AMERICAN ACADEMY OF OTOLARYNGOLOGY–HEAD AND NECK SURGERY FOUNDATION

Otolaryngology–
Head and Neck Surgery
149(6) 907–913

DOI: 10.1177/0194599813505828
http://otojournal.org
SAGE

Rinne Revisited: Steel versus Aluminum Tuning Forks

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No sponsorships or competing interests have been disclosed for this article.

Abstract

Objective. (1) Determine whether tuning fork material (aluminum vs stainless steel) affects Rinne testing in the clinical assessment of conductive hearing loss (CHL). (2) Determine the relative acoustic and mechanical outputs of 512-Hz tuning forks made of aluminum and stainless steel.

Study Design. Prospective, observational.

Setting. Outpatient otology clinic.

Subjects and Methods. Fifty subjects presenting May 2011 to May 2012 with negative or equivocal Rinne in at least 1 ear and same-day audiometry. Rinne test results using aluminum and steel forks were compared and correlated with the audiometric air-bone gap. Bench top measurements using sound-level meter, microphone, and artificial mastoid.

Results. Patients with CHL were more likely to produce a negative Rinne test with a steel fork than with an aluminum fork. Logistic regression revealed that the probability of a negative Rinne reached 50% at a 19 dB air-bone gap for stainless steel versus 27 dB with aluminum. Bench top testing revealed that steel forks demonstrate, in effect, more comparable air and bone conduction efficiencies while aluminum forks have relatively lower bone conduction efficiency.

Conclusion. We have found that steel tuning forks can detect a lesser air-bone gap compared to aluminum tuning forks. This is substantiated by observations of clear differences in the relative acoustic versus mechanical outputs of steel and aluminum forks, reflecting underlying inevitable differences in acoustic versus mechanical impedances of these devices, and thus efficiency of coupling sound/vibratory energy to the auditory system. These findings have clinical implications for using tuning forks to determine candidacy for stapes surgery.

Keywords

tuning fork, Rinne, conductive hearing loss, otosclerosis

Received June 24, 2013; revised August 16, 2013; accepted August 29, 2013.

Background

Prior to the development of the electric audiometer, otologists relied on as many as 20 named tuning fork tests in order to determine the type and estimated degree of hearing loss.[1] Only the Weber and Rinne tests have remained a part of the otologist's armamentarium, particularly with respect to determination of candidacy for otosclerosis surgery.[1-4]

A positive Rinne is considered by most surgeons to be an absolute contraindication to surgery for otosclerosis.[5] A negative Rinne assures that the conductive loss is significant enough to warrant undertaking the risks of surgery and, with the Weber test, protects the surgeon from operating on the basis of a flawed audiogram (ie, a shadow curve due to insufficient masking of the contralateral ear). Some surgeons advocate extending surgical candidacy to include patients with equivocal Rinne tests.[6] Nevertheless, accuracy of the outcome of the Rinne remains critical in routine practice.

The reported air-bone gap (ABG) necessary for detection of a conductive hearing loss by Rinne testing ranges between 15 dB and 40 dB.[7-10] This variability may be due to numerous factors, including clinical technique or experience, tuning fork size or material, and patient factors. In order to more rationally apply the results of Rinne tuning fork testing in a clinical context, further investigation into the potential sources of variation in Rinne testing is warranted.

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This article was presented at the 2012 AAO-HNSF Annual Meeting & OTO EXPO; September 9-12, 2012; Washington, DC.

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This prospective comparison of steel and aluminum forks was motivated by anecdotal observations of discrepancies between Rinne tests using the 2 materials. Steel forks seemed more likely to detect lesser ABGs. To complement our clinical observations, we also sought to determine whether these 2 materials have relative differences in acoustic and mechanical outputs that might explain our observations.

Materials and Methods

In this prospective, observational, University of Pittsburgh Institutional Review Board–approved study, subjects were recruited from the outpatient otology clinics and screened by performing a Rinne test. Both stainless steel and aluminum 512-Hz tuning forks were used for screening. Subjects over the age of 18 years with a negative or equivocal Rinne in at least 1 ear using either steel or aluminum forks were included. To ensure that the audiogram results represented each subject in the same clinical condition as his or her Rinne test, only subjects receiving a same-day audiogram were included. Rinne testing results were collected from 100 ears for steel and 99 ears for aluminum (50 subjects). To avoid sequence bias, subjects recruited on odd calendar days were tested with aluminum first, and subjects recruited on even calendar days were tested with steel first. Testing was performed after cerumenectomy.

The Rinne test was performed twice with each fork. The base of a vibrating fork was held firmly to the posterolateral surface of the mastoid (No. 1) to test bone conduction (BC), and then approximately 2 cm from the external auditory canal (No. 2) to test air conduction (AC).[11] In testing AC, the fork was held with the tip of the proximal tine slightly above the ear canal entrance and off its broad side such that both tines lay in the coronal plane. The subject was asked if he or she perceived the sound to be louder in the back (No. 1) or the front (No. 2). If the sound was perceived as louder by AC than by BC, the Rinne was scored positive. If the sound was louder by BC than by AC, the Rinne was scored as negative. If no loudness difference was perceptible, the test was considered equivocal.

Each subject then underwent same-day audiometric testing. For most subjects with a unilateral conductive hearing loss (CHL), Rinne results and audiometric data were collected from both ears. Therefore the data analysis includes ears with normal hearing and ears with small air-bone gaps, which were associated with a positive Rinne test. Some patients had unilateral audiograms because only the abnormal ear needed to be tested for provision of clinical care. Audiometric data were available for 91 ears. The ABG was calculated at 500 Hz for each ear and compared to the results of Rinne testing using 512-Hz tuning forks.

Acoustical and Mechanical Testing

The 4930 Artificial Mastoid (Brüel & Kjær, Copenhagen, Denmark) was used to record tuning fork vibrational output while simultaneously recording sound output using a sound level meter (Type 2231, Brüel & Kjær). Post hoc analysis was performed via Adobe Audition. Tuning forks analyzed included steel and aluminum 256-Hz forks, a standard aluminum 512-Hz fork, a large aluminum 512-Hz fork, and a steel 512-Hz fork (**Figure 1**).

Figure 1. Tuning forks used to measure relative bone/air conduction. From left to right, mallet used to strike the forks, 256-Hz steel, 256-Hz aluminum, 512-Hz steel, 512-Hz aluminum (standard), and 512-Hz aluminum (large).

Figure 2. Setup for simultaneous measurement of air and bone conduction. Left: Tuning fork being applied to membrane of artificial mastoid. A ruler was used to control the distance (1 cm) between the microphone and the nearest tine across forks. Right: Close-up view of artificial mastoid.

The tuning fork was held 1 cm from the sound level meter (microphone) as measured by a ruler suspended behind the artificial mastoid (**Figure 2**). A 2-dimensional (2D) bubble was used to ensure that similar force was applied with the handle of the fork against the membrane of the artificial mastoid across trials. The fork was hit on the tines with a mallet and then placed on the artificial mastoid with enough force to move the air into the central region of the 2D bubble. In order to assure comparable overall levels of excitation, data were collected starting at a nearly equivalent intensity on the audio channel (air conduction) across trials, but recording over epochs of decay of the excitation (as naturally occurs) to permit comparable ranges of AC and BC intensities across forks examined. This approach avoided drawing from sound/vibration samples that were saturations of the audio input (too high, if not nonlinear) or too low outputs (if not into the noise floor) for AC versus BC components. It was determined that absolute levels of excitation of the fork were not critical by repeating measures at different points along the decay envelopes (AC vs BC), demonstrating a consistent difference in decibels.

The relative gain of the 2 recording channels (AC and BC) were set arbitrarily to provide relatively broad dynamic ranges of recording across all forks tested, for both components, after some preliminary tests of the set-up. Once set, the gain settings were held constant throughout the testing of all forks, completed on the same day and within 1 test session. Coincidentally, these settings produced similar levels of AC and BC outputs for steel forks.

Statistical Analysis

For all analyses, each ear was considered to be one sample, yielding 2 × N ''subjects'' where N is the number of patients. The Rinne test result for each ear was taken to be the arithmetic mean of 2 Rinne test trials for that ear, where on each trial a patient report of AC > BC (positive Rinne) was taken to be a 0, AC = BC (equivocal Rinne) as 0.5, and BC > AC (negative Rinne) to be a 1. Thus, the probability of a negative Rinne can be estimated by taking the mean of these numbers across the relevant sample.

A McNemar's test was performed to compare the results of Rinne testing using steel versus aluminum forks. This is a test of the null hypothesis that both materials have a similar proportion of negative outcomes in the Rinne test. The null hypothesis was rejected for a range of definitions of ''negative outcome,'' from the most liberal (any equivocation in the patient's report on either trial was taken as a negative Rinne) to the most conservative (only a bone > air report on both trials was taken as a negative Rinne), indicating that the results are robust to a range of clinical interpretations of the Rinne test. A 2-tailed P value < .05 was considered significant.

Parametric estimation of the probability of a negative Rinne test as a function of ABG was computed using binomial regression. The Rinne outcome (ranging from 0 to 1 as previously described) was predicted using the ABG at 500 Hz (in dB). Most outcomes were either 0 or 1, with few equivocal responses producing intermediate values. The binomial regression was computed using a logistic link function, so the final computational equation for the estimate was of the form:

$$\text{Rinne} = 1/(1+\exp(-\beta\neg_0 - \beta\neg_1 {}^{*}\text{CHL}))$$

where $\boldsymbol{\beta}_0$ is related to the proportion of negative Rinne tests when there is no CHL, and $\boldsymbol{\beta}_1$ is related to the increase in the proportion as CHL increases. These parameters were estimated for each material and used to construct the logistic curves. The standard errors of these curves were obtained by resampling values of $\boldsymbol{\beta}_0$ and $\boldsymbol{\beta}_1$ from their estimated means and covariance matrix according to a bivariate normal distribution to obtain new curves.

Table 1. Frequency of each Rinne test result.[a]

	+	=	−	Mean
Aluminum	112	13	73	.41 (.05)
Steel	96	12	92	.49 (.05)

[a]Means are computed across tests (2) within each ear, and then across ears, with each negative test quantified as 1, and each positive test as 0, and each equivocal test as 0.5. Means are significantly different at $P < .01$ (paired t-test). Standard error of the mean is indicated in parentheses. n = 199 for aluminum, n = 200 for steel.

A chi-square test was utilized to compare Rinne results to the air-bone gap at 500 Hz.

For laboratory data, the difference between, ostensibly, the logarithm of sound energy (ie, in dB) and the logarithm of vibrational output (in dB) was taken at all time points. Since log(A) – log(B) = log(A/B), this is also equal to the log of the ratio of the raw intensities. The median difference over time was then calculated to eliminate outliers such as values obtained when the fork was struck or during voice overlays.

Results

Comparison of Negative Rinne (BC > AC) Using Steel versus Aluminum Forks

Looking across all ears, the mean Rinne test result was .41 ± .05 for aluminum and .49 ± .05 for steel (**Table 1**). Within subject, the mean difference between steel and aluminum was .07 ± .03 ($P < .01$) (paired t-test). Thirty-four ears had unequivocal negative Rinne testing (BC > AC) with both steel and aluminum forks (**Table 2**). Every ear that had an unequivocal negative Rinne with the aluminum fork also had an unequivocal negative Rinne with the steel fork, namely, condition (b) in **Table 2** was not observed. However, the converse was not the case—that is, there were 10 ears with unequivocal negative Rinne testing using the steel fork that had equivocal or positive Rinne testing using the aluminum fork (c). The differences in Rinne test results were statistically significant ($P < .01$, McNemar's test), as there were far more ears for which (c) occurred (10 ears) than for which (b) occurred (0 ears).

Proportion of Negative Rinne Tests Relative to ABG at 500 Hz

Overall, subjects had a mean audiometric air-bone gap at 500 Hz of 23.3 ± 18.1 dB, with a range of 0 to 75 dB (**Table 3**). The 75 dB ABG was noted in a single patient and persisted with repeated testing. All other ABGs were

Table 2. Proportion of ears that demonstrated an unequivocal negative Rinne (BC > AC on both trials) for: (a) neither aluminum nor steel, (b) aluminum but not steel, (c) steel but not aluminum, and (d) both aluminum and steel.[a]

		Steel	
		Other (AC > BC, AC = BC)	Uneq BC > AC
Aluminum	Other (AC > BC, AC = BC)	56	10
	Uneq BC>AC	0	34

[a]Uneq, unequivocally, namely, 2 tests confirming the indicated result. Other, positive and equivocal results. Equivocal results include ears for which there was a lack of consistency between the 2 trials for the same fork or trials in which air conduction (AC) was perceived as having the same intensity as bone conduction (BC; AC = BC). n = 99 ears.

Table 3. Air-bone gap (ABG) at 500 Hz measured via audiometric testing.[a]

	All	+/+	+/–	–/+	–/–
n	91	46	10	0	35
ABG (dB)	23.3 (18.2)	12.0 (13.5)	27.0 (12.1)	—	36.4 (15.1)

[a]+/+, +/–, –/– indicates Rinne test result for aluminum fork/steel fork as in **Table 1**, for example, +/– indicates a positive Rinne test with aluminum and a negative Rinne test with steel, –/+ indicates a negative Rinne with aluminum and a positive Rinne with steel. Values are reported as mean conductive hearing loss for each group, with standard deviation indicated in parentheses. Sample size is slightly smaller than previously because some subjects only had audiologic testing for the abnormal ear.

<60 dB, as would typically be expected. Mean air bone gaps relative to Rinne test results are also indicated in **Table 3**. **Figure 3** illustrates the distribution of air-bone gaps for each Rinne test result along with the cumulative histograms. The steel positive Rinne slope (light purple) is shifted up compared to the aluminum positive Rinne (pink), namely, for aluminum a higher percentage of the positive Rinnes occurred at greater air-bone gaps.

To quantify this, logistic regression was used to calculate the probability of a negative Rinne at any given air-bone gap for steel compared to aluminum forks. For all degrees of conductive hearing loss, the steel fork has a greater likelihood of producing a negative Rinne. The probability of a negative Rinne reached 50% at 19 dB for the steel fork compared to 27 dB for the aluminum fork (**Figure 4**).

Relative Output of Fork by Air Conduction and Bone Conduction

Simultaneous air and bone conduction outputs were measured for three 512-Hz forks (large and small aluminum, steel) and two 256-Hz forks (aluminum and steel) (**Figure 5**). Mass and tine dimensions of the forks are in **Table 4**. These tracings allowed comparison of the relative efficiency by air and bone conduction varying both material (aluminum vs steel) and size (standard vs large). The steel 512-Hz fork (**Figure 5A**) revealed tracings of similar amplitude by AC (audio, bottom channel) and BC (vibration, upper channel), as a matter of relative gain of the 2 recording channels (see Methods). The standard aluminum fork (**Figure 5B**), by contrast, demonstrated relatively smaller amplitudes by bone compared to air. This difference in relative acoustic and mechanical efficiency was even more pronounced for the large aluminum fork (**Figure 5C**). Similar results were noted for the steel and aluminum 256-Hz forks (data not shown), and therefore further analysis was focused on the three 512-Hz forks.

Audio and vibrational outputs were tracked in relative amplitude (dB) over time; differences were then computed (**Figure 6**). For the steel fork, again, the amplitude (dB) by air conduction (blue) and bone conduction (red) are fairly close. The green tracing represents the difference between air and bone amplitudes. For the standard aluminum fork, there is a larger difference in amplitudes by air and bone conduction. For both forks, the difference in median amplitude by air conduction and bone conduction remains fairly constant over time. Comparing the differences in median amplitudes by air versus bone for steel (bone – air = +3.2) and aluminum (bone – air = −12.8) allows us to predict that the steel fork should flip at ~16 dB less of an air-bone gap.

Discussion

Tuning forks are designed to generate a pure tone that is sustained, allowing time for tuning of a musical instrument. The shape of the fork allows the user to hold the handle with minimal effect on the sound energy released by the tines. Serendipitously, the stem can efficiently deliver vibratory energy to materials like bone (ie, much higher impedances than that of air). To our knowledge, tuning forks are not manufactured to keep the relative ratio between vibrational output of the stem and acoustic output of the tines constant. Exclusively steel in the early years of clinical applications, diagnostic tuning forks largely transitioned to aluminum, which is resistant to corrosion, lighter than steel,

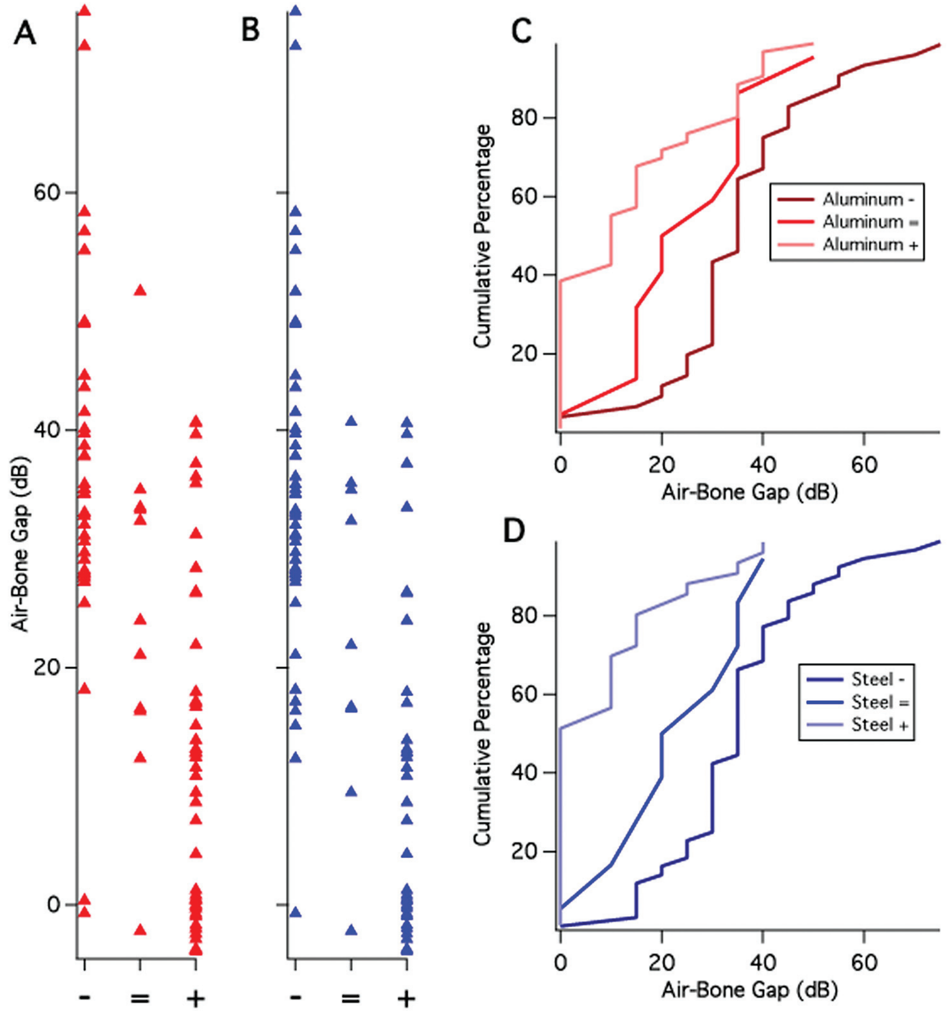

Figure 3. Distribution of air-bone gaps (ABG) for each Rinne test result. Measured ABGs for each Rinne test result using an aluminum fork (A) and steel fork (B): negative (–), equivocal (=), and positive (+). C, D: Cumulative histograms for the data in *A* and *B*.

and cheaper to manufacture.[1] During the changeover, it was perhaps assumed that the Rinne would remain ''internally consistent,'' that is, the relative ratio of acoustic and vibrational output will be fixed irrespective of material composition. Our results demonstrate that this is not the case. In the ears we studied, tuning forks composed of steel were more likely to produce a negative Rinne test at a given ABG than an aluminum tuning fork (**Figure 4**). Since we could not test every existing 512-Hz fork, we cannot conclude that the findings are representative of all forks in current clinical use. We included the forks that were ''standard'' both at our institution and at the varied departments at which the coauthors trained. Based on the differences between the 2 materials on bench testing, we feel it is likely that our results are generalizable. Regardless, the presence of statistically significant differences across the limited number of forks that we did test is sufficient cause for concern regarding the variability of Rinne test results in forks of differing materials.

Laboratory testing of steel and aluminum tuning forks revealed, at a given acoustic output, the vibrational output

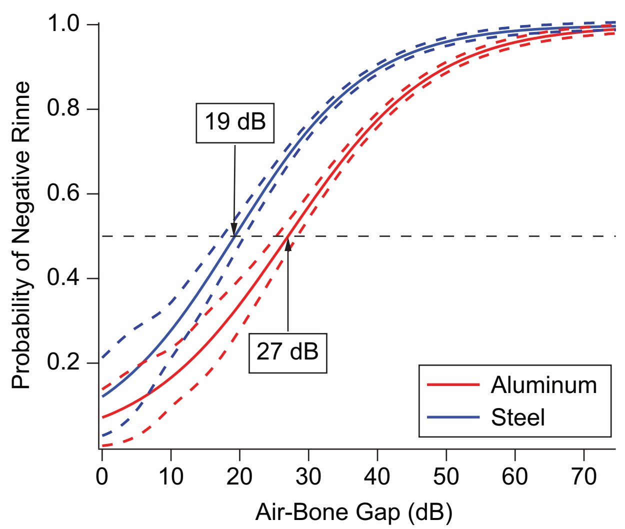

Figure 4. Probability of negative Rinne as function of air-bone gap (ABG). Logistic regression indicates the probability of a negative Rinne test as a function of ABG. Test results are quantified as 1 (negative), 0.5 (equivocal), or 0 (positive) Rinne. Standard errors are shown as dashed lines.

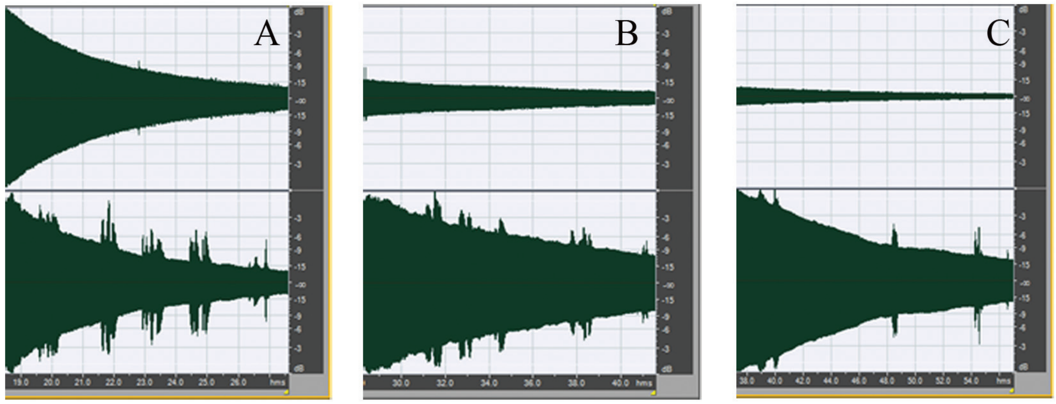

Figure 5. Relative acoustic and mechanical outputs of steel, standard aluminum, and large aluminum 512-Hz forks. Upper, artificial mastoid recording. Lower, simultaneous recording via the sound meter. (A) Steel; (B) Standard aluminum; (C) Large aluminum 512-Hz forks. (Transients in audio sample are vocal annotations, removed by median filtering for quantitative analysis.)

Table 4. Mass and tine dimensions of tuning forks used for impedance testing.

		Weight (g)	Tine length (mm)	Tine width (mm)	Tine depth (mm)
512-Hz					
	Large aluminum	113.2	129.5	9	12
	Standard aluminum	55.5	114.5	7	9
	Stainless steel	83.9	85	4.5	7.5
256-Hz					
	Aluminum	117.9	161	7	12
	Stainless steel	119.5	129	5	7.5

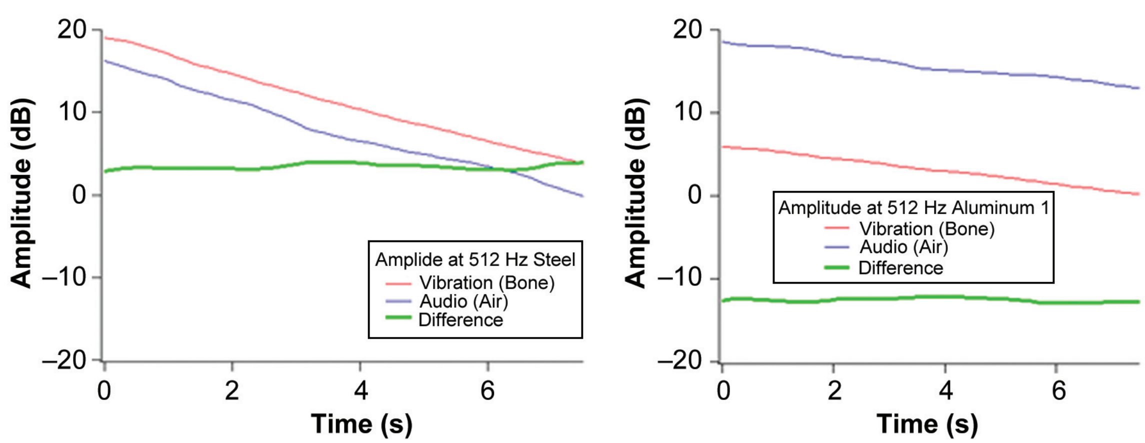

Figure 6. Relative amplitudes (dB) of audio (blue) and vibrational (red) outputs over time. Left: steel 512-Hz fork (left). Right: aluminum 512-Hz fork. The difference in median amplitudes (bone – air) is in green. The median of these differences was taken to eliminate perturbations due to vocal annotations.

from a steel fork to be increased compared to aluminum. This finding substantiates our clinical finding that steel tuning forks were more likely to produce a negative Rinne. In analyzing the bench-top data (and without any knowledge of the clinical results), our auditory scientist (JD) predicted that a stainless steel fork would flip at a 16 dB lesser air-bone gap compared to the standard aluminum fork under laboratory conditions reasonably approximating the clinical test.

Many previous studies of the Rinne test have focused on sensitivity and specificity with varying results. Gelfand found that an ABG of 55 to 60 dB was required to meet a sensitivity of 75% with a 512-Hz fork,[12] and Burkey et al showed a sensitivity of detecting a CHL of 20 dB or greater was 89.8%.[7] Browning et al showed a sensitivity of 80% for a 40 dB ABG using a Rinne with a 512-Hz fork.[13] Chole et al found a 44.8% sensitivity of a 512-Hz fork at an ABG greater than 10 dB.[14] The 256-Hz tuning fork was found to be more sensitive for the Rinne test, although it was associated with a higher rate of false positives. The 512-Hz fork was more specific and was felt to be optimal for the Rinne test. None of these studies compared Rinne results using tuning forks made of different materials; in fact, the fork material often was not indicated.

Deciphering the physics underlying our results is not trivial. Although impedance-matching provides a natural basis for framing energy transfer, the range of properties (stiffness, mass, structure, and friction) affecting impedance limits our ability to pinpoint a key characteristic. Of the 512-Hz forks tested, the large aluminum fork weighed the most, followed by the steel fork and the standard aluminum fork. However, the relative difference in mechanical/acoustic energy did not correlate with increasing net mass. The 256-Hz steel and aluminum forks were close in weight, yet the differences in relative outputs by air and bone conduction were akin to those noted for the 512-Hz forks (data not shown). On the other hand, the bulk modulus of elasticity is different between steel and aluminum (steel being much stiffer) and might well be the dominant factor for effective BC coupling.

Greater tine width is a structural issue that may provide an acoustic advantage in driving sound waves that are effectively planar down the ear canal. The result is a greater radiating surface, which would reduce adverse effects of poor tine alignment and varying ear-canal–cross-sectional areas across patients. Indeed, we did find that the dimensions of the tines corresponded to the relative efficiency by bone versus air conduction—the fork with the smallest tines (steel) yielded the lowest air conduction relative to bone conduction, followed by the fork with the intermediate tine dimension (''standard'' aluminum) and the fork with the largest tines (''large'' aluminum) yielding the biggest difference in relative outputs.

Conclusions

We have found Rinne tests using steel tuning forks to be more sensitive than with aluminum in detecting the presence of an air-bone gap. This is substantiated by significant differences in the relative acoustic versus mechanical outputs of steel versus aluminum forks. These findings have clinical implications for using tuning forks to determine candidacy for stapes surgery. The tuning fork continues to serve as a tool in preventing otologic surgeons from offering intervention on the basis of a flawed audiogram (ie, inadequate masking creating a shadow curve of an apparent conductive loss in what is actually a profoundly deaf ear). On the other hand, the results considerably vindicate audiological testing given different tuning fork materials across clinics/surgeons introduce a large variance in the Rinne test result. Given such variance across aluminum and steel forks, we believe that tuning fork material needs to be standardized if the field of otology continues to regard a positive Rinne as a contraindication to stapes surgery. The fork material that ought to be accepted as the standard should be determined by consensus as to the degree of hearing loss at which we are willing to expose patients to surgical intervention.

Acknowledgments

The authors would like to thank Daniel Zuckerman and Monica Devey for their editorial assistance.

Author Contributions

Cheryl A. MacKechnie, design, conduct, analysis, manuscript preparation; **Jesse J. Greenberg**, design, conduct of clinical arm of study, analysis, manuscript preparation; **Richard C. Gerkin**, statistical analysis, preparation of tables/figures, manuscript preparation; **Andrew A. McCall**, design, conduct of clinical arm of study, analysis, manuscript preparation; **Barry E. Hirsch**, design, conduct of clinical arm of study, analysis, manuscript preparation; **John D. Durrant**, design, conduct of benchtop recordings, manuscript preparation; **Yael Raz**, design, conduct, analysis, manuscript preparation.

Disclosures

Competing interests: None.

Sponsorships: None.

Funding source: None.

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