

# Psychoacoustic Quantification of Mechanical Heart Valve Noise

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**Background and aim of the study:** Mechanical heart valves produce short clicking sounds during closure. These closing sounds are annoying for some patients and their partners by causing sleeping disorders or social embarrassment. Various methods for measuring the sounds have been developed both in vitro and in vivo using calculation of A-weighted sound pressure level or loudness according to ISO 532 B. The study aim was to evaluate the relevance of different psychoacoustic parameters in the evaluation of closing sounds.

**Methods:** Closing sounds were recorded from patients with ATS valves (n = 13), On-X valves (n = 18) and St. Jude Medical heart valve prostheses (n = 16). The sounds were recorded 5 cm above the chest of patients in a supine position, in a sound-insulated chamber. The mean peak values of loudness and sharpness were calculated and used to determine the

psychoacoustic annoyance using a modification of the Widmann formula. This was verified by a listening test for ranking closing sounds of different level and sharpness by annoyance.

**Results:** There was no statistically significant independence between loudness difference or psychoacoustic annoyance difference and agreement among the test persons. For the valves, loudness ranged from 0.07 to 2.57 sone, and the psychoacoustic annoyance from 0.1 to 5.4.

**Conclusion:** The results of this study showed that both sharpness and loudness have a significant influence on annoyance from closing sounds from mechanical heart valves, and indicated that the substantial variation in the parameters may be due to individual patient physiology.

The Journal of Heart Valve Disease 2005;14:89-95

In recent years, increasing interest has been devoted to the assessment of sound levels generated from mechanical heart valves. This interest is stimulated by the fact that some mechanical heart valve patients experience considerable annoyance from the valve closing sound. Moritz et al. (1) showed that 65% of their patients could hear their own heart valve. Some of these patients had sleeping disorders and daytime complaints, and 12% would have preferred a less noisy heart valve.

Moritz et al. (1) also investigated the residual noise after eliminating air-transmitted sound perceived by the patient, and found that 51% of the patients could still hear their heart valve. This implies that the sound energy must be transmitted within the body, most likely through bones and vessels. Another study conduct-

ed by Nygaard et al. (2) showed that patients with heart valve prostheses seem to perceive the sound from their valve at a level which is two- to four-fold higher than as perceived by nearby persons, mainly due to additional bone- and tissue-transmitted vibrations. Accordingly, it is still possible for patients with a considerable conductive hearing loss to be annoyed by the sound of their heart valve.

For several years researchers have attempted not only to measure the heart valve sound by objective means (dB(A)) but also to describe the annoyance that patients experience from their prostheses. Two different sounds with the same dB(A) value can be perceived very differently. To give a better description, loudness including temporal effects was chosen in the present study because it is based on a physiological model of the human ear endeavoring to a scaling according to the perceived loudness (3). In the present study, other sound parameters were examined such as tonality, roughness and sharpness, as these might be necessary for describing the annoyance of a sound. The formula used to calculate the psychoacoustic

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annoyance (PA) was a modification of the formula used by Widmann (4). An evaluation was made as to whether this modified formula was applicable for small transient clicking sounds from mechanical heart valves.

The hypothesis was that existing psychoacoustic parameters would provide a more appropriate evaluation of the annoyance that patients perceive from their mechanical heart valves than the previously used objective physical parameters. Thus, the study aim was to evaluate the relevance of different psychoacoustic parameters in the evaluation of mechanical heart valve noise.

### Sound measurement

A-weighted sound pressure level (SPL) is the most frequently used measure for the evaluation of noise. Theoretically, the A-weighting is only valid for pure tones in a small range of SPL values. The extensive use of dB(A) values is due to simplicity of the measurement and its accuracy in ranking noise signals which do not vary considerably in time or frequency.

Zwicker (5) standardized a method for loudness calculation called ISO 532B. In this calculation of loudness level, equal loudness contours are used for a SPL-dependent frequency weighting. In the calculation of loudness, the scale is linear with the perceived level. The calculation is based on a physiological model of the human ear, and includes the effect of simultaneous masking (a sound hiding other sounds at certain frequencies resulting in a lower loudness). In an analysis of temporally varying sounds, the temporal effects of loudness must also be included. These are not included in the standard, but they were described by Zwicker and Fastl (3), and some computer programs for loudness calculations use a model of the temporal effects of loudness.

In psychoacoustics, parameters other than loudness are also used to describe a sound. These include tonality, fluctuation strength, roughness and sharpness (3). *Tonality* is a measure of the relative content of pure tones in a signal.

*Fluctuation strength* is a measure of amplitude modulation - that is, variations in amplitude, with frequencies up to about 30 Hz. Frequencies at about 4 Hz elicit the largest fluctuation strength.

*Roughness* is a measure of modulation with frequencies in the range about 15 Hz to 300 Hz. Frequencies at about 70 Hz elicit the largest roughness, but the frequency which elicits the largest roughness decreases if the center frequency of the modulation is lower than 1 kHz.

*Sharpness* is a measure of the relative content of high frequencies in a signal. A curve for weighting the frequencies is used in this calculation.

Various formulas for combining some of these parameters to generate a measure of the pleasantness and annoyance of a sound have been developed.

### Psychoacoustic annoyance (PA)

Zwicker and Fastl (3) described a formula developed by Widmann (4) for the calculation of PA, which includes the parameters of loudness, sharpness, fluctuation strength and roughness:

$$PA = N_5(1 + \sqrt{w_S^2 + w_{FR}^2}) \quad (1)$$

$$w_S = \left( \frac{S}{\text{acum}} - 1.75 \right) \cdot 0.25 \cdot \log \left( \frac{N_5}{\text{sone}} + 10 \right) \quad (2)$$

for  $S > 1.75$  acum

$$w_{FR} = \frac{2.18}{(N_5/\text{sone})^{0.4}} \left( 0.4 \cdot \frac{F}{\text{vacil}} + 0.6 \cdot \frac{R}{\text{asper}} \right) \quad (3)$$

where  $N_5$  is the percentile loudness (sone),  $S$  is the sharpness (acum),  $F$  is the fluctuation strength (vacil), and  $R$  is the roughness (asper).

Zwicker and Fastl (3) also described a formula for calculation of sensory pleasantness developed by Aures (6,7). In this formula, sensory pleasantness was calculated from the parameters of fluctuation strength, roughness, tonality and sharpness.

A major difference between annoyance and pleasantness is that loudness has a greater influence on annoyance than on pleasantness. Therefore, characterization of annoyance should be used rather than a characterization of pleasantness. According to Aures (6), the tonality increases the pleasantness, while Kryter and Pearson (8) state that tonal sounds are more annoying than noises under the same circumstances. Tonality was not included in this formula for PA which presupposes no pure tones in the sound, and it was assumed small because of the spectral width of the impulsive closing sounds.

Because of the short duration of the closing sounds, a modification of the formula for PA calculation developed by Widmann was carried out in the present study. Since the closing sounds were of extremely short duration, the percentile loudness  $N_5$  was replaced by a mean of peak values of loudness, including temporal effects. Calculations of fluctuation strength and roughness were omitted in this modified formula. This emission was performed because the modulation frequencies which elicit the largest roughness are about 70 Hz. These frequencies correspond to a time period of about 14 ms, which is longer than the duration of a common closing sound. The time periods of

fluctuation strength are even longer, corresponding to time periods of about 33 ms and more. The third modification to the formula of Widmann is that sharpness was calculated using Aures' method (7), thus improving level independence. As for loudness, a mean of peak values (corresponding to the loudness values) was used.

The modified Widmann formula thus became:

$$PA = \frac{N}{\text{sone}} \left( 1 + \left( \frac{S}{\text{acum}} - 1.75 \right) \cdot 0.25 \cdot \log \left( \frac{N}{\text{sone}} + 10 \right) \right)$$

for  $S > 1.75 \text{ acum}$  (4)

## Materials and methods

### Measuring procedure

The procedure of measuring the closing sounds described by Nygaard et al. (2) was used for the present study. The patients were placed in a supine position within a sound-insulated chamber in which heavy curtains dampened the reflection of sound waves. The full background noise in the chamber was 19 dB(A), and this was reduced to 9 dB(A) with a 250 Hz high-pass filter.

Closing sounds were recorded with a microphone positioned 5 cm above the patient's chest. The raw signal provided a good signal-to-noise ratio, and was independent of the individual patient's hearing ability and his or her subjective impression. The procedure is explained schematically in Figure 1.

The microphone (type 4155; Brüel & Kjaer, Naerum, Denmark) was connected to a preamplifier (Brüel and Kjaer 2671), a measuring amplifier (Brüel and Kjaer 2610) and a 250 Hz high-pass filter. An accelerometer (Brüel and Kjaer 4371) was mounted on the patient's chest and connected to a charge amplifier (Brüel and Kjaer 2635), a measuring amplifier (Brüel and Kjaer 2609) and a 250 Hz high-pass filter. The accelerometer signal was used as trigger for detecting closing sounds when calculating SPL. The raw signals from the microphone and accelerometer were stored on a DAT tape recorder (TEAC RD-180T PCM Data Recorder; TEAC Corporation, Tokyo, Japan) for later analysis.

### Loudness and sharpness calculation

ISO 532B is a standard for calculating loudness, and the standard DIN 45631 contains the source code for a computer program for loudness calculation. This standard has a resolution of 240 lines for the Bark scale, a frequency scale used in psychoacoustics to calculate loudness. A PC-program (Sound Quality 7698; Brüel and Kjaer) was used for calculations of loudness and sharpness. The data were sampled into the program at a rate of 48 kHz. Sound Quality 7698 has a resolution

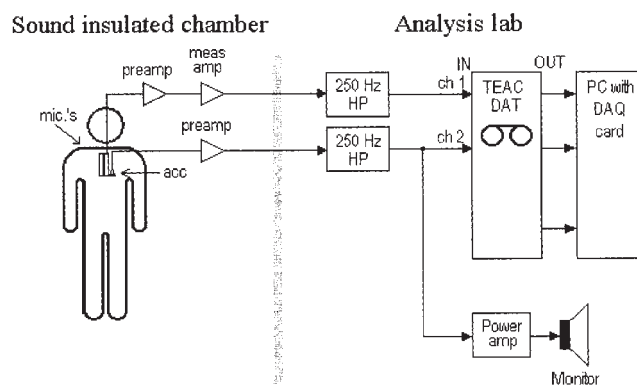


Figure 1: Measurement set-up. The patient is placed in a supine position within the sound-insulated chamber. Valve closing sounds were recorded and amplified inside the chamber and led through the wall into the analysis laboratory. The sounds were 250 Hz high-pass (HP)-filtered and stored on a DAT tape recorder. The accelerometer signal was amplified and used as a monitoring signal.

of 3,088 lines for the Bark scale, which is an improvement of the standard frequency resolution. In addition, Sound Quality 7698 includes a model of the post-masking properties of the human ear, which is necessary for analyzing non-stationary sounds.

In the loudness calculation, the assumption of either a free or diffuse sound field must be made because the different sound fields produce different equal loudness contours. Even though heavy curtains dampen reflections in the sound-insulated chamber, and the sound is measured only 5 cm from the patient's chest, a diffuse sound field was assumed. This assumption was made because of the sound's phase displacements during complex transmissions through the body to the air.

Sound Quality 7698 produced a graph showing the loudness as a function of time for a recording of about 20 s, with a time resolution of 1 ms (Fig. 2a). In this graph, peak values of loudness produced by closing sounds were then marked. Closing sounds which were disturbed by respiration sound or noise were not included. Because of their spectral width, respiration sound and noise can have large loudness relative to their SPL.

A graph showing sharpness calculated by Aures' method (7) as a function of time was produced from the same signal, and peak values in sharpness magnitude corresponding to the peak values of loudness magnitude were marked. An example of the graphic display is shown in Figure 2. Because of the SPL independence in the sharpness calculation, the opening sounds and closing sounds have sharpness values of almost the same magnitude.

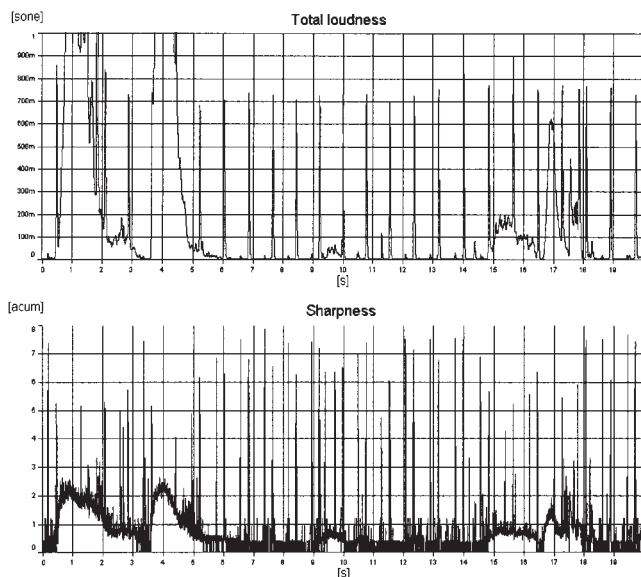


Figure 2: An example of loudness and sharpness as functions of time. In the first approximately 5 s the closing sounds were disturbed by respiration sound, which produces a large loudness magnitude.

The mean values of loudness and sharpness were calculated respectively, and used to calculate PA using the modified Widmann formula.

#### Test of modified Widmann formula

A listening test was performed to test the validity of Eq. (4). This test consisted of several heart valve sounds that had been modified by filtering specific acoustic frequencies. The modification was created by the application of a digital filter, resulting in six different sounds A-F with three different degrees of loudness and two different degrees of sharpness.

The characteristics of these six sounds are shown in Table I. Sounds A-F were combined two-by-two in all possible combinations (15 in total). The sounds were played in pairs; each clicking sound was repeated seven times with an interval of 1 s. After each pair, there was a pause of approximately 4 s, during which the subjects were asked to identify the most annoying sound. In total, 20 subjects participated in these exper-

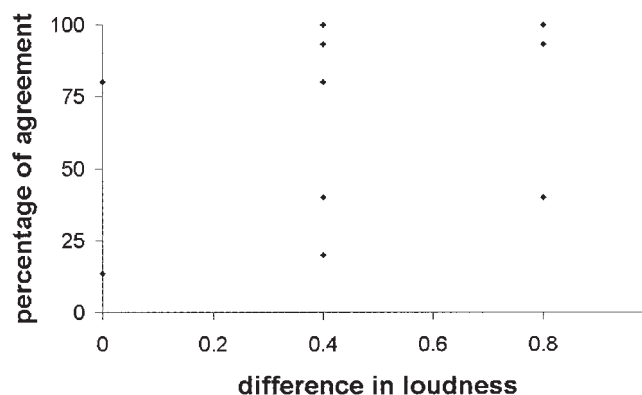


Figure 3: Percentage of mutual agreement among the test persons as a function of difference in loudness by each pair comparison. Only persons with normal hearing are included.

iments, including 15 persons with normal hearing ability and five with a reduced hearing at high frequencies.

#### Statistical analysis

Spearman's rho ( $\rho$ ) was used to compare ranking of the sounds by percentage of mutual agreement among test persons and respectively loudness difference and PA difference. A p-value  $<0.05$  was considered to be a statistically significant.

## Results

#### Listening test findings

As shown in Table I, the sharpness had a considerable effect on the calculation of PA by Eq. (4). Sounds B and C were equally 'annoying', even though the sound C had a larger value of loudness. More convincing was a comparison of sounds D and E; sound D had a larger PA than sound E, even though E had a larger value of loudness.

Figure 3 shows the percentage of mutual agreement among the listening test participants as a function of difference in loudness by each pair comparison. Figure

Table I: Characteristics of the six different transient sounds A-E used in the listening test.

Sound	Loudness (sone)	Sharpness (acum)	Psychoacoustic annoyance
A	0.6	3	0.8
B	0.6	6	1.3
C	1.0	3	1.3
D	1.0	6	2.1
E	1.4	3	1.9
F	1.4	6	3.0

Table II: Results of the measurement procedure: Sound pressure level (SPL), loudness, sharpness and psychoacoustic annoyance (PA) calculated for each patient.

Patient no.	Age/gender	BMI	Valve*	SPL (dB(A))+	Loudness (sone)	Sharpness (acum)	PA
1	65M	26	ATS 23 a	33	0.70	4.5	1.2
2	64M	30	ATS 25 a	30	-	-	-
3	75M	25	ATS a	34	0.99	5.5	1.9
4	62F	34	ATS 19 a	27	0.35	4.8	0.6
5	61F	32	ATS 19 a	36	0.30	4.8	0.5
6	65M	22	ATS a	28	0.18	4.0	0.3
7	65M	24	ATS a	37	0.67	5.4	1.3
8	64F	35	ATS 19 a	30	0.16	5.1	0.3
9	73M	28	ATS a	32	0.54	4.9	1.0
10	71M	30	ATS 23 a	36	0.78	5.5	1.5
11	66M	28	ATS 27 a	37	0.82	5.8	1.7
12	68M	26	ATS a	37	0.44	6.7	1.0
13	73M	29	ATS 23 a	34	0.35	7.2	0.9
14	55M	29.3	On-X 27 a	47	0.87	6.8	2.0
15	57M	25.3	On-X 21 a	36	0.38	6.5	0.8
16	68M	24.3	On-X 27 a	36	-	-	-
17	68M	31.1	On-X 31/33 m	37	0.79	6.7	1.8
18	69F	29.2	On-X 27/29 m	42	1.13	6.7	2.6
19	66F	29.1	On-X 21 a	37	0.68	6.0	1.4
20	58M	17.9	On-X 31/33 m	37	0.74	6.1	1.6
21	60F	29.8	On-X 19 a	35	0.57	6.9	1.3
22	60M	28.7	On-X 25 a	41	1.14	6.9	2.7
23	65M	27.4	On-X 23 a	38	0.86	6.6	1.9
24	57F	27.8	On-X 31/33 m	38	0.72	7.0	1.7
25	52F	25.8	On-X 27/29 m	33	0.82	5.6	1.6
26	21M	23.8	On-X 25 a	47	2.57	5.8	5.4
27	70M	24.9	On-X 23 a	37	1.07	5.9	2.2
28	49M	22.0	On-X 23 a	29	0.74	5.2	0.9
29	69F	24.1	On-X 27/29 m	37	0.85	6.8	2.0
30	56M	28.4	On-X 25 a	34	0.52	6.9	1.2
31	69M	23.6	On-X 27/29 m	37	1.51	7.3	3.7
32	52F	31.3	SJM 31 m	40	0.92	6.7	2.1
33	69F	28.0	SJM 21 a	29	0.34	6.3	0.7
34	58M	25.4	SJM 25 a	41	0.76	6.7	1.7
35	63M	26.9	SJM 27 a	32	0.58	4.0	0.9
36	66M	21.6	SJM 23 a	19	0.07	3.2	0.1
37	50M	32.4	SJM 31 m	32	0.31	6.4	0.7
38	56F	27.6	SJM 23 a	33	0.30	7.0	0.7
39	70F	30.0	SJM 25 m	34	0.40	6.6	0.9
40	48M	31.5	SJM 25 a	36	0.72	6.8	1.7
41	56M	23.8	SJM 23 a	42	1.14	8.4	3.1
42	71F	26.6	SJM 21 a	26	0.20	5.3	0.4
43	73M	23.1	SJM 25 a	36	0.38	7.3	0.9
44	48M	34	SJM 27 a	34	0.14	6.6	0.3
45	26M	23.7	SJM 25 a	44	0.5	6.2	1.1
46	63M	23.4	SJM 23 a	41	0.61	6.6	1.4
47	66M	25.8	SJM 23 a	37	0.38	5.5	0.8

\*Valve manufacturer; number = valve size in mm; a = aortic, m = mitral.

+Measured 5 cm above the patient's chest.

BMI: Body mass index (kg/m<sup>2</sup>).

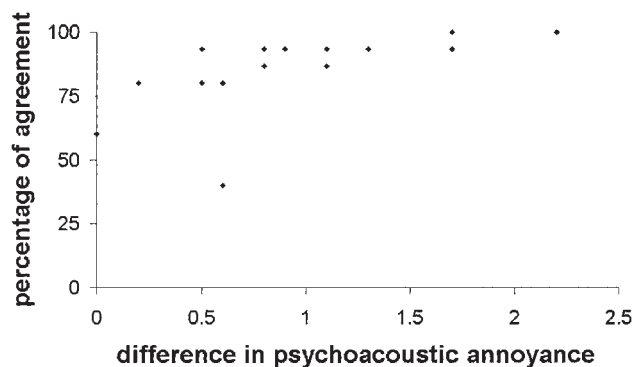


Figure 4: Percentage of mutual agreement among the test persons as a function of difference in psychoacoustic annoyance by each paired comparison. Only persons with normal hearing are included.

4 shows the percentage of mutual agreement among the listening test participants as a function of difference in PA by each paired comparison. Only persons with normal hearing are included in these figures. Figure 3 shows that a larger difference in loudness does not necessarily result in better agreement among the listening test participants of the most annoying sound. Figure 4 shows that a larger difference in PA gives a better agreement among the listening test participants of the most annoying sound. There was no statistically significant independence between loudness difference and percentage of agreement ( $\rho = 0.52$ ,  $p = 0.047$ ), nor between PA difference and percentage of agreement ( $\rho = 0.78$ ,  $p = 0.0006$ ) for persons with normal hearing.

There was no statistically significant independence between loudness difference and percentage of agreement ( $\rho = 0.57$ ,  $p = 0.028$ ) for persons with reduced hearing at high frequencies.

### Sound measurements

Loudness, sharpness and PA calculated from measurements in patients with three different bileaflet valves are presented in Table II. The SPL values were calculated according to the procedure described by Nygaard et al. (2). For two patients, the loudness was not calculated because of prominent respiration sounds in addition to the closing sounds. Loudness values ranged from 0.07 to 2.57 sone (mean  $0.67 \pm 0.43$  sone), and PA from 0.1 to 5.4.

An analysis of frequency content and specific loudness of the closing sounds showed that these values varied consistently from patient to patient, independent of valve type. Patients #14 and #26 both had an On-X valve, and both had a measured SPL of 47 dB(A), but the loudness values were 0.87 and 2.57 sone, respectively.

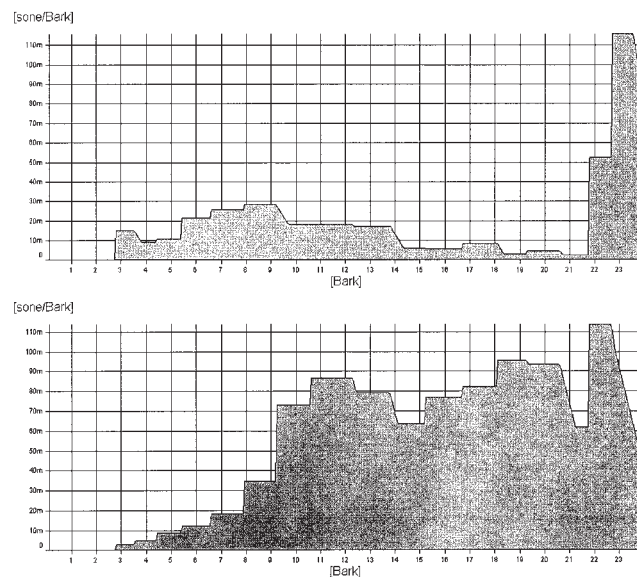


Figure 5: Specific loudness as function of frequency for patients #14 (upper) and #26 (lower). Loudness, which is an integration of the specific loudness curve, is larger for patient #26, although both sound pressure levels were 47 dB(A).

## Discussion

### Listening test

Figure 3 indicates that, among the listening test participants, a larger difference in loudness does not necessarily result in better mutual agreement about the most annoying sound. A comparison of Figures 3 and 4 indicates that the tested modified Widmann formula, which includes sharpness, is a better description of how annoying the clicking sounds are from mechanical heart valves than loudness alone. Thus, sharpness is important in describing the annoyance of mechanical heart valve closing sounds in patients with normal hearing. The p-values were calculated from Spearman's rho, which uses a ranking of the data. A lower p-value means a better agreement in the ranking. The test results also indicated that persons who have a reduced hearing at high frequencies could not distinguish between magnitudes of sharpness, because sharpness is a measure of the relative content of high frequencies in a sound. For these persons loudness likely has a greater dominance in how they perceive the annoyance. Further evaluation of the formula used with respect to differences in temporal and spectral shape of the sounds should show potential dependencies or limitations.

### Sound measurements

The study results revealed loudness values with a larger deviation ( $0.48 \pm 0.29$  sone for St. Jude Medical;

SJM) than in an in-vitro study by Erickson et al. (9) ( $0.97 \pm 0.04$  sone for SJM). Most likely, this difference could be attributed to the fact that the present study was conducted in vivo, and differences in the patients' physiology had a considerable impact on the sounds produced by their mechanical heart valves. The patients' body and hemodynamic statuses may influence this. The relatively large deviation of PA for some individuals is also considered to be caused by physiological circumstances.

An explanation of the fact that patients #14 and #26 had the same valve and SPL, but different loudness values, can be provided by observing the specific loudness for these two series of closing sounds shown in Figure 5. The frequency spectrum for patient #26 was seen to be much wider than for patient #14, and this resulted in a larger loudness, despite the same SPL. This shows the necessity of using the physiological model of the ear, which is included in the calculation of loudness, but not of A-weighted SPL (note that the graphs have been averaged from the total recorded time signals, and the mean peak value of loudness cannot be calculated by this). However, this also showed the importance of the level and spectrum of the recorded sounds being comparable to the properties of the sound perceived by the patient. This was the same problem as encountered in previous studies measuring SPL above the chest or a phantom, though the impact on the units may be different. It might be expected that the sounds undergo a low-pass filtering to the ear as well as through the thorax.

The results listed in Table II should be considered with caution, because there was substantial patient-to-patient variation in the calculation of loudness and PA among this relatively small patient group. One type of heart valve prosthesis, when implanted in two different persons, may result in significant differences in PA.

The use of psychoacoustic parameters provides a more accurate measure of perceived annoyance than physical parameters, and is still independent of the individual patient's subjective impression. Therefore, this approach it is useful to compare the noise generated by clinically used mechanical heart valves. Information about the annoying factors in closing sounds may also be useful for the development of future mechanical heart valve prostheses.

#### Study limitations

One limitation of the present method might be that the frequency spectra of recorded sounds may deviate

from the spectra of body-transmitted sounds perceived by patients due to different acoustic damping through the thorax. Further knowledge about transfer functions through the body, and further evaluation of the PA formula, will improve this assay for mechanical heart valve noise quantification.

*In conclusion*, the results of the present study showed that sharpness, as well as loudness, has a significant influence on annoyance from the closing sounds of mechanical heart valves in patients with normal hearing ability. Values of loudness calculated in this study showed a much larger deviation than those shown earlier in vitro. The frequency spectrum of the closing sounds was highly patient-dependent, and had a significant influence on both loudness and sharpness, with individual patient physiology being considered as the main cause.

#### References

1. Moritz A, Steinseifer U, Kobina G, et al. Closing click of St. Jude Medical and Duromedics Edwards bileaflet valves: Complaints created by valve noise and their relation to sound pressure and hearing level. *Eur Heart J* 1991;12:673-679
2. Nygaard H, Johansen P, Riis C, Hasenkam JM, Paulsen PK. Assessment of perceived mechanical heart valve sound level in patients. *J Heart Valve Dis* 1999;8:655-661
3. Zwicker E, Fastl H. *Psychoacoustics: Facts and Models*. 2nd edn. Berlin: Springer-Verlag, 1999
4. Widmann U. A psychoacoustic annoyance concept for application in sound quality. *Proc Noise Con* 1997:491-496
5. Zwicker E. Meaningful noise measurement and effective noise reduction. *Noise Control Engng J* 1987;29:66-76
6. Aures W. Der sensorische Wohlklang als Funktion psychoakustischer Empfindungsgrößen. *Acustica* 1985;58:282-290
7. Aures W. Berechnungsverfahren für den sensorischen Wohlklang beliebiger Schallsignale. *Acustica* 1985;59:130-141
8. Kryter KD, Pearson KS. Judged noisiness of a band of random noise containing an audible pure tone. *J Acoust Soc Am* 1965;38:106-112
9. Erickson RL, Thulin LI, Richard GJ. An in vitro study of mechanical heart valve sound loudness. *J Heart Valve Dis* 1994;3:330-334