Genesis of the Mechanical Heart Valves’ Ultrasonic Closing Clicks

1. Introduction

The sounds, or clicks, produced by mechanical heart valve (MHV) prosthesis have been studied for the purpose of functional diagnosis. Hylen et al. reported spectral analysis of the clicks in 1969 [1]. Much research was reported thereafter. However, all of those studies reported before 1994 were limited to the clicks in the audible frequency range (audible clicks). In 1994, we reported that clinically measured clicks include ultrasonic signal components of up to 100 kHz (ultrasonic clicks) [2], [3]. Then, it was confirmed that the ultrasonic closing clicks can be generated without the existence of cavitation. Simultaneous measurements of the valve motion were made with a high-speed video camera, and the analysis of the video frames and clicks showed that higher frequency signal components of more than 50 kHz could be generated only at the instant of the closure, which means the collision of the occluder with the housing. Eighteen miniature accelerometers with an area of one square millimeter were developed and stuck on the housing to monitor the distribution of the housing vibrations in detail, and it was found that the vibrations correspond to the ultrasonic closing clicks propagated from the valve stop: the collision point of the occluder with the housing. This fact indicated that the generation of ultrasonic closing clicks is limited to the small area of the collision. From those results, it was concluded that the major origin of the ultrasonic closing clicks’ genesis should be the collision of the occluder with the housing.

2. Background

The first hypothesis proposed to explain ultrasonic closing clicks was cavitation. From early 1970’s, many studies on cavitation of MHV have been reported under in vitro accelerated testing conditions [7], [8]. In 1994, Chandran et al. [9] and Garrison et al. [10] reported high frequency pressure oscillations (HFO) in the blood analog fluids. Since the time traces and spectra of HFO agreed with those of clinically measured ultrasonic closing clicks, they can be considered as the same signals. Garrison et al. suggested that HFO were the result of the collapse of cavitation bubbles. Nowadays, this explanation is widely accepted. However, we found it difficult to explain all the characteristics of the ultrasonic closing clicks simply by the cavitation.

It was one feature of the ultrasonic closing clicks of Medtronic Hall valve that we noticed especially. Figure 1 shows an example of time-frequency domain distribution of an ultrasonic closing click of Medtronic Hall valve calculated with short-time fourier transform (STFT). Just before the major signal, lower-powered signal can be observed. We named this signal the “pre-closure signal” to distinguish from the major closure signal. In almost all clini-

SUMMARY A new in vitro experimental tool was developed to study the mechanism of the ultrasonic closing clicks’ genesis of mechanical heart valves. Since the newly developed tester adopted compressed air flow directly instead of the blood analog fluid to drive the mechanical heart valve, it is not possible to generate any cavitation. Closing clicks were measured with a small accelerometer at the surface of the valve holder made of silicone rubber. Ultrasonic closing clicks as well as audible closing clicks, similar to those measured clinically, could be observed using this setup. Thus, it was confirmed that the ultrasonic closing clicks can be generated without the existence of cavitation. Simultaneous measurements of the valve motion were made with a high-speed video camera, and the analysis of the video frames and clicks showed that higher frequency signal components of more than 50 kHz could be generated only at the instant of the closure, which means the collision of the occluder with the housing. Eighteen miniature accelerometers with an area of one square millimeter were developed and stuck on the housing to monitor the distribution of the housing vibrations in detail, and it was found that the vibrations correspond to the ultrasonic closing clicks propagated from the valve stop: the collision point of the occluder with the housing. This fact indicated that the generation of ultrasonic closing clicks is limited to the small area of the collision. From those results, it was concluded that the major origin of the ultrasonic closing clicks’ genesis should be the collision of the occluder with the housing.

key words: mechanical heart valve, clicks, ultrasonic closing clicks, cavitation, in vitro experiment

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An example of STFT of ultrasonic closing click.

Fig. 1
cal measurements, those pre-closure signals were observed for Medtronic Hall valves. To clarify the characteristics of those signals, we picked up their time variance of several frequency components as shown in Fig. 2. It is evident that the pre-closure signal and the major closure signal are completely independent damped vibrations. Hence our objective was to show whether or not it is possible to explain the generation of pre-closure signals by cavitations.

It has been shown that MHV cavitation can be generated by 3 mechanisms.

- Water hammer effect, that is Negative pressure.
- Venturi cavitation, that is High-speed leakage jet.
- Squeeze flow phenomenon between occluder and housing.

Can those mechanisms generate the pre-closure signals? Since Medtronic Hall valves are mono-leaflet valves, it is not possible for the water hammer effect to generate cavitations twice. Leakage jet may only occur once per closure, so Venturi cavitation is also unable to generate HFO two times. Squeeze flow seems to be able to generate split HFOs. But, considering the power of clinically measured ultrasonic closing clicks, which is larger than that of audible closing clicks, it is unlikely that the HFOs are generated by the squeeze flow. Combinations of above mechanisms are possible. However, there is no reasonable explanation, which can clearly explain the order and amplitude of the signals. The previously present reasons explain why we thought that cavitations are not the only origin of the ultrasonic closing clicks. Therefore, we planned to develop a system for in vitro experiments without any cavitation.

3. Method

As far as a blood analog fluid is used, it is difficult to avoid the generation of cavitation. Therefore, we decided to drive the valves by compressed air instead of a blood analog fluid. By adopting this strategy, our tester avoids the generation of cavitation.

Figure 3 shows the diagram of the tester. A Medtronic Hall valve, without a sewing ring, is held by silicon rubber softly not to prevent its natural vibrations. Two air nozzles spray compressed air alternatively from both sides of the valve simulating the opening and the closure motions. Figure 4 shows the main parts of the air driven tester.

For the vibration monitoring, we prepared two types of accelerometers. A small accelerometer (B&K: type 4374, with the sensitivity of 1.86 mV/G and the first resonance of 85 kHz), which has been used in the clinical measurement [6], is used to monitor the audible and ultrasonic clicks at the surface of the silicon rubber valve holder (Fig. 5). To monitor housing vibrations directly, we developed miniature accelerometers. They were made of barium titanate (thickness of 0.4 mms, which corresponds to the resonance of 5 MHz) of one square mm in area (Fig. 6 (a)). Since these accelerometers work only with the mass of barium titanate, their sensitivity is very small. A calibration experiment...
showed that the value of the sensitivity was 0.62 mV/G at 2.5 kHz. However, since the housing vibrations are large enough and the wide band-width is more important than the sensitivity, we decided to use these sensors. Eighteen miniature accelerometers were fixed on the housing with cyanoacrylate at intervals of 20 degrees to record the distribution of housing vibration (Fig. 6 (b)).

Figure 7 shows the block diagram of the click measurement system. The output signal of the small accelerometer is amplified and separated into ultrasonic and audible frequency range by filters. The band-width of the filter for audible range is 0.5–8 kHz (−42 dB/Oct.), while that of the filter for ultrasonic range is from 8 kHz (12 dB/Oct.) to 1 MHz (−84 dB/Oct.). Up to four outputs out of the eighteen miniature accelerometers are selected and amplified. Four signals per measurement were digitized simultaneously by an AD converter (National Instruments; PCI-6110E) with the resolution of 12 bits and at a maximum sampling frequency of 5 MHz. A high-speed video camera (Photron; FASTCAM-hvc), which is synchronized with the vibrations recordings by a timing controller, is used to monitor valve’s motion.

4. Results

Figure 8 shows a comparison between the time-traces of the clicks in audible and ultrasonic frequency ranges. Clicks shown in Fig. 8 (a) are measured by the small accelerometer (B&K: type 4374) at the surface of valve holder of the air-driven tester, while those in Fig. 8 (b) are the actual data measured clinically [6]. Their frequency spectra are shown in Fig. 9. It is interesting to note that not only the audible closing clicks but also the ultrasonic closing clicks can be observed in the simulated data, even though the cavitation could not be generated.

Figure 10 is an example of simultaneous recording of the clicks and the valve motion captured by the high-speed video camera. High-frequency vibrations can also be observed in the recordings measured by the miniature accelerometers at the surface of the housing. In Fig. 10, time a, b, c, d, and e correspond to: the beginning of the closure, closure in progress, the first closure, the rebound, and the re-closure, respectively. We observed other signals at the instants b and e different from the pre-closure and closure signals (instant c). Figure 11 shows the comparison of FFT spectra of those vibration signals.

For each experiment, housing vibrations were mea-
Fig. 9  Measured click data in frequency domain.

Fig. 10  Simultaneous measurement of valve motion and clicks.

Fig. 11  Comparison of FFT spectra of ultrasonic vibrations in Fig. 10.

Fig. 12  Measured housing vibrations of major closure signal (pattern 1).

The measured click data in frequency domain (Fig. 9) show a distinct pattern that can be analyzed to identify specific differences in the wave fronts of the major closure signals. Figures 12 and 13 are examples of measured housing vibrations with the enlargement of their wave fronts. In both figures, the position marked with number 1 corresponds to the valve stop, where the occluder collides with the housing. Apparent phase delays of the wave front from position 1 to 4 can be seen in Fig. 12. These phase delays indicate that the housing vibration generated by the closure is propagating from position 1 (valve stop) to position 4. Figure 13 represents the results from the measurement with different arrangements. It shows that there exist both a counter-clockwise propagation (from position 1 to 3) and a clockwise propagation (from position 1 to 4) symmetrically from the valve stop (position 1). These results suggest that the housing vibrations are generated at the valve stop and then propagate over the housing.

To confirm this fact, phase delay values of the wave fronts from the valve stop to other measuring points were...
calculated based on the velocity of transverse wave over the housing made of titanium and compared with the measured values. Results are shown in Fig. 14. There was very good agreement between the calculated and the measured values.

Similar propagations can also be observed for the pre-closure signal. Figure 15 shows an example of the measured wave fronts of the pre-closure signal. It seems that the propagation starts from position 3, which means from one of the stoppers.

5. Discussions

*In vitro* experiments with an air-driven tester revealed that the ultrasonic closing clicks of MHV can be generated without cavitation (Fig. 8). It seems that the simulated audible closing clicks have higher frequency components compared with those measured clinically. It may be due to the differences in the characteristics of the supporting area (silicon rubber versus heart muscle). However, since the rest of the results deals only with the signals in the ultrasonic range, this difference could not affect the results. Over the frequency range of more than 30 kHz, spectra of the simulated signal and the clinical data agreed very well as shown in Fig. 9.

Results of the simultaneous measurement of the vibrations with valve motions (Fig. 10) indicated that some vibrations other than the major and pre-closure signals may occur. However, the bandwidth of the vibration at time b is more narrow than those at time c and e, i.e., no significant power can be observed over the frequency range of more than 50 kHz (Fig. 11). From the high-speed video data, time b can be considered the instant of pivot motion, which means the contact of the occluder with the support. This fact may indicate that the ultrasonic closing clicks are generated mainly by the collision of the occluder with the housing.
Since the wave fronts of the major closure signal have phase delay from the valve stop along the housing (Figs. 12 & 13) and their delays agree with the transverse wave velocity of the housing very well (Fig. 14), it can be concluded that the major closure signals are generated by the collision of the occluder with the housing at the valve stop. Then these vibrations travel along the housing. Meanwhile, the pre-closure signals seem to be generated at the stoppers where other collisions of the occluder with the housing occur. These results suggest that the ultrasonic closing clicks are mainly generated by the collision of the occluder with the housing over a very small colliding area.

This conclusion may not deny the genesis of HFO based on cavitation. However, considering the large level of clinically measured ultrasonic closing clicks, the major cause of their genesis should be the collision of the occluder with the housing.

6. Conclusions

We developed a new air-driven MHV closing click tester that generates no cavitation. With this tester, we found that, at the surface of MHV holder (made of silicone rubber), not only the audible closing clicks but also the ultrasonic closing clicks can be measured. From the multi-point measurement of housing vibration, it was concluded that the ultrasonic closing clicks are mainly generated by the collision of the occluder with the housing at the valve stop. Then, these vibrations propagate over the whole housing. Still, there is the possibility that some part of the ultrasonic closing clicks might be generated by cavitation. However, the major cause of the ultrasonic closing clicks’ genesis should be the collision of the occluder with the housing.

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