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Original Article

Acoustic Analysis of Used Tuning Forks

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OBJECTIVE: In this study, we evaluated used aluminum tuning forks (TFs) for fundamental frequencies (FF), overtones, and decay times.

MATERIALS and METHODS: In total, 15 used (1 C1, 11 C2, and 3 C3) and 1 unused (C2) TFs were tuned, and the recorded sound data were analyzed using the Praat sound analysis program.

RESULTS: It was found that FFs of the recorded sounds produced by the used C2-TFs presented a high variability from 0.19% to 74.15% from the assumed FFs, whereas this rate was smaller (1.49%) in the used C3-TFs. Further, decay times of the used C2-TFs varied from 5.41 to 40.97 s.

CONCLUSION: This study, as the first of its kind in the literature, reported that some of the used aluminum TFs lost their physical properties that are important for clinical TF tests. It could be said that this is a phenomenon related to metal fatigue, which is common in aluminum products due to the cyclic load.

KEYWORDS: Tuning forks, aluminum, hearing loss

INTRODUCTION

Tuning fork (TF) is a device that produces a fundamental frequency (FF) and at least one additional overtone when it is struck. Vibrations and sounds of other frequencies diminishes within few milliseconds as a result of the design of tuning fork (forks and handle) and only FF is left to be heard; hence, this sound is accepted as a pure tone [1].

Different TFs are used for various purposes. While A note tuning forks (A-TFs), whose fundamental frequencies are in or close to 440 Hz are used in the musical field since the first invention of TF by Shore (1711), in the medical field C note tuning forks (C-TFs) are used for evaluation of vibration, vibration-induced pain, and hearing senses by practitioners, otologists, neurootologists, neurologists, and trauma surgeons [2]. As reported by Bickerton and Barr (1987), TFs in medical use today are based on the so-called "philosophical" or "scientific" pitch stated in terms of C at 512, which accords with Handel's A at the original figure of 422.5 Hz.

For evaluation of hearing, C2 (512 Hz) and C3 (1024 Hz) TF tests are one of the major routines of otologic–neuorotologic examination for years [3-7], although their clinical value to find out air-bone gap is arguable as pointed out by Ng and Jackler [8]. It has been shown that better results are provided by experienced physicians when the basic rules are followed [6, 9]. Briefly, the prongs of any TF should be sharply struck at a point approximately one-third of its length from the free end against some resistant, but elastic, object [6]; palmar strike on the physicians' thenar eminence of the other hand is mostly recommended [6, 9].

The first TF invented by Shore in 1711 [8, 10], the first TF given to the Foundling Hospital of London in 1751 by Hendel [10], and the first TF which was known to be clinically used by Sir Charles Wheatstone in 1827 [8] were all steel.

As pointed out by MacKechnie, Greenberg [11] diagnostic TFs were transitioned to aluminum in time, as aluminum is resistant to corrosion, lighter than steel, and cheaper to manufacture. In the literature, the only study comparing the steel and aluminum TFs was by MacKechnie, Greenberg [11], and it demonstrated that steel ones are better able to detect a lesser air-bone gap. They suggested that this difference could be important for using TFs to determine candidacy for surgeries in which indication is mainly based on the amount of air-bone gap such as in stapes surgery.

On the other hand, metal fatigue [12] must be another topic for consideration as related with aluminum TFs. In mechanical engineering, it is very well known that aluminum products are more sensible to metal fatigue [12]. However, in the literature, there is no study

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presenting the effect of metal fatigue on acoustic properties of TFs. Using practically available sound analysis programs, recorded sound of the vibrated TF can be easily analyzed for the FF, overtones, and their decay time. Our purpose in this study is to evaluate acoustic properties of TFs in use by the department for years.

MATERIALS and METHODS

This study was performed using 15 aluminum TFs [1 in 256 Hz (C1), 11 in 512 Hz (C2) and 3 in 1024 Hz (C3)], which were in use by the department for 15–20 years and one aluminum C2 TF, which remained unused during the same period was used as the control. No information about the manufacturer company was present on all. As we did not use any human or animal subjects, no ethical committee approval or informed consent were needed.

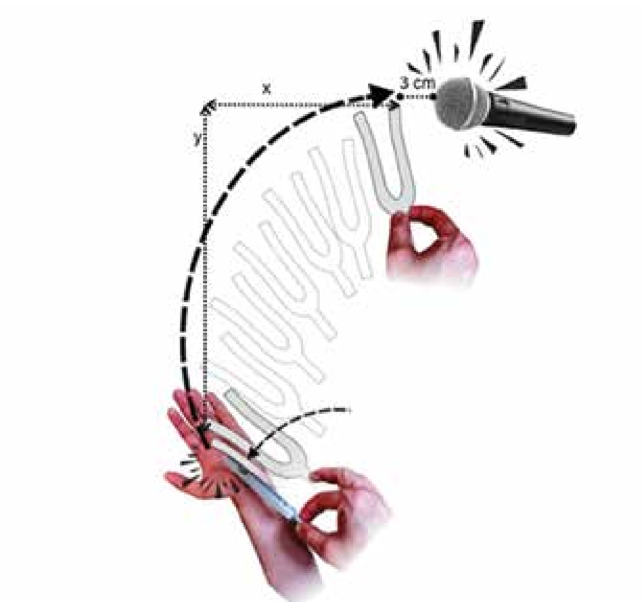

Figure 1. Scheme of the striking and recording of tuning forks (x: 25 cm; y: 40 cm).

The same person vibrated all tuning forks three times by striking the pisiform bone of his left hand in an acoustically treated room. After being struck, TFs were moved to a distance 3 cm away from the microphone, and the air-transmitted sound was recorded for digital storage (Figure 1). Sound samples of TFs were directly recorded into the Praat sound analysis software using a 44000 kHz sampling rate and 16-bit quantization; frequencies and amplitudes were analyzed in the Praat. As pointed out by Boersma [13] Praat uses straightforward and robust algorithm for periodicity detection, working in the lag (autocorrelation) domain.

The long-lasting frequency was accepted as FF, and higher frequencies in the recorded sound were taken as the overtones. The first and second overtones were only analyzed from each recording.

The difference in rate between the original FF (oFF) written on the TF and recorded FFs (rFF) of each TF was calculated as follows: 100 × (1 - oFF/rFF). Using the same formula, differences in overtone frequencies from their assumed harmonic frequencies were also calculated. Further, ratio of the recorded frequencies of the overtones to rFF was calculated.

Decay time of FF for each TF was calculated as the period in which the sound amplitude reached the noise floor of the room, which is 17.25 dB SPL.

RESULTS

In Table 1, the frequency components of sound data recorded from each activated TF are seen. It was clearly observed that each TF produced a dominant long-lasting frequency (rFF) with higher amplitude and further overtones.

Table 1. Assumed and recorded fundamental frequencies and overtones of the tuning forks

	TF	oFF (Hz)	rFF (Hz)	D-FF (%)	Assumed frequency of the first harmonic	rOT1	D-OT1 (%)	Assumed frequency of the second harmonic	rOT2	D-OT2 (%)
	unused	512	514	0.39	1024	1033	0.87	2048	2184	6.23
Used	1	256	296	13.51	512	1656	69.08	1024	4621	77.84
	4	512	540	5.19	1024	3150	67.49	2048	3772	45.71
	5	512	540	5.19	1024	3130	67.28	2048	3792	45.99
	10	512	511	−0.20	1024	3043	66.35	2048	3792	45.99
	2	512	562	8.90	1024	1012	−1.19	2048	3427	40.24
	3	512	582	12.03	1024	1025	0.10	2048	3768	45.65
	8	512	540	5.19	1024	1162	11.88	2048	3192	35.84
	11	512	495	−3.43	1024	1023	−0.10	2048	3268	37.33
	12	512	461	−11.06	1024	1058	3.21	2048	2860	28.39
	13	512	294	−74.15	1024	585	−75.04	2048	1738	−17.84
	14	512	503	−1.79	1024	1018	−0.59	2048	3181	35.62
	15	512	513	0.19	1024	1082	5.36	2048	3133	34.63
	6	1024	1038	1.35	2048	2073	1.21	4096	3047	−34.43
	7	1024	1058	3.21	2048	2094	2.20	4096	3067	−33.55
	9	1024	1023	−0.10	2048	2048	0.00	4096	3088	−32.64

D-FF: difference of rFF from oFF; D-OT1: difference of rOT1 from the assumed first harmonic; D-OT2: difference of rOT2 from the assumed second harmonic; FF: fundamental frequency; oFF: assumed fundamental frequency by the manufacturer; OT1: the first overtone; OT2: the second overtone; rFF: recorded FF when tuning; rOT1: recorded frequency of the first overtone; rOT2: recorded frequency of the second overtone; TF: tuning forks

Table 2. Peak amplitudes and decay time values of the tuning forks

	TFs	oFF (Hz)	dB SPL Peak	rFF Decay Time	OT1 Decay Time*	OT2 Decay Time*	OT1 Decay Rate	OT2 Decay Rate
unused	512	86.73	51.32	34.13	12.78	1.5	4.02	
Used	1	256	85.58	11.11	3.01	1.56	3.69	7.12
	2	512	81.58	8.42	4.06	1.78	2.07	4.73
	3	512	84.08	8.8	3.07	1.76	2.87	5
	4	512	85.1	31.43	17.8	8.5	1.77	3.7
	5	512	88.9	32.61	13.85	6.77	2.35	4.82
	8	512	81.31	6.51	1.87	1.65	3.48	3.95
	10	512	85.83	38.19	19.35	8.87	1.97	4.31
	11	512	81.38	8.77	3.24	2.33	2.71	3.76
	12	512	72.62	5.41	1.67	1.19	3.24	4.55
	13	512	88.52	21.76	12.1	7.5	1.8	2.9
	14	512	81.75	19.87	7.68	4.76	2.59	4.17
	15	512	77.51	40.97	18.31	16.65	2.24	2.46
	6	1024	78.16	47.71	27.85	11.7	1.71	4.08
	7	1024	75	41.35	22.38	6.95	1.85	5.95
	9	1024	90.82	47.85	26.62	11.16	1.8	4.29

FF: fundamental frequency; oFF: assumed FF by the manufacturer; OT1: the first overtone; OT2: the second overtone; rFF: recorded FF when tuning; TF: tuning forks; *: seconds

If was found that the unused C2-TF produced rFF at 514 Hz, and difference rate from 512 Hz was calculated as 0.4%, whereas the difference rates of rFFs produced by the used C2-TFs presented a high variability from 0.19% to 74.15%. As seen in Table 1, the difference in rFF was <1% in only TF-10 and TF-15. Although 8 TFs presented differences between 1% and 10%, approximately +/-10% differences were seen in 2 TFs. Besides, TF-13 produced rFF at 294 Hz with the difference of -75.15%.

Difference of rFF from oFF (D-FF) of C1-TF was found to be 13.51% rFF from 256 Hz. On the other hand, mean rFF of 3 used C3-TFs was found to be 1039.67 +/- 17.56 Hz with D-FF of 1.49%.

The overtones detected in each TF when tuned are also given in Table 1. The unused C2-TF produced the overtones, which were closer to the assumed harmonic frequencies (1024 Hz and 2058 Hz); the first and second overtones were 2.0 and 4.25 times higher than its rFF, respectively. In the used C2-TFs, the first overtone frequencies varied from 585 Hz to 3150 Hz, and 4 (TF-4, 5, 8, and 13) of them disclosed more than 60% difference from the assumed harmonic (1024 Hz). In 3 C2-TFs (TFs-4, 5, and 10), the first overtone frequencies were 5.86 times higher than rFF, whereas this rate was 2.01 in the other 8 C2-TFs (Table 1).

Mean value of the second overtone frequencies recorded from the used C2-TFs was 3265.73 +/- 601.4 Hz (mean difference from 2048 Hz, the assumed second harmonic was 34.32% +/- 18.26%), which was 6.46 times higher than their mean of rFF (Table 1).

The used C1-TF disclosed overtones with differences of 13.51% and 77.53% from the assumed harmonics (512 Hz and 1024 Hz), respectively. On the other hand, 3 C3-TFs included in this study produced reasonably closed first overtones (mean frequency: 2071.67 +/- 23.03 Hz) to the first assumed harmonic (2048 Hz), but not to the second one (4096 Hz). Mean frequency of the second overtones of the used C3-TFs was 3067.33 +/- 20.5 Hz (mean difference from the assumed harmonic, 4096 Hz, was 33,54 +/- 0,89% in the negative direction) (Table 1).

In Table 2, the peak amplitudes of the sound data recorded from the activated TFs are seen. Whereas it was 86.73 dB-SPL in an unused one, mean peak amplitude of the used TFs was 82.54 +/- 5.2 dB-SPL. In Table 2, decay times of the rFF and overtones were also presented. Although it was found to be 21.32 s in the unused C2-TF, decay times of the rFF recorded from the used C2-TFs varied from 5.41 to 40.97 s. It was found that 5 (45.45%) of them presented rFF with a decay time shorter than 10 s.

As seen in Table 2, mean decay time of the first overtones in the used C2-TFs was 2.46 times lower than mean decay time of their rFF, while this rate was 1.5 in the unused C2-TF. For the second overtones, this rate was 4.03 in the used C2-TFs and 7.65 in the unused one.

DISCUSSION

This is the first study presenting changes in the acoustic properties of used TFs with time. We noticed that when tuned, some, but not all, of the used TFs presented differences in both rFFs and overtones and shorter decay times in both rFFs and overtones. According to Ng and Jackler [8] in the following sentence, clinical creditableness of TFs are not questionable: In today's era of technologic sophistication, TFs may seem an anachronism to some, but they have an appeal to others both for their elegant simplicity and for their ability to alert the clinician to occasional inaccuracies that occur in even the most carefully performed audiologic investigations. Based on the data of this study, we suggest that the changing properties of TFs could be related with clinical inconvenience.

As previously described [6], TFs produce one FF and additional overtones, which are non-harmonic. The overtones have smaller amplitudes and subside in shorter duration than do FFs. Further, as documented [14], TFs produce a clang mode with a very high amplitude when struck and fades very soon. Therefore, TFs were accepted as pure-tone generators in practice for years. Our data showed that none of the used TFs lost their "pure-tone" specialty. However, some of them presented different rFF from the assumed FF by the manufacturer. Even in the recording taken from the TF, which was assumed as C2 by the manufacturer but produced rFF at 294 Hz when tuned, its overtones frequencies were far from its rFF and lasted in shorter duration than rFF. Decay times of the overtones recorded in all used TFs in this study were shorter than rFF. Even in the C2-TFs presenting very short decay time (<10 seconds), rFF were approximately 2,87 times longer than the first overtone.

However, although the used TFs still retained their characteristic as pure-tone generator, the FF and its decay time are of major importance during clinical tests. It is well known that the hearing threshold of each frequency is different (ISO, 2003), and 512 Hz was used as major standard for TF tests to determine air-bone gap and level of hearing loss [6, 15]. No data on how many percent change in rFF changes clinical value of the TF tests have been presented. In our study, we analyzed only unused C2-TF, and the difference rate of its rFF from 512 Hz was 0.4%. In the second figure of the study published by Stevens and Pfannenstiel [9], the tested C2-TF produced FF in 509 Hz, which meant 0.58% in difference rate according to the formula used in our study. It is known that audible energy levels change through frequency of the sound wave; hence, 5 dB-SPL at 500 Hz equals to 0 dB-HL in audiometric tests [16], and it becomes 15 dB-SPL at 250 Hz. Furthermore, although sensitivity of 250 Hz to air-bone gap is higher than that of 512 Hz [6, 15, 17, 18], 256 Hz tends to enhance perception with vibration [15]. Thus, one of the used C2-TFs in our study produced rFF at 249 Hz, which is almost equal to C1, which has different audible level and perception.

Furthermore, decay time of TFs is very essential in many TF tests, at least for calling the subject's attention to the sound. It could be said lower decay time indicates less test duration, which probably makes the tests less convenient. Besides, particularly for Rinne test, decay times in both bone and air condition is crucial. Our experiment design did not allow the determination of real air-conduction-decay time of TFs, and we did not measure bone-conduction-decay time. However, using the same experimental design, we observed that air-conduction-decay time of 5 used C2-TFs decreased more than 80% in comparison with the unused C2-TF.

Altogether, data presented in this study clearly point out that aluminum TFs, at least some of the TFs in the market, tend to lose their properties with time, making TF test less reliable. Aluminum is a material prone to metal fatigue, and metal fatigue is a micro-fracture concept mainly related to cyclic load [12], which is the main job of TFs. In our study, the shift in rFFs and shortening in its decay times were more common in C1- and C2-TFs, whereas C3-TFs presented rFF closer to the assumed values by the manufacturer and reasonably longer decay times. Stevens and Pfannenstiel [9] provided similar data that additional non-harmonic frequencies were noted when C1 and C2-TFs, but not C3-TF, were struck off metal and wooden surfaces. It could be said that longer wave-lengths during cyclic action are more prone to metal fatigue. Although we activated all TFs with a psiform strike in our study, they must have been struck on various materials through the years as well-known in otorhinolaryngology practice. The additional pressure waves produced when struck with metal and wooden surfaces [9] could be one of the factors responsible for the predisposition to the metal fatigue.

Further, we should emphasize that reported changes in the physical properties of the used TFs could be specific to only "no-name – no brand" ones in the market. Further research needs to be conducted to address branded products.

CONCLUSION

In conclusion, for the first time in the literature, we pointed out metal fatigue in TFs in this study; hence, it is recommended to check acoustic properties of used aluminum TFs.

Ethics Committee Approval: This study does not include any human or/and animal subjects, therefore no ethical approvel has been taken.

Informed Consent: This study does not include any human or/and animal subjects, therefore no informed consent has been taken.

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