Full-Quantitative Analysis of Cementless Stem Hammering Sound Changes During Total Hip Arthroplasty.

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Research Article

Keywords: total hip arthroplasty, cementless stem, hammering sound, fast Fourier transform, femoral morphology

Posted Date: December 7th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-115355/v1

Abstract

Full-quantitative characterization has not been performed to analyze changes in the hammering sound in cementless hip arthroplasty. We analyzed the frequency spectrum of the hammering sound during stem insertion for 20 cases of uncomplicated cementless total hip arthroplasty for osteoarthritis using a proximal-coated stem. The absolute sound pressure (Pa) and normalized sound pressure of each frequency bands in early and late stage of femoral stem insertion were determined by the Fast Fourier Transform analysis. The absolute sound pressures (Pa) of a majority of frequency bands was significantly higher in the late-stage stem insertion than in the early stage The 1.0–1.5-kHz frequency band showed a significant change in normalized sound pressure in all cases between the early and late stages of stem insertion (p=0.000). The femoral morphology and canal fill ratio were correlated with late stage normalized sound pressure in specific frequency bands. In the 5.0–5.5 kHz band, the Dorr A femoral morphology was significantly higher normalized sound pressure than those in the Dorr B (p=0.004). This study revealed the hammering sound frequency with full-quantitative value altered during cementless stem insertion. Frequency bands of 1.0–1.5 kHz, 5.0–5.5 kHz were the key bands for predicting stem fixation.

Introduction

Total hip arthroplasty (THA) is one of the most successful surgical treatments and is reported to greatly reduce pain and restore hip function and the quality of life of patients with end-stage hip disease in both short-term and long-term follow-up [1,2]. As the population ages, the demand for primary THA and revision THA has increased rapidly in recent years [3].

Although the use of cementless fixation in THA has increased globally, complications, such as intraoperative femoral fracture and implant subsidence, can occur after inappropriate and inadequate stem implantation [4,5]. These complications can compromise the surgical effect and increase the risks of dislocation, aseptic implant loosening and revision surgery [6,7].

Several new technologies, such as preoperative three-dimensional (3D) templating and intraoperative navigation, have been used to avoid inadequate stem selection and achieve better stem positioning. Schiffner et al. reported that the accuracy of predicting the right stem size improved from 45.7% to 58.6% using 3D templating compared with 2D surgical planning [8]. Weber et al. found similar accuracy in biomechanical hip reconstruction of the leg length and global and femoral offset in THA between intraoperative navigation and fluoroscopy [9].

Addition to those new imaging tools, because experienced surgeons use the auditory sensation of a hammering sound during stem insertion to determine proper/improper stem sitting, researchers have attempted to analyze the hammering sound. Morohashi et al. reported on acoustic frequency patterns and found that a natural hammering frequency of approximately 7 kHz was the most prominent frequency in patients without complication [10]. Connell et al. reported that a frequency around 1 kHz could better predict an adequately sized stem using spectrographs [11].

However, no full-quantitative characterization has been performed for the changes in hammering sound frequency during cementless stem insertion, and the relationship between the hammering sound frequency and the femoral morphology and canal fill ratio is unknown. Therefore, we asked two questions. 1) Is the hammering sound frequency with full-quantitative value altered during cementless stem insertion? 2) Is the hammering sound frequency correlated with the femoral morphology and canal fill ratio of the stem? This study was conducted to objectively analyze the changes in hammering sound frequency during cementless stem insertion and the relationship between the hammering sound frequency and femoral morphology and canal fill ratio of the stem.

Methods

Preliminary experiments

The natural frequencies (<10 kHz) of surgical instruments used in THA surgery, including a hip prosthesis (Accolade II, Stryker, Tokyo, Japan), surgical hammer (stainless hammer 01-412-01 Large, Mizuho, Tokyo, Japan), and modular handle and stem impactor (1020-2900, 1020-1870, Stryker, Tokyo, Japan), were analyzed in an anechoic room using a previously described method [10].

Patients

All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The study protocol was approved by the Ethics Committee of Juntendo University Hospital, Tokyo, Japan. Informed consent was obtained in a manner approved by the Ethics Committee from all individual participants included in this study. From November 2018 to October 2020, 62 patients (65 hips) undergone Primary THA who agreed to participate to this study were initially included (Fig. 1). Exclusion criteria were (i) patients who underwent THA for osteonecrosis, femoral neck fracture, or rheumatoid arthritis (ii) the surgery used a prosthesis other than the Accolade II stem, (iii) the surgery was performed by a junior surgeon, and (iv) patients had stem subsidence (>2 mm) at 1 month post-operation. After reviewing the inclusion and exclusion criteria, 17 women and 3 men were included, with an average age of 66.4±8.23 years and an average body mass index of 23.76±2.77 kg/m^2. One patients had simultaneous bilateral THA. To investigate the sound frequency changes among femoral morphologies, these patients were divided into the Dorr A and Dorr B groups (no patient had a Dorr C-type femur) based on Dorr classification [12].

Surgical procedure

The surgeries were performed by four experienced orthopedic surgeons via the direct anterior approach with a cementless proximal hydroxyapatite-coated stem (Accolade II, Stryker, Tokyo, Japan) using the distal part of the Smith-Petersen approach with the patient in the supine position on a surgical traction table as previously described [13]. The following is the brief description of this surgical procedure [13]. The fascia of the tensor fascia lata muscle was incised at approximately 2 cm lateral to the skin incision to prevent lateral femoral cutaneous nerve injury. The intermuscular space between the tensor fascia lata and sartorius muscles was then bluntly entered. The anterior articular capsule was exposed and incised. Intraoperative X-ray photography was used to confirm that the broach was appropriately aligned, and the porous part of the broach contacted the cortical bone. The stem size was determined using the same size of the last trial insertion of the broach. All patients underwent standardized postoperative rehabilitation with full weight bearing 1-day post-surgery.

Sound data collection during the THA

A highly sensitive sound level meter (LA-7500, Onosokki, Kanagawa, Japan) was used to record the hammering sound of the stem insertion. In all cases, the sound level meter was set on a tripod mount at 1 m high and 2 m away from the surgical table in the same operating room (Fig. 2). Recordings were made in the range of 40–110 dB using

Z frequency weighting (flat-weighted filter) and fast time weighting at a sampling rate of 64 kHz and a 16-bit sampling depth.

Sound data analysis

Oscope ver 2.1, (Onosokki, Kanagawa, Japan) was used for the sound analysis. Recorded sound data were analyzed using a rectangular weighted window and 50% overlap at a maximum range of 12.5 kHz via fast fourier transform (FFT) analysis (Fig. 3). The first three and last one hammering sounds during the stem insertion were excluded from the analysis to avoid potential hammering inconsistencies, The fourth to sixth hammering sounds were defined as early-stage insertion hammering sounds. The second to fourth hammering sounds from the end were defined as late-stage insertion hammering sounds. If noises were mixed in with these hammering sounds, or an improper hammering was detected on the spectrogram, those hammering sound would be switched to the previous or next one.

The following analysis compared the early- and late-stage insertion hammering sounds. The overall spectrum frequency of the recorded sound was divided into 25 frequency bands in the range of 0.5 kHz from 0–12.5 kHz. Because frequency bands below 0.5 kHz were mixed with noises ranging from 0.08–0.26 kHz, such as voiced speech from a typical adult, 0–0.5 kHz was thought to inaccurately reflect sound changes during the stem insertion. Moreover, previous studies detected no changes below 0.5 kHz [10,11,14]. Therefore, the 0–0.5 kHz frequency band was excluded from the comparison. Sound changes between the early and late stages were compared first by using the absolute sound pressure (Pa) and then by using the normalized sound pressure in each frequency band. Because the average overall absolute sound pressure (Pa) differed between the early and late stages, the analysis using the normalized sound pressure was used. Normalized sound pressure was calculated as the ratio of the absolute sound pressure (Pa) of each frequency band to the average overall frequency spectrum (0.5–12.5kHz). Next, correlations were determined between the femoral morphology, canal fill ratio and absolute sound pressure (Pa), followed by normalized sound pressure in the late stage. Finally, sound changes between Dorr A and B were determined for the late stage.

Assessment ofthefemoral morphology and canal fill ratio of the stem.

Radiographs of the femoral morphology and canal fill ratio were assessed using the final preoperative and immediate postoperative Anterior Posterior hip radiographs. Preoperative radiographs were used to analyze five morphologic parameters as follows.

(i) Canal-calcar ratio (CCR): ratio of the intracortical diameter of the femoral canal isthmus at 10 cm below the lesser trochanter to the intracortical diameter of the proximal femur at the medial tip of the lesser trochanter [15].

(ii) Canal-flare index (CFI): ratio of the intracortical diameter of the proximal femoral isthmus at 2 cm above the lesser trochanter to the intracortical diameter of the femoral canal isthmus at 10 cm below the lesser trochanter [16].

(iii) Morphologic cortical index (MCI): ratio of the extracortical diameter of the femur at the medial tip of the lesser trochanter to the intracortical femoral diameter at 7 cm below the lesser trochanter [15,17].

(iv) Canal-bone ratio (CBR): ratio of the intracortical and extracortical diameters of the femoral canal isthmus at 10 cm below the lesser trochanter [18].

Postoperative radiography was used to assess the canal fill ratio (CFR) of the stem, defined as the stem width divided by the canal width at four points at the lesser trochanter, 2 cm above, 2 cm below, and 7 cm below the lesser trochanter. The proximal-distal matching ratio of the CFR at 2 cm above and 7 cm below the lesser trochanter was also considered [19].

A single observer (S.I.) who was not involved in the sound analysis analyzed the measurements. Radiographs were assessed using the ruler function of the Picture Archiving and Communication System at our institution (Fujifilm Synapse 3.2.1 SR-356; Fujifilm Corp, Tokyo, Japan).

Statistical analysis

Statistical analysis was performed using SPSS software, ver 26.0 (IBM, Armonk, NY, USA). Patient demographics are expressed as the mean ± standard deviation. Two-tailed paired t-tests and Wilcoxon signed-rank tests were used to compare paired data. Spearman rank correlation was used to evaluate relationships between variables. Differences and correlations were considered statistically significant if $p < 0.05$.

Results

Natural frequencies of the surgical instruments

Fig. 4 shows the natural frequencies of the surgical instruments. Four frequencies dominated in the Accolade II femoral stem. Both 2.7 and 4.1 kHz were observed in sizes 3 and 4. The other two frequencies (6.4 and 9.2 kHz) of stem size 4 were slightly lower than those of size 3 (6.6 and 9.7 kHz). The dominant surgical hammer frequencies were 2.1, 4.4, and 8.2 kHz. Four frequencies (1.1, 2.9, 5.6 and 9.0 kHz) dominated with the stem impactor and three frequencies (2.0, 5.2 and 7.7 kHz) dominated with the modular handle. When hitting the modular handle with the stem impactor attached, all three dominant frequencies of modular handle (2.0, 5.2 and 7.7 kHz) and only 9.0 kHz from the stem impactor occurred. An additional dominant frequency of 3 kHz was noted when the impactor was hit.

Full-quantitative analysis of the sound changes between the early and late stages

The absolute sound pressures (Pa) of a majority of frequency bands except 5.0–6.0, 8.5–10.0 and 12.0–12.5 kHz was significantly higher in the late-stage stem insertion than in the early stage (Fig. 5A).

The normalized sound pressure of 0.5–1.0 ($p=0.012$), 1.0–1.5 kHz ($p=0.0004$) in the late stage were significantly higher than that in the early stage The normalized sound pressures of 5.0–5.5 ($p=0.022$), 5.5–6.0 kHz ($p=0.00004$) and 9.0–9.5 kHz ($p=0.01$) were lower than those in the early stage (Fig. 5B).

Correlations between femoral morphology, CFR and normalized sound pressure

The CCR and MCI were significantly correlated with the normalized sound pressures of 5.0–5.5 kHz (CCR: $r=-0.567$, $p=0.009$; MCI: $r=0.490$, $p=0.028$) in the late-stage stem insertion (Table.1). The CBR was significantly correlated with the normalized sound pressures of 3.5–4.0 kHz ($r=-0.484$, $p=0.031$), 7.0–7.5 kHz ($r=0.552$, $p=0.012$). The CFI was not significantly correlated with normalized sound pressure in any frequency spectrum (Table.1).The CFR at 2 cm above the lesser trochanter was significantly positively correlated with the normalized sound pressures of 1.5–2.0 kHz ($r=0.463$, $p=0.040$) and 3.0–3.5 kHz ($r=0.530$, $p=0.016$). The CFR at the lesser trochanter was significantly positively correlated with the normalized sound pressures of 0.5–1.0 kHz ($r=0.472$, $p=0.036$), 3.0–3.5 kHz ($r=0.460$, $p=0.041$) and negatively correlated with the normalized sound pressure of 5.0–5.5 kHz ($r=-0.493$, $p=0.027$). The

CFR at 7 cm below the lesser trochanter was negatively correlated with the normalized sound pressure of 4.0–4.5 kHz (r=−0.450, p=0.047) and 8.0–8.5 kHz (r=−0.448, p=0.048).

Comparisons between Dorr A-type and Dorr B-type femurs

Patients characteristic in each group is shown in Table.2. In the Dorr A group, the normalized sound pressure of 1.0-1.5 kHz in the late stage was significantly higher than that in the early stage (p=0.022), (Fig. 6). The normalized sound pressure of 5.5-6.0 and 6.0-6.5 kHz in the late stage were significantly lower than those in the early stage (p=0.008, p=0.016, Fig. 6A). In the Dorr B group, 0.5-1.0 and 1.0-1.5 kHz in the late stage were significantly higher than those in the early stage (p=0.005, p=0.019). And the normalized sound pressure of 2.0-2.5, 5.0-5.5, 5.5-6.0 and 9.0-9.5 were significantly lower than those in the those in the early stage (p=0.045, p=0.004, p=0.002, p=0.033, Fig. 6B). Comparing the normalized sound pressures in the late stage between Dorr A and B, 5.0–5.5 kHz (p=0.006) in the Dorr A group were significantly higher than those in the Dorr B group (Fig. 6C).

Discussion

Although cementless THA can relieve pain and restore mobility, the incidence of specific complications, such as intraoperative fractures or postoperative subsidence, remain problematic. Previous studies have shown the acoustic evaluations based on the hammering sounds during THA can predict stem stability [10,11,20]. However, the sound changes reported in these studies differed and could not easily be distinguished. Moreover, no full-quantitative analysis of the sound frequency has been performed thus far. In the present study, we performed a full-quantitative analysis using normalized sound pressure to quantify the sound quality and found that the characteristic of the sound frequency changed during cementless stem insertion and that the sound frequency was correlated with the femoral morphology and CFR.

We believe that using normalized sound pressure to assess the hammering sound frequency is more reliable and objective. Assessments based on absolute sound pressure make the results unclear because they are affected by the different hammering forces. Although the surgeons who participated in our study were asked to deliver a consistent hammering force during the stem insertion, standardizing the hammering force among the surgeons was difficult. The absolute sound pressure was higher in the late stage than in the early stage, likely because the surgeons are more cautious and more likely to deliver less force at the beginning of a stem insertion. Previous studies suggested that presence of the prominent frequency accentuation of the absolute sound pressure could effectively predict stability of the broach or stem [10,11]. However, some of our FFT analysis results showed that the prominent frequency differed among patients despite the surgery having been performed flawlessly without complications (Fig. 3). In some cases, the prominent frequency occurred in the early-stage rather than late-stage stem insertion. Regarding the femoral morphology and CFR, McConnell et al. reported a positive correlation between sound change in the recorded frequency and femoral length, but not with the cortical thickness [11]. Our study yielded that hammering sound in the late stage were significantly correlated with the femoral morphology/CFR with the assessment of normalized sound pressure.

Our data suggest that two principals are important for understanding the sound analysis and further study of the sound frequency. First, the hammering sound frequency depends on femoral morphology. Second, the hammering frequency differs in whether the cementless stem reaches the aimed fixation contact area of the femur. Ideally, a high CCR indicates that the intracortical diameter of the distal femoral canal isthmus will be relatively large, and the stem is more likely to become fixed at the proximal femur. Our results showed that sound pressures of 5.0–5.5 kHz in the late stage were significantly lower in the Dorr B group than in the Dorr A group (those with “champagne-flute” morphology of the proximal femur). In addition, the normalized sound pressure of 5.0–5.5 kHz between the early and late stages was decreased in the Dorr B group (Fig. 6B) but not in the Dorr A group (Fig. 6A). We speculate that the sound pressure changes of 1.0–1.5 kHz could be used to predict whether the stem is well-fixed and that 5.0–5.5 kHz could distinguish whether the stem is fixed proximally or distally.

Regarding 1.0–1.5kHz, our data showed that the changes from early to late stem insertion at 1–1.5 kHz of normalized sound pressure were significantly higher in both Dorr A and B patients (Fig. 6A, 6B). This finding is similar to that of McConnell et al., who analyzed frequency changes during the femoral broach. McConnell et al. found an additional frequency band around 1 kHz in the final femoral broach, which they thought indicated that the broach was well fitted [11]. Whitwell et al. theorized that the 1-kHz frequency band was the sound wave created by the femoral canal, as a well-fitted broach yields better bone contact, leading to more efficient energy transfer and hence a greater bone vibration [21]. Although we agree with the theory of McConnell et al., we postulate that the stem impactor could also generate the sound change around 1 kHz. Although measuring the natural bone-muscle composite frequencies was difficult, our preliminary experimental results confirmed that 1 kHz was a natural frequency of the impactor. When the stem is fixed with the bone, both the bone and the stem impactor yield greater vibrations owing to increased reaction forces, leading to the changes around 1 kHz.

At 5.0–5.5 kHz, we believe that the femur-stem system generates the sound change when the stem is fixed at the proximal part. When the proximal-coated stem is fixed proximally at the femoral canal, the stem is sufficiently filled proximally, whereas if the proximally-coated stem is fixed distally, the stem moves like a windshield wiper, known as proximal-distal-mismatch [1922]. The bone cannot be well integrated with the stem and thus cannot vibrate as a single system. Jaecques et al. reported a similar result after using an artificial bone and a custom made stem to simulate the vibration system change between a “loosely inserted” initial stage to a well fixed final stage, but without using a stem impactor. The sound value around 4 kHz was gradually increased and the sound value around 8.5 kHz was gradually decreased as the stem became more fixed to the bone[23].

This study had several limitations. First, the sample size was small. However, despite the small number of patients, the characteristic objective data showed significant differences. Second, the hammering style and force were not practically standardized; thus, different vibration modes may have affected the accuracy of the results. Although we used normalized sound pressure to quantify sound changes, this method still required a baseline of the average overall frequency spectrum. Thus, the frequency range should be chosen carefully. Third, noises in the operating environment, such as the electrocardiograph monitoring alarm, could affect the recorded sound quality. Although the hammering sounds with obvious background noise were excluded, they will inevitably have influenced the results. However, the possible sound effects from the noises in the operating environment were minimal in our analysis compared with the hammering sounds. Moreover, we aimed to determine the possibility of clinically using the sound analysis in the most practical sitting environment with general noise from the operating field.

Conclusion

This study revealed the full-quantitative sound changes during proximal-coated cementless stem insertion using normalized sound pressure, which was useful for quantifying the sound analysis with no effect of hammering force. The sound changes were correlated with the femoral morphology and CFR. Frequency bands of 1.0–1.5 kHz, 5.0–5.5 kHz were the key bands for predicting stem fixation. Further study is needed to determine the relationship between complications and characteristic sound frequencies in the key bands.

Declarations

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Acknowledgment

This work was supported by JSPS KAKENHI Grant-in-Aid for Early-Career Scientists JP19K18542.

We thank Traci Raley, MS, ELS, from Edanz Group (https://en-author-services.edanzgroup.com/) for language editing a draft of this manuscript.

Author contributions

YH conceived and designed research. SI, TW, SB, HT and TB obtained the data. YH and XZ analyzed data. XZ wrote the initial manuscript. YH revised the manuscript. IM, HI, KK, and IM interpretated the data. All authors read and approved the manuscript.

Additional information

The authors declare no competing interests.

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Tables

Tab.1 Correlations between femoral morphology and canal fill ratio with the normalized sound pressure of each frequency band in the late stage of stem insertion

	Femoral morphology index			Canal fill ratio					
Frequency (kHz)	Canal-calcar ratio	Canal-flare index	Morphologic cortical index	Canal-bone ratio	2 cm above	lesser trochanter	2 cm below	7 cm below	Proximal-distal matching ratio
0.5-1.0	0.210	-0.137	0.020	-0.353	0.317	.472*	0.259	0.022	0.208
1.0-1.5	0.040	0.018	0.096	-0.232	-0.266	-0.059	-0.111	-0.038	0.047
1.5-2.0	0.307	-0.355	-0.159	0.138	.463*	0.293	-0.056	0.137	0.224
2.0-2.5	-0.125	0.039	0.066	-0.125	0.056	-0.053	-0.337	-0.292	0.278
2.5-3.0	0.327	-0.341	-0.361	0.062	0.385	0.364	0.141	-0.318	0.401
3.0-3.5	0.250	-0.341	-0.083	0.008	.530*	.460*	0.161	0.179	0.063
3.5-4.0	-0.220	0.108	0.232	-.484*	0.073	0.038	0.161	0.257	-0.154
4.0-4.5	0.060	-0.143	-0.304	0.119	-0.071	-0.063	-0.042	-.450*	0.328
4.5-5.0	-0.252	0.065	0.149	0.362	-0.335	-0.433	-0.143	0.269	-0.337
5.0-5.5	-.567**	0.412	.490*	0.168	-0.290	-.493*	-0.370	0.196	-0.287
5.5-6.0	-0.294	0.400	0.250	-0.047	-0.130	-0.220	-0.331	0.068	-0.205
6.0-6.5	0.251	-0.174	-0.041	0.232	0.146	0.077	-0.006	0.099	0.130
6.5-7.0	0.412	-0.298	-0.233	0.239	0.123	0.284	0.223	-0.062	0.108
7.0-7.5	0.147	-0.138	-0.197	.552*	-0.175	-0.039	0.156	0.077	-0.194
7.5-8.0	0.028	-0.011	-0.030	0.143	-0.396	-0.182	0.104	0.154	-0.401
8.0-8.5	0.136	0.008	-0.304	-0.183	-0.071	-0.041	0.140	-.448*	0.244
8.5-9.0	0.187	-0.140	-0.405	0.129	0.096	0.125	-0.030	-0.190	0.254
9.0-9.5	-0.105	-0.018	-0.075	0.233	-0.012	-0.208	-0.026	-0.031	-0.047
9.5-10.0	-0.369	0.408	0.269	-0.012	-0.366	-0.423	-0.072	0.114	-0.346
10.0-10.5	-0.345	0.408	0.274	-0.023	-0.293	-0.147	-0.150	-0.017	-0.237
10.5-11.0	-0.137	0.212	0.140	0.182	-0.058	0.053	0.053	0.229	-0.276
11.0-11.5	0.276	-0.081	-0.307	0.290	-0.157	0.134	0.247	0.010	-0.034
11.5-12.0	0.175	-0.135	-0.101	0.182	0.268	0.144	0.183	0.137	0.074
12.0-12.5	0.248	-0.206	-0.353	0.158	0.259	0.268	0.286	-0.344	0.318

*. Correlation is significant at the 0.05 level. **. Correlation is significant at the 0.01 level.

Tab.2 Patient characteristics, femoral morphology and canal fill ratio

		Total	Dorr A	Dorr B	P value
	Number	20	12	8	
Basic characteristic	Gender (F/M)	17/3	10/2	7/1	0.798
	Age	66.4 ± 8.23	64.8± 7.14	68.8 ± 9.15	0.157
	Height	1.55 ± 0.06	1.54 ± 0.07	1.56 ± 0.05	0.518
	Weight	57.10 ± 6.55	57.07 ± 5.65	57.15 ± 7.71	0.979
	BMI	23.76 ± 2.77	22.66 ± 2.84	25.42 ± 1.60	0.670
Femoral morphology	CCR	0.47 ± 0.09	0.41 ± 0.03	0.56 ± 0.09	<0.001*
	CFI	3.69 ± 0.65	4.10 ± 0.46	3.08 ± 0.34	<0.001*
	MCI	2.91 ± 0.31	3.08 ± 0.25	2.65 ± 0.20	0.001
	CBR	0.46 ± 0.04	0.45 ± 0.05	0.47 ± 0.04	0.346
Canal fill ratio (%)	At 2 cm above the LT	66.80 ± 6.30	64.01 ± 5.28	70.99± 5.32	0.013*
	At the LT	87.12 ± 7.23	83.63 ± 5.49	92.36 ± 6.31	0.006*
	At 2 cm below the LT	87.14 ± 11.32	83.97 ± 10.86	91.88 ± 10.27	0.140
	At 7 cm below the LT	79.21 ± 15.82	90.88 ± 11.47	79.92 ± 11.62	0.064
	Stem size	S2: n=3, S3: n=5 S4: n=9, S5: n=1 S6: n=2	S2: n=2, S3: n=3 S4: n=4, S5: n=1 S6: n=2	S2: n=1, S3: n=2, S4: n=5	
BMI: Body Mass Index, CCR: Canal-Calcar Ratio, CFI: Canal Flare Index, LT: Lesser Trochanter, MCI: Morphologic Cortical Index, CBR: Canal-Bone Ratio. *: Significant Difference.					

Figures

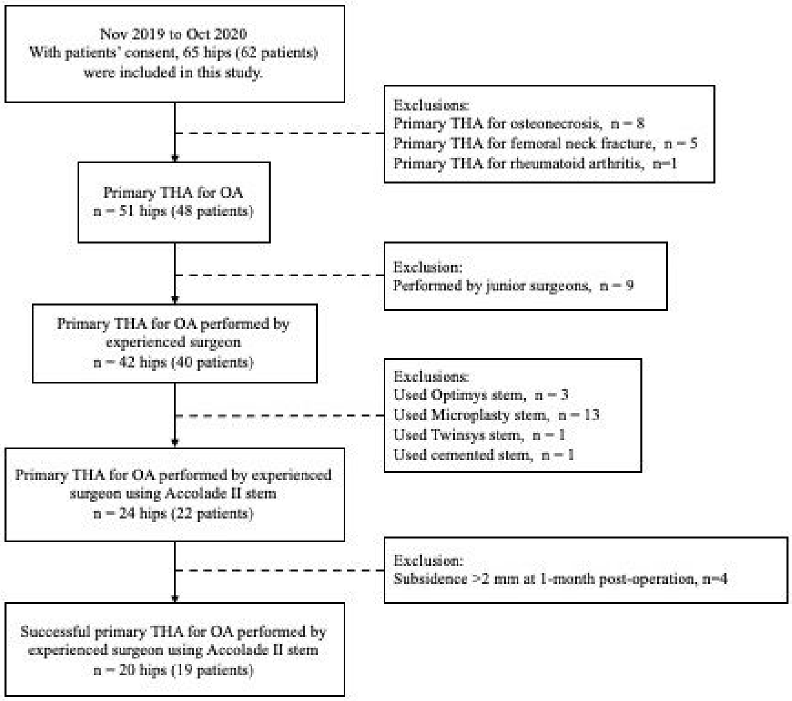
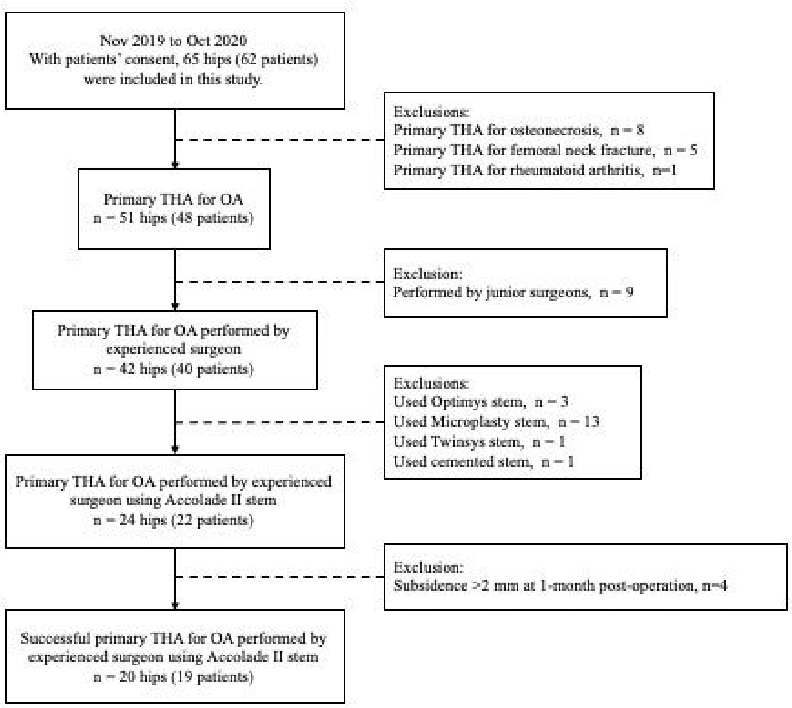


Figure 1

Study flowchart. THA, total hip arthroplasty; OA, osteoarthritis.



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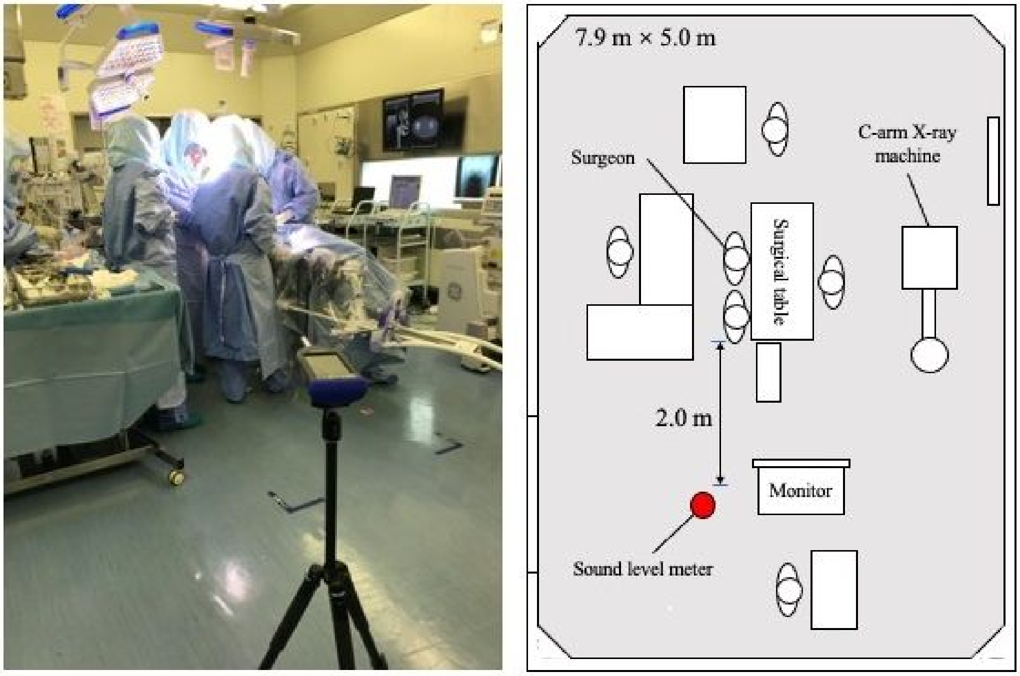
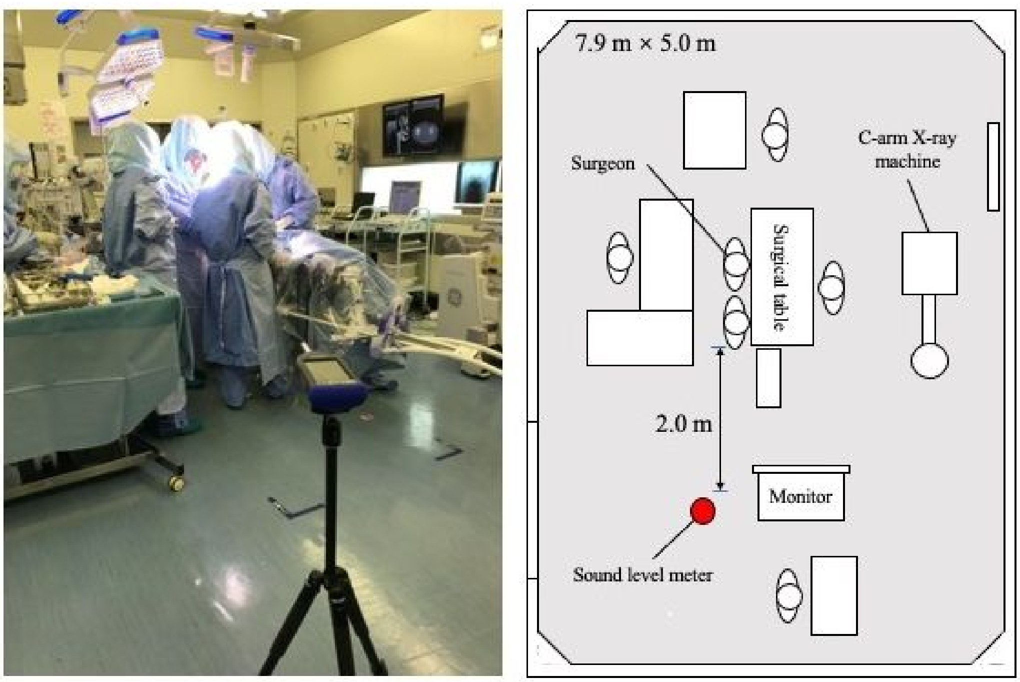


Figure 2

Recording environment, the sound level meter was set 2 m away from the surgical table.



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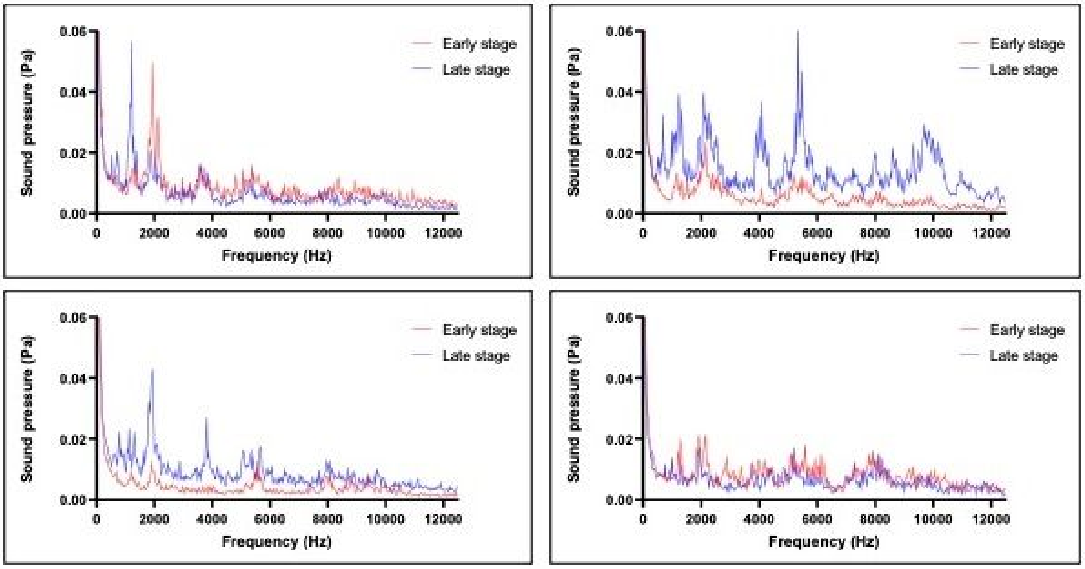
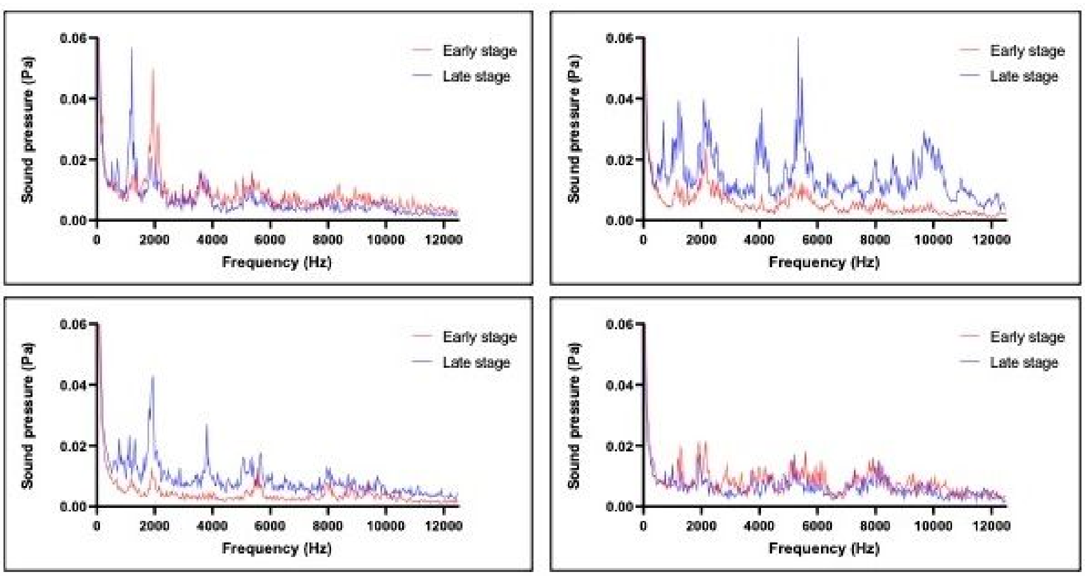


Figure 3

Fast Fourier transform (FFT) is a measurement method which converts a sound signal into individual spectral components and provides frequency information of the signal. Examples of different patterns of FFT analysis results of the hammering sound between early-stage and late-stage stem insertion. Distinguishing a stable stem using only absolute sound pressure is difficult as the prominent frequency accentuation could appear at different frequencies with different amplitudes.



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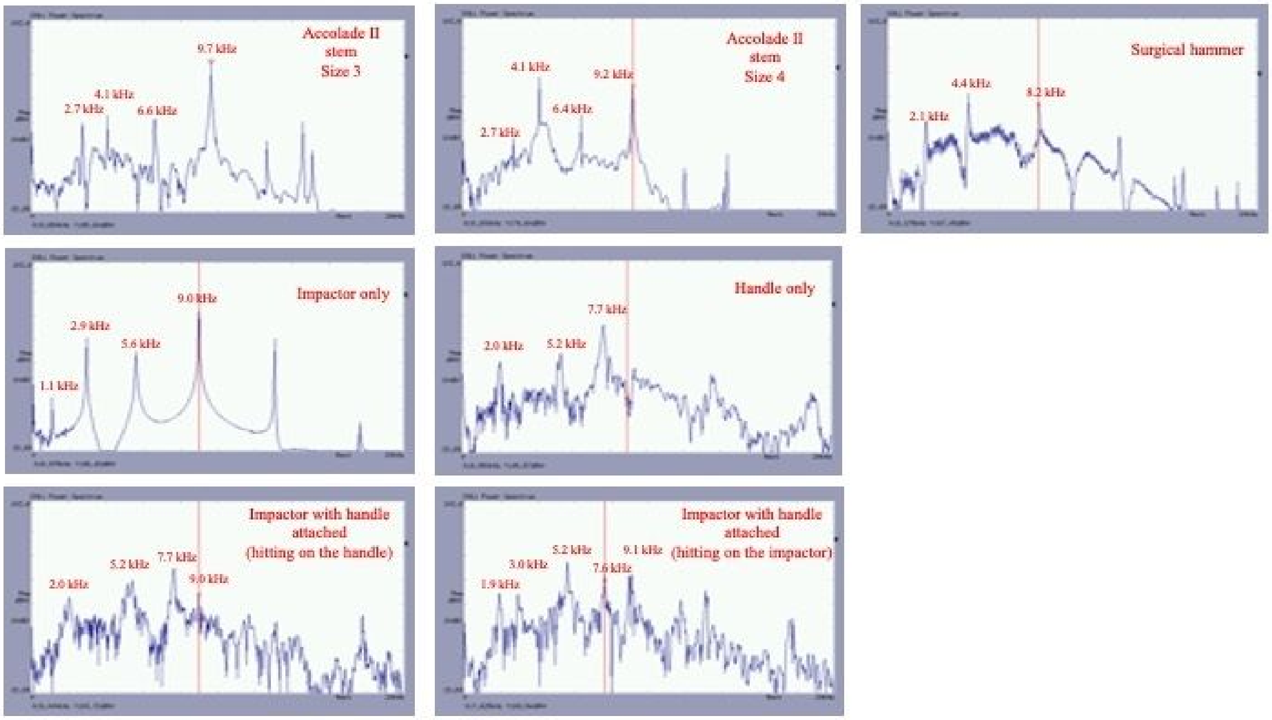
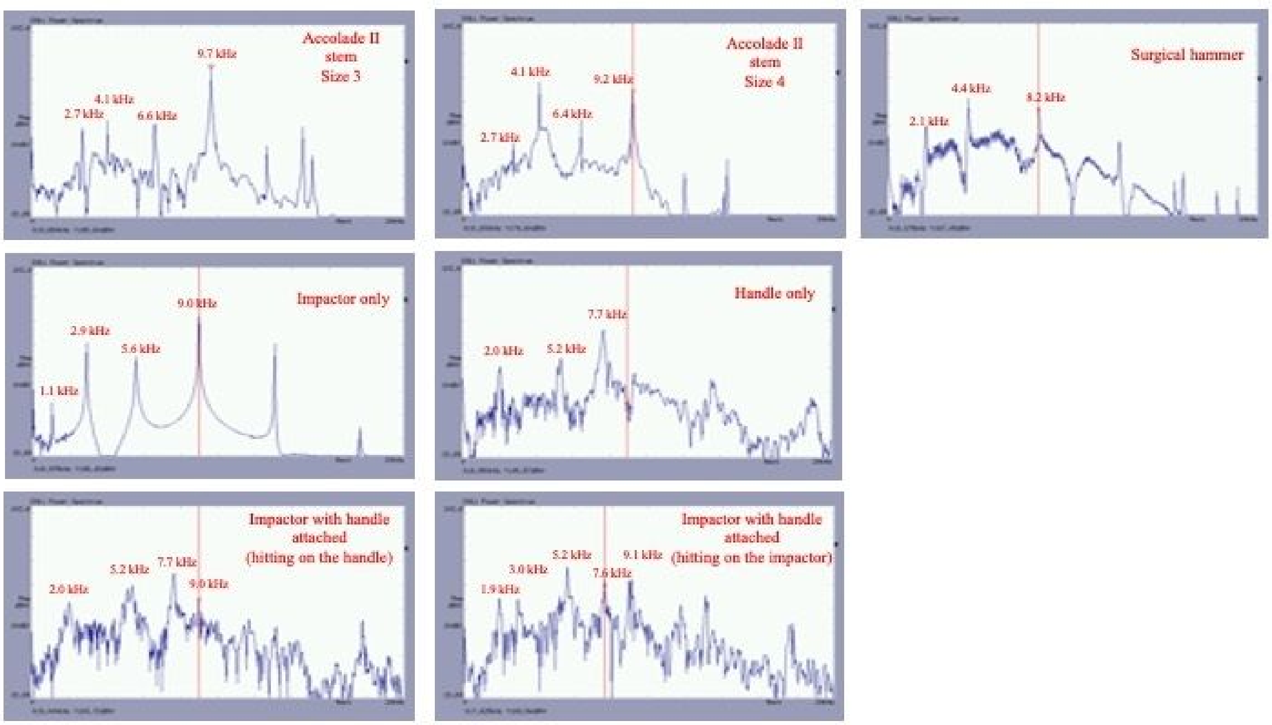


Figure 4

Natural frequencies of each surgical instrument.



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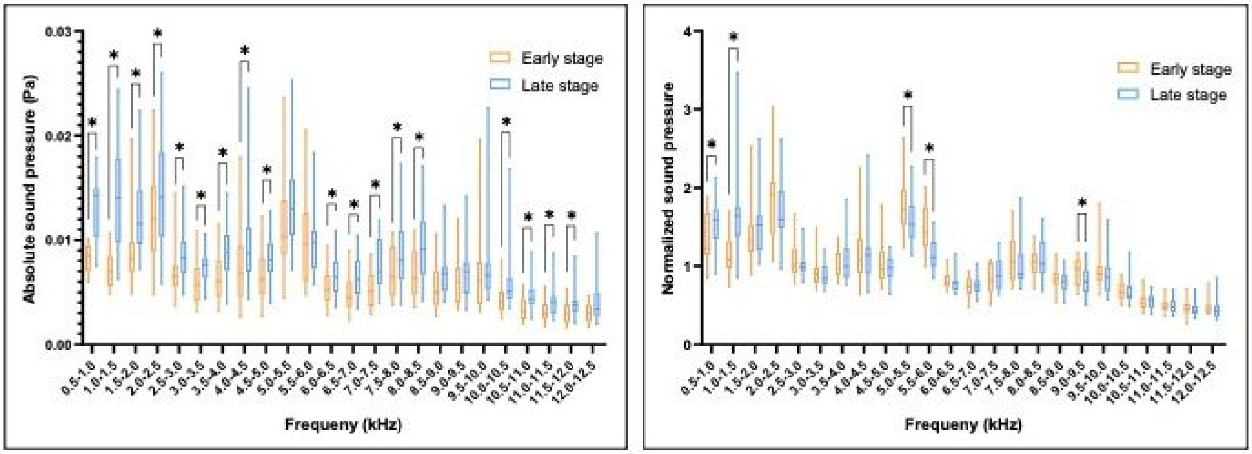
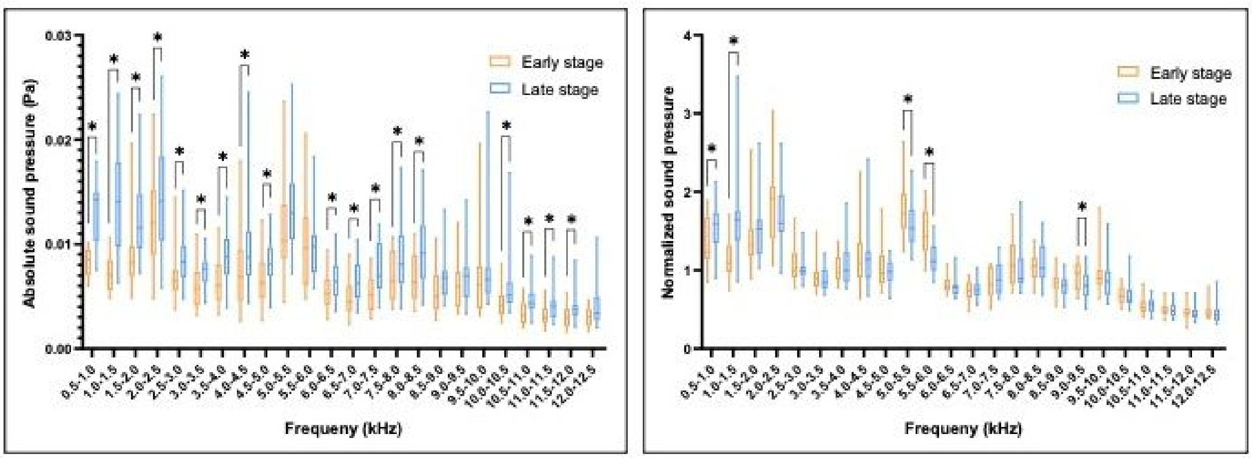


(5-A)
Absolute sound pressure between early and late stage (20 cases)

(5-B)
Normalized sound pressure between early and late stage (20 cases)

Figure 5

Sound analysis of the hammering sounds using absolute and normalized sound pressures. Normalized sound pressure is average absolute sound pressure of each frequency band (Pa) / average absolute sound pressure of overall spectrum (Pa). * Significant difference.



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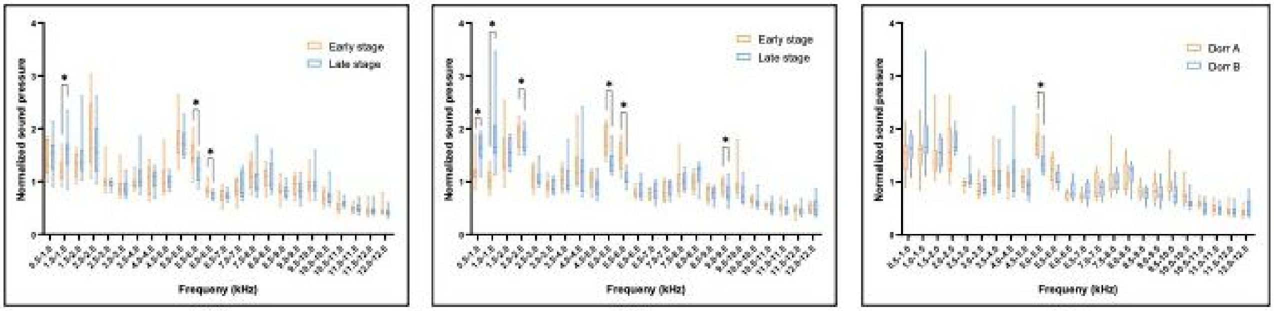


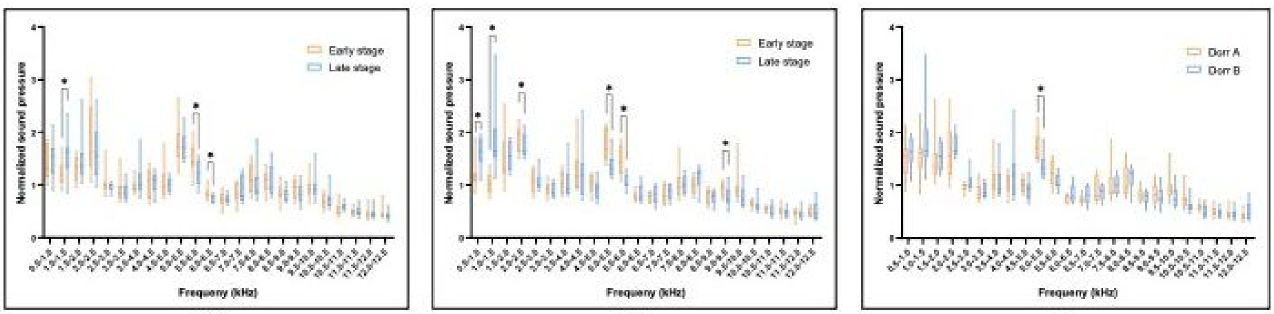
(6-A) Normalized sound pressure between early and late stage (Dorr A)

(6-B) Normalized sound pressure between early and late stage (Dorr B)

(6-C) Comparison of normalized sound pressure in the late stage between Dorr A and B

Figure 6

Analysis of the hammering sounds between Dorr A and Dorr B groups using normalized sound pressure. Normalized sound pressure is average absolute sound pressure of each frequency band (Pa) / average absolute sound pressure of overall spectrum (Pa). * Significant difference.


(6-A) Normalized sound pressure between early and late stage (Dorr A)

(6-B) Normalized sound pressure between early and late stage (Dorr B)

(6-C) Comparison of normalized sound pressure in the late stage between Dorr A and B

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Analysis of the hammering sounds between Dorr A and Dorr B groups using normalized sound pressure. Normalized sound pressure is average absolute sound pressure of each frequency band (Pa) / average absolute sound pressure of overall spectrum (Pa). * Significant difference.