tensile modulus |E| and **b** tan(δ).

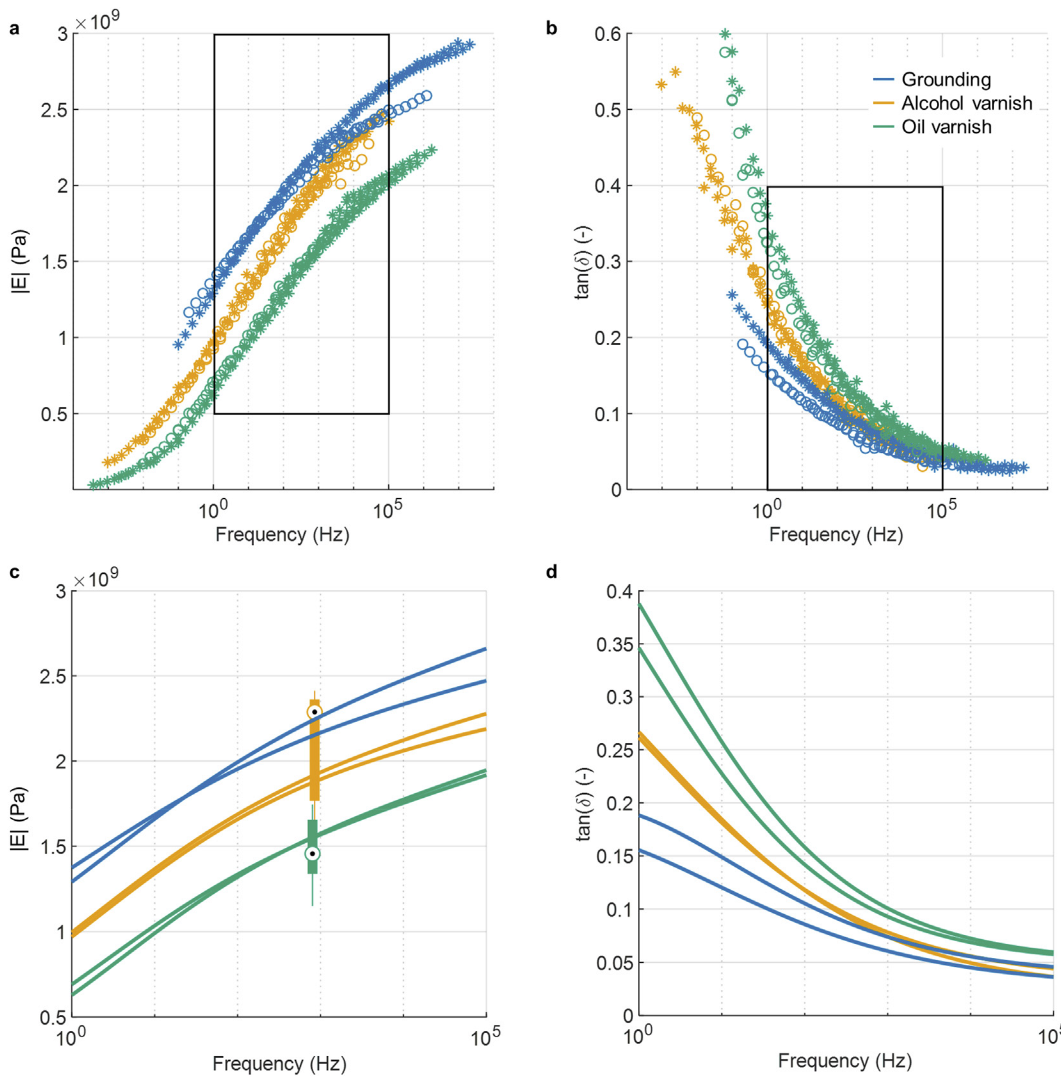


Fig. 4. DMA master curves for all samples for **a** complex modulus |E| and **b** tan(δ). The symbols indicate the sample replicates. The applicability of the corresponding fitted models for **c** complex modulus |E| and **d** tan(δ) are restricted to frequencies greater than 1 Hz. In **c**, the inverse determined E for the alcohol and oil varnishes are shown as boxplots.

Table 2
Model parameters for the five-parameter fractional derivative model for the DMA samples (cf. equations (1)–(3)). The values for E_0 derive from the static tensile tests, the remaining parameters were obtained by fitting the model to the experimental results.

	Sample	E_0 (MPa)	E_∞ (GPa)	α (−)	β (−)	t (s)
Grounding	1	500	2.08	0.309	0.288	0.268
	2	500	2.12	0.346	0.318	0.132
Alcohol	1	70	1.89	0.330	0.314	0.125
	2	70	1.83	0.335	0.313	0.179
Oil	1	20	1.37	0.391	0.360	0.127
	2	20	1.41	0.402	0.370	0.075

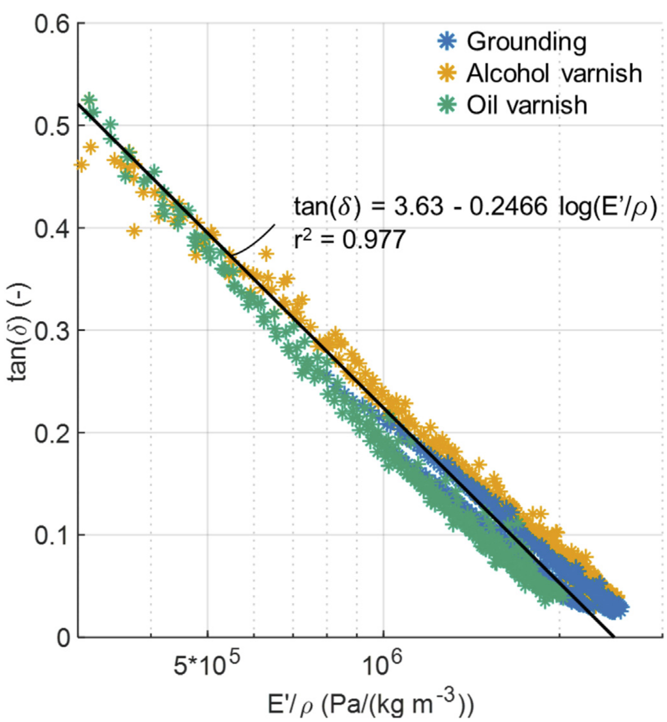


Fig. 5. Relation between tan(δ) and E'/ρ for the master curves of the different samples.

investigated varnishes showed similar behaviours and both were strongly dependent on the frequency; especially tan(δ) for frequencies lower than 1000 Hz.

When analyzing the input parameters for the dynamic model, especially in the case of tan(δ), the static tensile modulus *E* appears to be relatively high. However, due to the difference in nature between static and dynamic measurements, the results of the two methods cannot be directly compared. Moreover, the static modulus is also dependent on the strain rate. A further decrease in the strain rate and an associated reduction of the static tensile modulus would bring the values closer to those obtained by optimization.

The differences between the values of the various varnish materials are attributed to the properties of the individual ingredients and their combination within the varnish recipes. The latter determines the film formation and cross-linking processes that are governed by physical changes and chemical reactions [23]. The high stiffness and brittle behaviour of the grounding can be attributed to the application of pumice powder, which functions as a reinforcement. The alcohol varnish mainly consists of shellac dissolved in ethanol. The film forming process will emanate from physical changes and crosslinking of the polyester matrix and the simultaneous formation of aleuritic acid establishing a stiff three-dimensional network of macromolecules. In contrast, the film formation of linseed oil (in grounding and oil varnish) is dominated by chemical reactions, mainly oxidation and polymerization at the carbon-carbon double bonds [23,24]. Turpentine (in the oil varnish) and drying oils are subjected to both. Firstly, evaporation of the volatile components will take place followed by a crosslinking of the unsaturated fatty acids similar to the processes occurring for linseed oil [23]. As observed for linseed oil, the oxidation and polymerization is a persistent process, that continues for years [24]. Accordingly, turpentine and linseed oil are expected to still contain unreacted compounds such as glyceride that act as plasticizers and therefore result in the observed low stiffness of the oil varnish.

3.3. Numerical studies of the vibrational and mechanical properties of varnished wood

3.3.1. Numerically determined dynamic mechanical properties (case 1)

The boxplots in Fig. 4 c show the resulting varnish properties obtained by the inverse determination for experimental measurements of the influence of the varnish on wooden plates. Generally, the resulting *E* are of the same order as for the DMA measurements. Moreover, as for the DMA measurements, the alcohol varnish had a higher *E* than the oil varnish. Nonetheless, deviations between the methods occur, which might be explained by the inverse determination on basis of four eigenmodes at different frequencies and the assumptions made for the numerical FEM model (i.e. non-penetrating varnish with constant E).

3.3.2. Numerically determined eigenfrequencies (case 2)

The comparison of the numerically and experimentally determined varnish-induced changes of the eigenfrequencies (Fig. 6) revealed an overall good match, when taking the value of *E* at the corresponding eigenfrequency. In contrast, pronounced differences were obtained when neglecting the frequency dependence of the varnish properties, i.e. when the tensile moduli of the varnishes were evaluated at 1 Hz. The comparison confirmed the applicability of the mechanical varnish models for numerical evaluations of the influence of the varnish and demonstrates that the frequency dependency cannot be neglected, at least for the varnishes studied. The influence of the frequency is particularly noticeable for modes that exhibit a strong varnish influence. The variance of the varnish influence for the different modes resulted from the specific wood and varnish properties, as well as from manual varnishing procedure: the same varnish has a different effect on a plate with lower stiffness compared to a plate with a higher stiffness and again different when applied thicker or thinner.

However, a numerical determination of the varnish influence requires that the corresponding frequency range is known to be correctly reflected. Restrictions on the frequency range of the varnish properties thus directly limit the frequency range for the numerical calculation of the varnish influence. Furthermore, a realistic model must be considered. If, as in the present investigations, the varnishes only slightly penetrate into the wood, the assumption of a two-layer varnish model is well justified. For (varnish) systems with higher penetration depths or more complex structures (e.g. multi-layer varnish systems), more complex numerical models are likely to be required as well.

3.3.3. Influence of the varnishes on damping properties of tonewood (case 3)

The influence of the varnishes on the damping properties of wood, which was evaluated based on eq. (5), is provided in Fig. 7. As input for the varnish material properties, the fitted five-parameter fractional derivative model (without predetermined E_0) was used. The results show an increase in tan(δ), which was found to be more pronounced in radial than in longitudinal directions. As for the varnish properties themselves, the influence of the varnish on the wood was found to exhibit a strong frequency dependency. The highest influence of the varnishes was observed at low frequencies. With increasing frequency, this influence decreases continuously. However, this study does not consider the frequency-dependence of the wood damping properties. These latter properties are known to increase with frequency, especially for frequencies higher

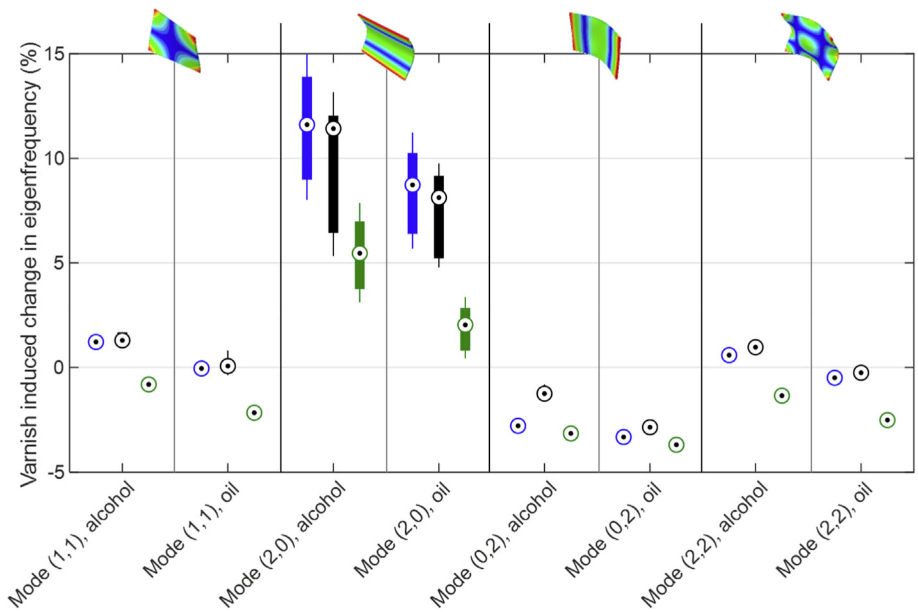


Fig. 6. Comparison of experimentally and numerically determined varnish-induced changes of eigenfrequencies for different eigenmodes of Norway spruce wood plates The experimentally measured changes (values taken from Ref. [25]) are shown by the black boxplots. The numerical results were determined in two different ways: (i) E_V was determined at the actual eigenfrequency (blue boxplots) and (ii) E_V was determined at 1 Hz (green boxplots). For each mode, the results of the alcohol varnish are plotted on the left and the results of the oil varnish are plotted on the right side.

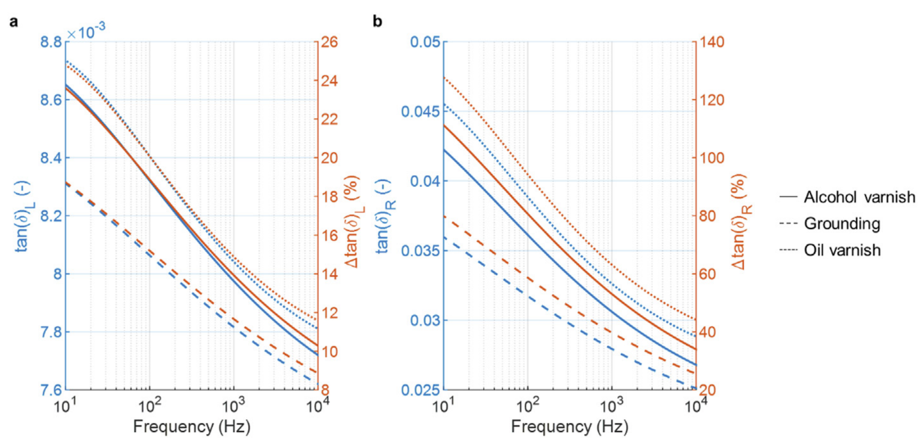


Fig. 7. Influence of the studied varnishes on the loss tangent of wood for the **a** longitudinal direction ($\tan(\delta)_{L,wood} = 0.007$, $E_{L,wood} = 15$ GPa) and **b** radial direction ($\tan(\delta)_{R,wood} = 0.020$, $E_{L,wood} = 0.8$ GPa). The obtained absolute values are shown as blue curves while the relative changes to the initial wood properties are shown in orange.

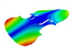
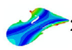
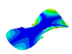
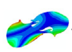
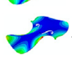
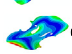
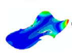
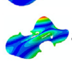
than 2000 Hz and for tan(δ) in the longitudinal direction [22,26]. Thus, the influence of varnish at high frequencies should be less pronounced than described in Fig. 7. Consequently, the frequency-dependence of the influence of the varnish on the damping properties of wood would be further enhanced. Differences in varnish materials are also apparent but remain less pronounced than the influence of the frequency for the frequency range considered (from 1 Hz to 10000 Hz).

3.3.4. Eigenfrequencies of a varnished violin soundboard (case 4)

The influence of a stiff and a compliant varnish on the eigenfrequencies of the first eight eigenmodes of a violin soundboard, evaluated by FEM calculations, are summarized in Table 3. Besides the stiffness of the varnishes, Table 3 summarizes the results for different thicknesses of the varnish applied to a stiff and a compliant Norway spruce soundboard. The observed changes arise from two overlapping aspects. The varnish-induced mass increase results in a (slight) decrease in eigenfrequencies. Subject to the tensile moduli of wood and varnish and depending on the specific eigenmode, this decrease will be further pronounced or counteracted.

For the performed study, the stiff varnish resulted in an increase for all eigenfrequencies, irrespective of the mode and the thickness of the varnish. However, the compliant varnish reduced the eigenfrequencies (expect for mode 2 of the compliant soundboard). Generally, the influence of the varnish on the eigenfrequencies of individual modes increased with increasing varnish thickness (except for the influence of the stiff varnish on the eigenfrequency of mode 6). The highest absolute increase was recorded for mode 8 (+26.2 Hz ≙ 5.4% on stiff Norway spruce wood, + 32.8 Hz ≙ 7.6% on compliant Norway spruce wood), while the highest relative increase was recorded for mode 2 (+7.1% on stiff spruce, + 9.6% on compliant Norway spruce wood). For the decreases, the highest absolute change was recorded for mode 6 (- 14.7 Hz ≙ −3.3% on stiff spruce, - 10.9 Hz ≙ −2.8% on compliant spruce), while the maximum relative decrease was recorded for mode 1 (- 3.7% on stiff Norway spruce wood, - 3.0% on compliant Norway spruce wood). Considering the mode shapes, major increases arise for stiff varnishes and modes that show a high sensitivity to radial wood properties (mode 2 and 8), while major decreases occurred for compliant varnishes and modes determined by E_L (mode 6) and G_{LR} (mode 1) [cf. 27]. The application of the compliant varnish on the stiff soundboard generally resulted in the highest observed decreases, whereas the application of the stiff varnish on compliant soundboard resulted in the highest observed increases and highest overall determined changes. In contrast to these extremes, the

Table 3
Comparison of eigenfrequencies (Hz) at different modes from unvarnished and varnished soundboards. Columns on the left show the influence of rather stiff on the right side for rather compliant Norway spruce tonewood. The "(…)" show the deviations (Hz) in eigenfrequency induced by the different varnish configurations (with varying E_V and varnish thickness t_V).

	Wood 1	Wood 1 with different varnish						Wood 2	Wood 2 with varnish					
	E_L = 15 GPa E_R = 1 GPa G_{LR} = 900 MPa	E_v = 1 GPa t_v = 50 µm	E_v = 3 GPa t_v = 50 µm	E_v = 1 GPa t_v = 100 µm	E_v = 3 GPa t_v = 100 µm	E_v = 1 GPa t_v = 150 µm	E_v = 3 GPa t_v = 150 µm	E_L = 12 GPa E_R = 0.8 GPa G_{LR} = 700 MPa	E_v = 1 GPa t_v = 50 µm	E_v = 3 GPa t_v = 50 µm	E_v = 1 GPa t_v = 100 µm	E_v = 3 GPa t_v = 100 µm	E_v = 1 GPa t_v = 150 µm	E_v = 3 GPa t_v = 150 µm
 1	100.4	99.2 (-1.3)	101.0 (+0.6)	97.9 (-2.5)	101.2 (+0.8)	96.7 (-3.7)	101.3 (+0.8)	89.2	88.3 (-0.9)	90.4 (+1.1)	87.4 (-1.8)	91.0 (+1.8)	86.5 (-2.7)	91.4 (+2.1)
 2	175.0	174.8 (-0.3)	181.2 (+6.2)	174.2 (-0.8)	185.0 (+10.0)	173.6 (-1.4)	187.5 (+12.5)	156.0	156.6 (+0.6)	163.5 (+7.5)	156.7 (+0.7)	168.0 (+12.0)	156.6 (+0.6)	170.9 (+14.9)
 3	256.8	254.8 (-2.0)	261.7 (+4.9)	252.6 (-4.2)	264.4 (+7.6)	250.4 (-6.4)	(+9.1)	228.4	227.5 (-0.9)	235.0 (+6.6)	226.2 (-2.2)	238.7 (+10.3)	224.8 (-3.6)	240.9 (+12.5)
 4	308.0	305.2 (-2.8)	312.5 (+4.4)	302.3 (-5.7)	314.7 (+6.7)	299.4 (-8.7)	315.7 (+7.7)	274.7	273.0 (-1.6)	280.9 (+6.2)	271.2 (-3.5)	284.3 (+9.6)	269.1 (-5.5)	286.1 (+11.4)
 5	417.6	413.0 (-4.5)	422.1 (+4.6)	408.5 (-9.1)	424.1 (+6.5)	404.0 (-13.6)	424.5 (+7.0)	371.5	368.6 (-2.9)	378.5 (+6.9)	365.5 (-6.0)	382.0 (+10.5)	362.2 (-9.3)	383.7 (+12.2)
 6	438.4	433.6 (-4.8)	441.0 (+2.6)	428.6 (-9.8)	440.6 (+2.2)	423.7 (-14.7)	439.0 (+0.5)	390.9	387.6 (-3.3)	395.5 (+4.6)	383.9 (-7.0)	396.3 (+5.4)	380.0 (-10.9)	395.6 (+4.7)
 7	470.3	467.0 (-3.3)	480.1 (+9.8)	463.3 (-7.0)	485.7 (+15.3)	459.5 (-10.8)	489.0 (+18.7)	418.4	417.0 (-1.4)	431.1 (+12.7)	415.0 (-3.4)	438.7 (+20.2)	412.6 (-5.8)	443.5 (+25.1)
 8	483.3	480.9 (-2.4)	495.7 (+12.4)	478.4 (-5.0)	504.1 (+20.8)	475.7 (-7.7)	509.5 (+26.2)	430.7	430.4 (-0.3)	446.5 (+15.8)	429.6 (-1.1)	456.9 (+26.2)	428.4 (-2.3)	463.5 (+32.8)

application of compliant varnish on the compliant soundboard showed the lowest influence of a varnish application on the eigenfrequencies. For the latter, the changes induced by the additional mass of the varnish are more or less balanced by the stiffening effect of the varnish.

As described above, the calculations were performed with exaggerated values for the tensile modulus of the varnishes. In the range of frequencies of the eigenmodes examined here, the frequency-dependent differences of E_v were less pronounced. Nevertheless, in addition to the different values for the various varnish materials, an influence of the frequency was already visible for these first eigenfrequencies, in the range of 100–500 Hz. However, it was not only attempted to represent the frequency dependence of the dynamic varnish properties with the selected E_v, but rather to cover a general range of E_v which can be expected for highly diverse varnish materials.

The comparison of the influence of a compliant and a stiff varnish on the eigenfrequencies of a soundboard, resulting mostly in decreases and increases respectively, highlights the importance of the varnish stiffness. The latter, however, might be subject to two factors as described before: the actual varnish material itself and the frequency of the eigenmode. While it is therefore not possible to make general statements on the sign of the shift of the eigenfrequencies for soundboard and violins, the results indicate that numerical models are able to correctly determine distinct changes provided that the viscoelastic properties of the varnish are known. Even though the calculated changes in eigenfrequency are smaller than changes induced by e.g. plate thickness and arching changes [cf. 28], they might be helpful for luthiers, who tune their plates and violins in the white, i.e. before any varnish application. The X and ring mode (here mode 2 and 6 respectively) are commonly used for plate tuning [29]. Both modes revealed (among the observed modes) a high sensitivity of the eigenfrequencies to a varnish application. These modes will be differently influenced depending on the varnish properties.

4. Conclusions

The viscoelastic properties of three different traditional varnishes were characterized over a wide frequency range, thereby covering the relevant audible frequency range. Comparisons to experimental measurements on the influence of varnishes on wooden plates show good agreement with numerical FEM calculations in relation to the determined varnish properties. Hence, the obtained material models can be used to perform further numerical evaluations, e.g. as done in this study for calculating the expected changes when applied on a violin soundboard. For general statements on the influence of the studied varnishes on the vibrational properties of wood, three main considerations should be taken into account with respect to the varnish properties: (i) the general trend of an increase in the complex tensile modulus and a decrease in tan(δ) for an increasing frequency is similar for the different varnishes, (ii) different varnish materials have different varnish properties. While for the studied varnishes the differences in E remains more or less constant over the frequency range, the differences in tan(δ) are most pronounced at low frequencies. Thereby, the relation of tan(δ) to log(E'/ρ) is independent of the varnish material and the frequency, (iii) the viscoelastic properties show a strong dependence on the frequency, which is most pronounced for tan(δ) in frequencies smaller than 1000 Hz. Thus, for any discussion of the influence of the varnish on the vibro-mechanical properties of wood, it is important to note and consider the frequency of the corresponding eigenmodes.

Despite the presented frequency changes, associated changes of the damping properties should be kept in mind. The influence on tan(δ) for the studied varnishes, is more pronounced for compliant than for stiff varnishes and most accentuated at low frequencies.

To further improve the understanding of the influence of varnishes on the vibro-mechanical properties of wood, research on additional varnish materials should be conducted. Investigations on the changes of the varnish properties over time would add to the picture. Moreover, the frequency dependent influence of varnishes on the vibrational properties of whole instruments could be studied. Finally, such investigations could help luthiers and scientists to select between different varnishes or for assessing the suitability of newly designed varnishes.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rinma.2020.100137.

Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time due to technical or time limitations.

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