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Original Research

Patients With Shorter Stature Exhibit Minimal Hammering Sound Changes During Cementless Stem Insertion in Total Hip Arthroplasty

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A B S T R A C T

Background: Listening to the change in the hammering sound is 1 of the elements used to assess the cementless stem stability. This study aimed to quantitatively investigate the change in the acoustic characteristics between the early and late phases of cementless stem insertion in total hip arthroplasty and to identify which patient characteristics contribute to the change in the hammering sound.

Methods: The acoustic parameters of the hammering sounds in the early and late phases of cementless taper-wedged stem insertion for 51 hips in 45 patients who underwent total hip arthroplasty (mean age = 68 years, height = 1.56 m, weight = 55.0 kg) were analyzed. Parameters including patient's basic characteristics, radiographical femoral morphology, and canal fill ratio were assessed as potential contributors to the change in the hammering sound.

Results: The low-frequency bands (0.5-1.0 kHz and 1.0-1.5 kHz) showed the largest changes during stem insertion and were therefore considered key bands for the analysis of sound alterations. Multivariate linear regression analysis showed that height (β = 8.312, P = .013) and proximal canal fill ratio (β = −3.8568, P = .038) were independently associated with the sound alterations. The decision tree analysis identified height (≥1.66 m or <1.66 m) as the best single discriminator for the sound alteration.

Conclusions: Patients with smaller stature showed the least change in the hammering sound during stem insertion. Understanding the acoustic characteristics of hammering sound alteration during cementless stem insertion may aid in the achievement of optimal stem insertion.

Introduction

Cementless stems are common implants in total hip arthroplasty (THA). Cementless THA reportedly achieves excellent long-term survivorship [1,2], but has specific complications such as intraoperative fracture and postoperative stem subsidence [3−6]. Although the risks of these complications are reduced by modern technologies including preoperative three-dimensional templating and navigation systems, the success of the hammering procedure to insert the cementless stem depends on the surgeon's ability to confirm adequate fixation.

To confirm the stem stability intraoperatively, it has long been advocated that it is important to listen to the changes in the hammering sounds during stem insertion. However, this evaluation is completely subjective. Moreover, in our experience, the change in the hammering sound is obvious in some cases and nonexistent in others. Inadequate hammering may result in stem subsidence, while excessive hammering may cause an intraoperative fracture. The change in the hammering sound during stem insertion has not been quantitatively evaluated.

We set out to answer the following 2 questions: 1) How do the acoustic characteristics of the hammering sound change during cementless stem insertion? 2) Which factors influence the alteration of the hammering sound during cementless stem insertion? This study aimed to quantitatively investigate the change in the

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acoustic characteristics between the early and late phases of cementless stem insertion and to identify which patient characteristics contribute to the change in the hammering sound during cementless stem insertion.

Material and methods

Patient demographics and preoperative femoral morphology

We initially included 157 hips in 144 patients who underwent primary THA via a direct anterior approach for osteoarthritis and osteonecrosis of the femoral head and agreed to participate in this study (Fig. 1). After excluding patients who received prostheses other than the Accolade II femoral stem (Stryker, Tokyo, Japan) and those lost to follow-up, there were 61 hips in 55 patients (average age: 66.6 ± 9.8 years) who underwent THA with the Accolade II femoral stem (Stryker, Tokyo, Japan). We also excluded patients with more than 5 mm of postoperative subsidence, insufficient data, or outlying acoustic data (described later). A final total of 51 hips in 45 patients were analyzed. Institutional review board approval was obtained before the initiation of the study, and written informed consent was obtained from all included patients.

Operative procedure

Preoperative conventional two-dimensional planning was performed using a transparent sheet with a magnification factor of 110% on a plain radiograph of the hip. The mediolateral metaphyseal contact of the stem was preoperatively planned. Surgery was performed via the direct anterior approach with the patient on a surgical traction table [7]. All surgeries were performed using identical surgical instruments and the same surgical techniques. Fluoroscopy was used to verify the positions of the femoral broach and stem after the broaching procedure and femoral stem insertion. All patients underwent standardized postoperative rehabilitation with full weight-bearing on the first postoperative day.

Sound data acquisition

All hammering sounds during femoral broaching were recorded using a highly sensitive sound level meter (LA-7500, Ono Sokki, Kanagawa, Japan) set on a tripod mounted 1 meter above and 2 meters away from the surgical table. Recordings were made in the range of 40-110 dB using a flat weighted filter and fast time-weighting at a 64 kHz sampling rate and a 16-bit sampling depth.

Sound data analysis

Sound analysis was performed using Oscope, version 2.1 (Ono Sokki, Kanagawa, Japan). The first three hammering sounds and the final hammering sound were excluded to avoid potential inconsistencies in the hammer strikes. The fourth to sixth hammering sounds were defined as the early phase, while the second to fourth hammering sounds from the end of the stem insertion procedure were defined as the late phase. To maximize accuracy and minimize background noise, only the first 0.3 seconds of each hammering sound were used. In this 0.3-second period, the hammer contacted the impaction handle and immediately caused a composite vibration that generated a sound wave at full amplitude without obvious sound attenuation, allowing us to record the hammering sound while the stem was still vibrating. A noise check was performed before the analysis of the selected hammering sounds; if background noises were detected along with the selected hammering sounds on the spectrogram, the recording with these noises was replaced by the previous or next recording.

The recorded hammering sounds were analyzed using a rectangular weighted window at a maximum range of 12.5 kHz via fast Fourier transform analysis. First, the frequency spectrum of the hammering sounds was divided into 25 frequency bands at 0.5 kHz intervals. The sound pressure (SP) and normalized SP (nSP) were assessed for each frequency band. The nSP was calculated as the ratio of the SP of each frequency band divided by the total frequency spectrum, which shows the spectral power distribution of the hammering sound to each frequency band, subject to the vibration pattern. The 0-0.5 kHz frequency band was excluded from the analysis because it was inevitably mixed with background noises such as the air conditioner and voices. Second, as an indicator of the change in the acoustic characteristics of the hammering sound during stem insertion, the alteration ratio was defined as the nSP of the late phase divided by the nSP of the early phase in each frequency band. Third, acoustic data outliers were detected via the Mahalanobis distance method using JMP Pro software, version 15.0.

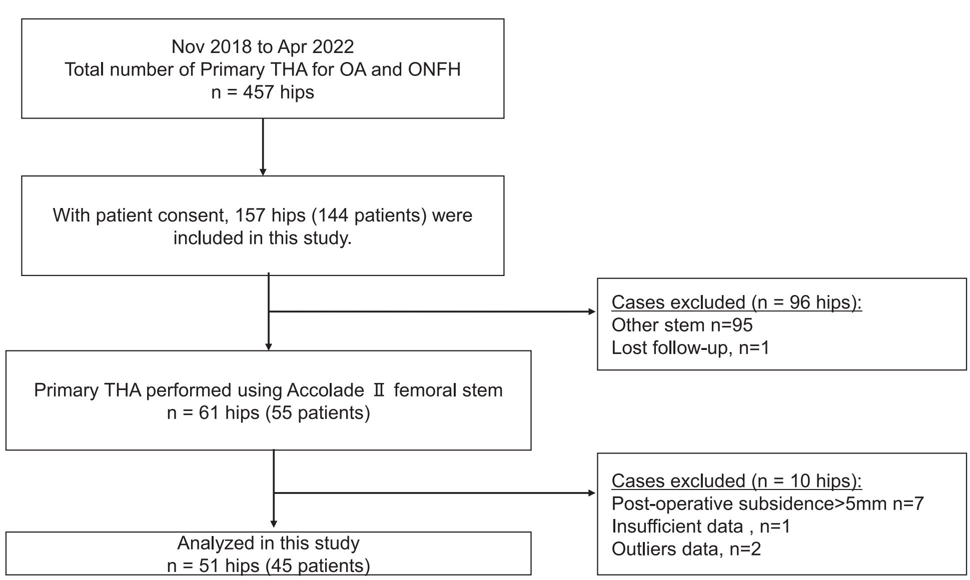

Figure 1. Study flowchart. THA: total hip arthroplasty, OA, osteoarthritis; ONFH, osteonecrosis of the femoral head.

Two patients had outlying acoustic data and were excluded. Fourth, the frequency band with the largest alteration ratio was identified. Finally, the parameters described below that might contribute to the alteration of the hammering sound were investigated.

Parameters assessed as potential contributors to the change in the hammering sound

Patient characteristics such as age, sex, height, and weight were investigated. The following four morphological parameters were analyzed on preoperative radiographs [8]. Canal-calcar ratio: ratio of the intracortical diameter of the femoral canal isthmus at 10 cm below the lesser trochanter to the intracortical diameter of the femur at the medial tip of the lesser trochanter. Canal flare index: 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. Morphologic cortical index: 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. Femoral shaft length (FSL): distance from the midpoint between the great trochanter and lesser trochanter to the intercondylar fossa [9].

The canal fill ratio (CFR) and stem alignment were assessed on immediately postoperative anterior-posterior hip radiographs. The CFR was defined as the stem width divided by the canal width at four points: at the lesser trochanter, 2 cm above the lesser trochanter (CFR2A), 2 cm below the lesser trochanter (CFR2B), and 7 cm below the lesser trochanter [8].

Statistical analysis

Patient demographics were expressed as the mean ± standard deviation. Student's t-tests or Mann-Whitney U tests were used to compare continuous independent data. Correlations were investigated between the alteration ratio and the patient's background characteristics, preoperative femoral morphology, and immediately postoperative radiographic parameters. Univariate and multivariate regression analyses were conducted to identify the factors affecting the sound alteration value. A decision tree was built using the partition method (SAS JMP Pro version 15.0). The objective variable was set as the sound alteration value (explained later). The assessed parameters were set as explanatory variables. Differences and correlations were considered statistically significant at $P < .05$. Statistical analysis was performed using JMP Pro software, version 15.0. The radiographic measurements were analyzed by 2 observers (S.I. and Y.S.) who were not involved in the sound analysis. 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).

Results

Patient characteristics and bone morphological parameters are shown in Table 1.

There were significant differences in the acoustic characteristics during stem insertion between the early and late phases in several ranges (Fig. 2A). The alteration ratios of low-frequency bands (0.5-1.0 kHz and 1.0 kHz) were obviously different from the alteration ratios of other frequency bands (Fig. 2B). The low-frequency bands (0.5-1.0 kHz and 1.0-1.5 kHz) showed the largest changes during stem insertion and were therefore considered key bands for the analysis of sound alterations. The alteration ratio of the 0.5-1.0 kHz frequency band multiplied by the alteration ratio of the 1.0-1.5 kHz frequency band was defined as a feature representing the sound alteration and named the sound alteration value.

Table 1
Patient characteristics, bone femoral morphology, and canal fill ratio.

Number of patients	51
Sex (male/female)	10/41
Age	68 (13)
Height	157 (10)
Weight	55.0 (12.4)
Body mass index	23.19 (3.39)
Bone morphological parameters	
CCR	0.428 (0.131)
CFI	3.870 (1.053)
MCI	2.999 (0.559)
FSL	325.72 (27.94)
Canal fill ratio	
2 cm above the LT	0.674 (0.112)
LT	0.845 (0.140)
2 cm below the LT	0.886 (0.152)
7 cm below the LT	0.833 (0.131)

Data are presented as medians with interquartile range.
CCR, canal-calcar ratio; CFI, canal flare index; MCI, morphologic cortical index; FSL, femoral shaft length; LT, lessor trochanter.

Table 2 shows the relationships between the sound alteration value and the assessed parameters. Height and FSL showed weak positive correlations with the sound alteration value. No other parameter was correlated with the sound alteration value.

Table 3 shows the results of univariate and multivariate linear regression analyses. Univariate analysis revealed that the variables significantly correlated with the sound alteration value were height ($P = .002$), weight ($P = .007$), FSL ($P = .152$), and CFA2A ($P = .022$). In accordance with the results of the univariate linear regression analysis, age, height, FSL, CFR2A, and CFA2B were selected for the multivariate linear regression analysis. Multivariate linear regression analysis showed that height and CFA2A were independently associated with the sound alteration value (root mean square error = 0.914, adjusted $R^2 = 0.208$).

The final decision tree classification is shown in Figure 3. Regarding the accuracy of this decision tree classification, the R^2 and root mean square error were 0.483 and 0.790, respectively. The decision tree analysis identified height (≥1.66 m or <1.66 m) as the best single discriminator for the sound alteration value. Patients with a height of ≥1.66 m had the largest sound alteration value (mean: 3.860, standard deviation: 1.714). Among those with a height of <1.66 m, the next best predictor was again the height (<1.56 m or ≥1.56 m). Among those with a height of ≥1.56 m, the next best predictor was the CFR2A (<0.679 or ≥0.679). Patients with a CFA2A of <0.679 had the second largest sound alteration value (mean: 1.982, standard deviation: 0.817). Among those with a height of <1.56 m, the next best predictor was the FSL (<323.87 mm or ≥323.87 mm). Patients with a FSL of <323.87 mm had the smallest sound alteration value (mean: 1.420, standard deviation: 0.568).

Discussion

The major drawbacks of cementless THA are specific complications such as intraoperative fractures and postoperative subsidence [3-6]. To achieve proper stem insertion, surgeons must perform adequate hammering. Listening to the change in the hammering sound is 1 of the elements used to assess stem stability. However, this is a completely subjective evaluation, and the change in the hammering sound differs among patients. The present study assessed the acoustic characteristics during stem insertion and identified factors that influenced the change in the hammering sound. It is important for surgeons to understand the acoustic characteristics of

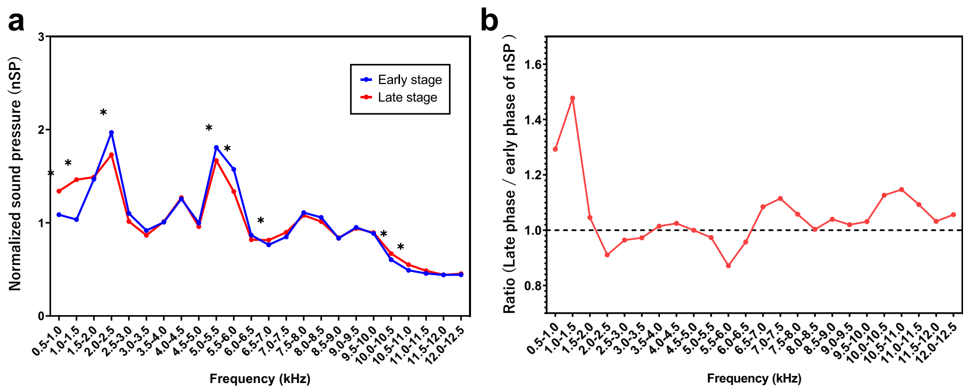

Figure 2. (a) Normalized sound pressure (nSP) of early and late phase in each frequency. (b) Ratio (Late phase/early phase of nSP). 0.5-1.0 kHz and 1.0 kHz were obviously highest alteration ratios among other frequency bands.

the hammering sounds during cementless stem insertion. Our results suggest that particular attention should be paid to patients with shorter stature, as such patients may exhibit a relatively small change in the hammering sounds during stem insertion.

There are several possible explanations for the acoustic characteristics identified in our study. The low-frequency band was augmented from the early to the late phase of stem insertion. As the stem is inserted into the femoral canal, the main vibrating object changes from the stem itself to the stem-femur composite. Because the stem is fixed to the femur and the femur is much heavier than the stem, the femur itself may become the main vibrating object. This speculation is supported by our finding that the augmentation of the low-frequency band (0.5-1.5 kHz) during stem insertion was correlated with stature-related characteristics, such as height, weight, and FSL. Our speculation is also consistent with previous studies [10,11]. McConnell et al. found that the emergence of a low-frequency band of sound in the 1 kHz range during final femoral broaching was a strong predictor of a well-sized implant stem [10]. They also speculated that the sound arose from the bone itself because the frequency was related to femoral length [10]. Whitwell et al. reported that the last broach and implant introduction spectra demonstrated low-frequency (0.44-1.2 kHz) spectral peaks that were not detected when using the first broach [11].

There are several possible reasons that patient factors (height, weight, FSL, and proximal CFR) were related to the change in the hammering sound during stem insertion. First, although it is difficult to precisely analyze the vibration mode of the femur, it is very likely that the natural frequency of the entire femur is around 1 kHz in patients with relatively large stature. McConnell et al. reported that 75 of 101 hips (74.3%) showed the emergence of low-frequency sounds (1 kHz) during final broaching in patients with a median body mass index of 29 kg/m^2 (interquartile range 26 to 32 kg/m^2) [10]. Furthermore, Whitwell et al. reported that low-frequency (0.44-1.2 kHz) spectral peaks corresponded to the natural resonant frequency of a standing sound wave within the femoral bone canal (approximately 0.894 kHz) [11]. Second, the wave might be augmented by the femoral canal after the stem is well fixed to the femur. In our study, the CFR at all levels were negatively weak correlation with the sound alteration value. Moreover, multivariate linear regression and decision tree classification showed proximal CFR negatively contributed to the sound alteration value. Although the stem was well fitted to the femur, it is speculated that more space between the stem and femur made more augmentation of the sound, especially in low frequency bands. This implies that different type of stem may exhibit different sound changes during the stem insertion.

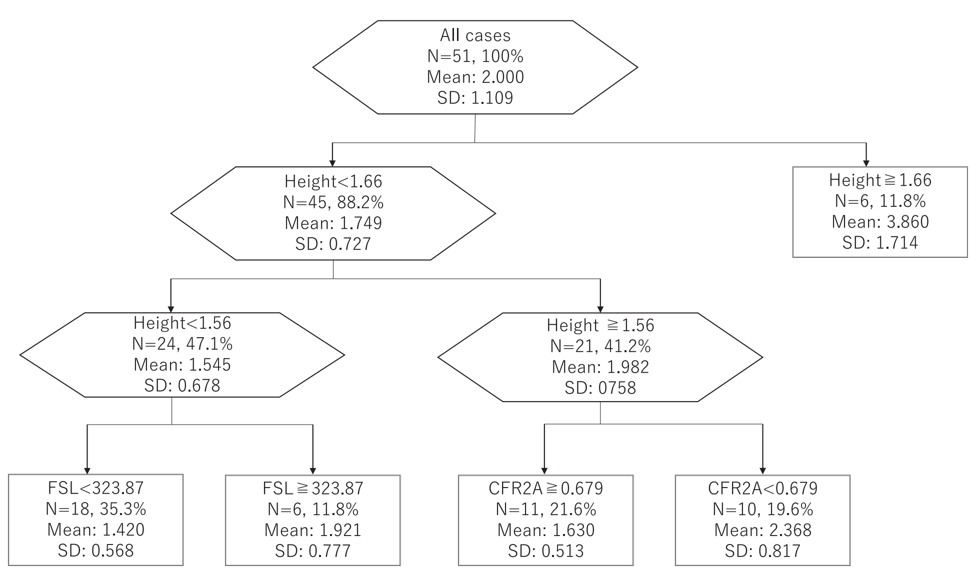

Figure 3. Decision tree classification for the sound alteration value.

Table 2
Correlations between the sound alteration value and parameters investigated.

		1	2	3	4	5	6	7	8	9	10	11	12	13
1	Sound alteration value	1.0												
2	Age	−0.0298	1.0000											
3	Height	0.388[a]	−0.345[a]	1.0000										
4	Weight	0.271	−0.219	0.537[a]	1.0000									
5	BMI	0.055	−0.076	0.036	0.811[a]	1.0000								
6	FSL	0.3773[a]	−0.161	0.791[a]	0.220	−0.249	1.0000							
7	CCR	0.068	0.119	0.071	−0.015	−0.023	0.029	1.0000						
8	CFI	−0.068	−0.091	−0.088	0.055	0.101	−0.068	−0.871[a]	1.0000					
9	MCI	0.059	−0.1973	0.037	0.115	0.102	0.004	−0.867[a]	0.825[a]	1.0000				
10	CFR2A	−0.223	−0.074	−0.120	−0.233	−0.145	−0.107	0.544[a]	−0.665[a]	−0.583[a]	1.0000			
11	CFRLT	−0.136	0.060	−0.140	−0.159	−0.051	−0.172	0.615	−0.515[a]	−0.616[a]	0.777[a]	1.0000		
12	CFR2B	−0.172	0.074	−0.061	−0.117	−0.005	−0.164	0.247	−0.183	−0.259	0.425[a]	0.669	1.0000	
13	CFR7B	−0.154	0.071	−0.036	−0.036	0.037	−0.197	−0.472[a]	0.320[a]	0.401[a]	0.0325	0.094	0.393[a]	1.000

BMI, body mass index; FSL, femoral shaft length; CCR, canal-calcar ratio; CFI, canal flare index; MCI, morphological cortex index; CFR, canal fill ratio; 2A, 2 cm above from the lesser trochanter; LT, lesser trochanter; 2B, 2 cm below from lesser trochanter.
[a] *P* value <.05.

We believe that quantitative evaluation of the hammering sounds should be the future gold standard in cementless THA, as auditory sensations are subjective and differ among individuals; in contrast, acoustic analysis is objective and far more precise and accurate. Many recent studies have demonstrated the potential usefulness of acoustic assistance in THA [10,12−15]. Better clinical outcomes of cementless THA have resulted from improvements in the cementless stem itself as well as technologies such as preoperative three-dimensional templating [16,17], navigation systems [18,19], and robotics [20−22]. These highly advanced technologies have made it easier and safer to insert an appropriately sized implant in the correct position, but are unable to judge whether the cementless implant is appropriately fixed. The implant fixation is still dependent on the surgeon's subjective judgment. Therefore, modern technologies such as noninvasive acoustic evaluation should be used to assist the surgeon in the future.

This study has several limitations. First, only 1 type of tapered-wedge, short cementless stem was analyzed. It is unclear whether the same acoustic characteristics can be generalized to stems with other shapes. Second, all the included patients were Japanese, and it is highly probable that they had a smaller stature compared with Western populations. Acoustic characteristics might be altered in different populations.

Table 3
Univariate and multivariate analysis for the sound alteration value.

Basic characteristics	Univariate linear regression		Multivariate linear regression	
	β	*P* value	β	*P* value
Age	−0.018	.274	0.009	.546
Height	6.565	.002[a]	8.312	.0126[a]
Weight	0.036	.007[a]	-	-
Body mass index	0.056	.179	-	-
Bone morphological parameters				
CCR	0.962	.591	-	-
CFI	0.014	.950	-	-
MCI	0.368	.375	-	-
FSL	0.011	.152	−0.015	.207
Canal fill ratio				
2 cm above the LT	−4.504	.022[a]	−3.856	.0384[a]
LT	−0.1.84	.234	-	-
2 cm below the LT	−1.563	.261	−0.460	.716
7 cm below the LT	−1.315	.340	-	-

CCR, canal-calcar ratio; CFI, canal flare index; MCI, morphologic cortical index; FSL, femoral shaft length; LT, lesser trochanter.
[a] *P* value <.05.

Conclusions

The change in the hammering sound during cementless stem insertion was characterized by the augmentation of low-frequency sounds (0.5-1.5 kHz). Patients with smaller stature showed the least change in the hammering sound during stem insertion. Understanding the acoustic characteristics of hammering sound alteration during cementless stem insertion may aid in the achievement of optimal stem insertion.

Conflicts of interest

The authors declare there are no conflicts of interest.

For full disclosure statements refer to https://doi.org/10.1016/j.artd.2023.101136.

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