Division of Signal Processing
Visiting address: Universitetsområdet, Porsön, Luleå
Postal address: SE-971 87, Luleå, Sweden
Telephone: +46 920 910 00. *Fax:* +46 920 720 43
URL: <http://www.sm.luth.se/csee/sp/>

Analysis and Classification of Secondary Sounds from the Disintegration of Kidney-Stones with Acoustic Shockwaves

Lennart Olsson, Lars-Olov Almquist, Anders Grennberg
and Nils-Gunnar Holmer

In Ultrasound in Medicine and Biology, vol. 17,
no. 5, pp. 491–495, 1991.

© 1991 Pergamon Press plc.

●Original Contribution

ANALYSIS AND CLASSIFICATION OF SECONDARY SOUNDS FROM THE DISINTEGRATION OF KIDNEY STONES WITH ACOUSTIC SHOCK WAVES

L. OLSSON,[†] L. -O. ALMQUIST,[‡] A. GRENNBERG[†] and N. -G. HOLMER[‡]

[†]Division of Signal Processing, Luleå University of Technology, S-95187 Luleå, Sweden, and

[‡]Department of Biomedical Engineering, Lund University, P.O. Box 118, S-221 00 Lund, Sweden

Abstract—Secondary sound emission, partly in the audible frequency range, from shock wave disintegration of kidney stones has been recorded during the treatment of two patients. A skilled operator can determine by listening if the stone is hit by the shock-wave or not. Spectral analysis of these recordings show differences between the sounds which can be used to evaluate the fragmenting effect on the stone. Results are presented of a preliminary discriminating method based on parameters in an autoregressive signal model.

Key Words: Extracorporeal lithotripsy, Renal calculus, Kidney stone, Acoustic shock-wave, Spectral analysis, Autoregressive model, Secondary sound, Classification of transients.

INTRODUCTION

Treatment of kidney stones can be done successfully without surgery by fragmenting the stones inside the kidney pelvis with focused ultrasonic shock-waves. The shock-waves can be generated with mainly three methods: spark, electromagnet or piezoelectric crystals. The piezoelectric transducer could be one large or many smaller transducers generating the sound wave in a water volume. The transducer arrangements are excited in such a way that the focus will be placed inside a patient, who is in direct contact with the water volume via a thin membrane. The reason for focusing the sound-wave is to obtain a very high pressure at a kidney stone and, at the same time, avoid damaging the surrounding tissue. It is essential not to treat an already fragmented stone in order to minimize the patient's exposure time to the shock-waves because long-term damages of tissue can occur.

The result of the treatment is highly dependent on the exact positioning of the focus relative to the stone. The immediate environment of the stone is also important because a thin tissue layer close to the stone can cause the treatment to fail. The best result is achieved when the stone is surrounded by liquid. The localization of stones is made with a B-mode ultrasonic scanner integrated in the shock-wave equipment. To position the acoustic pressure focus at the stone, only with the help of an ultrasound image,

can be rather difficult. Therefore, a skilled and well-trained operator is needed.

It has been observed that the shock-waves produce secondary sounds, partly in the audible frequency range. This has partly been studied and demonstrated (Holmer et al. 1991). The timbre of these sounds has been found to contain information about the efficiency of the treatment. A skilled operator can thus determine, by listening, if the focus has been correctly positioned.

This work is intended to develop an automatic method to classify these secondary sound pulses and to let a computer give an immediate indication of the success of the treatment. This method gives several advantages. One is that the operator gets more information about the localisation of the stone; another is that it is probably possible to tell when the stone is so fragmented that it is not necessary to continue the treatment any longer. This means less pain for the patient and a shorter treatment period.

EQUIPMENT

The lithotripter used was an EDAP LT01. It uses 320 piezoelectric elements arranged on the concave surface of a halfsphere. This is filled with water and sealed with a rubber membrane at the top. The patient is placed on the top of the halfsphere, with the kidney stones in the centre of the sphere (Fig. 1). The

Fig. 1. Schematic picture over the experimental arrangement.

distance from the transducers to the focal point is about 0.45 m, and the transducer resonant frequency is 0.4 MHz.

When the operator has positioned the focus in the correct position at the stone the treatment continues up to a maximum of 1 h, normally with 2.5 "shots" per second. If the stone is not completely fragmented the treatment will be repeated a few weeks later.

The equipment used for our measurements was a sound level meter (Brüel & Kjaer 2631) with a broadband microphone (Brüel & Kjaer 4135) and a digital oscilloscope (Tektronix 2430A with a computer unit TekMate 2402). The microphone was placed at a distance of about 0.2 m from the treated side of the patient. The characteristics of the secondary sounds could be heard anywhere in the room, so the microphone position was not considered as critical.

The resonant frequency of the microphone is 100 kHz, but due to a protecting grid, the sensitivity starts to decrease at approximately 50 kHz. However, strong signals at higher frequencies can still be registered. The memory size of the oscilloscope is limited to 1024 samples. Therefore, we chose a sampling frequency of 250 kHz as a compromise between a large enough time window and a sufficiently high Nyquist limit. The amplification of the microphone signal was chosen so that the registrations on the oscilloscope used the available dynamic range. This means that the energy in the recordings of the pulses have the same order of magnitude. All measurements were transferred to a computer and the data were processed with routines from the program package MATLAB including the System Identification Toolbox® (Math Works, Inc.) (Moler 1989; Ljung 1988). We also used the program Data Desk® (Odesta Corp.) to graphically present two-dimensional projections of points in higher dimensions. Thus, we could find a convenient transformation of our data that suggests a simple classification criterion.

RESULTS

We have measured the secondary sound emission from two patients under treatment and with differing positions of focus. In this report, we describe our results for a fixed sampling frequency and one microphone. We have developed a test based on data from one patient. This test is applied to data from a second patient. All those registrations fall in the category of "hits" according to the test. According to the classification made by the operator during the treatment, this is correct. We recorded 37 pulses from the treatment of patient 1 classified by the operator in the following groups: stone stuck in uretery (16), hit on stone free in the kidney pelvis (11), and miss (10). The operator observed the stone on the ultrasound display and we could hear the sounds and classify them from his instructions. The type of stones in these cases are unknown. The sound spectra will possibly have a different character if the stone is hard or soft. For some of the recorded pulses, the classification was uncertain, while for others the differences were easily heard.

We estimated the spectra of the different pulses with a nonparametric method. The method used has been described in Ljung (1987), and implemented as the command "spa" in System Identification Toolbox. Estimates of the covariance function, based on 1024 samples of the sound pulse, are multiplied by a Hamming window of lag size 64 and then Fourier transformed. Examples of results are shown in Figs. 3 and 4 for the registrations shown in Fig. 2.

This suggests that a classification method based on differences in spectral properties is possible. To get a compact spectrum representation we estimated the spectrum with a parametric model of autoregressive type. The method used is the covariance method (Marple 1987) implemented in the System Identification Toolbox as the command "ar" with the option "ls."

The parametric method can be described as a one-step linear predictor of order p , where it is desired to select parameters $a_1, a_2, \dots, a_p$ such that the prediction

$$\hat{x}(n) = -\sum_{k=1}^p a_k x(n-k)$$

approximates the observed samples of sound $x(n)$ best in the sense of minimizing the squared prediction error

$$\sum_n |x(n) - \hat{x}(n)|^2$$

Fig. 2. Examples of typical registrations of type "hit" and "miss."

The spectrum of this predictor approximates the power spectrum of the signal $x(n)$, and is given by

$$\hat{S}(f) = \frac{b_0}{|1 + \sum_{k=1}^p a_k e^{-j2\pi f}|^2}$$

Here, b_0 is a normalizing constant that does not affect the shape of the spectrum.

We found that an order of 10, *i.e.*, with 10 parameters $a_1, a_2, \dots, a_{10}$, was sufficient for our data. Apparently, these 10 parameters represent the spectrum of sound pulses of this type quite well. Since the pulses

Fig. 3. Parametric and nonparametric estimates of the spectrum of the "hit" registration in Fig. 2.

Fig. 4. Parametric and nonparametric estimates of the spectrum of the "miss" registration in Fig. 2.

are registered as records of 1024 samples, we have thus reduced the amount of data by 99%. These results are shown in Figs. 3 and 4.

In our experiment, the pulses of category "hit" seem to be characterized by one or more strong spectral components below 20 kHz, while the other pulses

Fig. 5. Plot of the projection from 10 parameters to 2.

have most of their energy in many smaller components above 20 kHz.

We found that it was also necessary to have an autoregressive model with at least 10 parameters to catch the main features of the spectrum. We suspected that our parametric models were separated in different clusters in the 10-dimensional space. Therefore, we tried to project them from the 10-dimensional space to two dimensions. Only the first five parameters showed distinct differences between our classes. By linearly combining these five parameters, we have produced Fig. 5, which shows the projection of our parametric representations to a plane. The coordinates are

$$x = -12a_1 - 346a_2 - 321a_3 - 231a_4 - 143a_5$$

$$y = 40a_1 + 165a_2 + 137a_3 - 534a_4 - 105a_5$$

Here, the horizontal x -coordinate alone can be used as a separator between the cases. All hits (*) lie to the right of the vertical line. All misses (○) lie to the left of the line. In the figure, the 16 cases where the stone is "stuck in the uretery" (+) are also shown. They are well separated from the hits on a free stone.

We made 14 registrations on patient 2 with a similar microphone arrangement and the same sampling frequency. The operator classified all the pulses as "hits." We had difficulties in hearing any differences in the sound timbre. The same parametric spectrum estimation method was applied giving 10 model parameters for every pulse. The projections of these parameters into the two-dimensional subspace defined by patient 1 is shown (x) in Fig. 5. They all fall in the same category as the "hits" on patient 1. Our difficulties in subjectively discriminating the pulses can now be explained by the relatively small spread in the parameter values. The time registrations are also almost identical.

We have also recorded sound when "phantoms" (artificial objects of plaster, *etc.*, mounted in a water tank) have been treated. These registrations are of another type and we think that the situation is too far from the real one to be of use. We did not hear the same type of sounds in these experiments.

CONCLUSIONS

Our work indicates a possible way of classifying the secondary sounds emitted, coupled with the fragmenting effect on the stone during treatment. With modern microprocessors or digital signal processors (DSPs) it is possible to calculate the spectral parameters and the combination of them to one or two discriminators during treatment. The construction of an automatic classifier working in real-time to assist the operator in the focusing is possible.

FURTHER WORK

More data have been and must continue to be recorded on patients under different situations and with information of the fragmenting effect on the stones. We also hope to study the effect on some kind of phantom, where the conditions are more like the real clinical situation, but where it is possible to observe the effect of the ultrasound pulses directly. It is also necessary to study all signal components with frequencies up to the emitting pulses' to be absolutely certain of having the total spectral content of the sound. After that, we can probably concentrate the interest to a narrower frequency band. We also plan to use methods known from speech recognition for comparisons of the secondary sound spectra. Another line of development is to identify wavelets in the signal and use them to classify the sounds. The emerging theory of higher-order spectra seems useful for classification of transients and nonlinear phenomena and will also be applied to this problem.

REFERENCES

- Holmer, N. G.; Almqvist, L. O.; Hertz, T. G.; Holm, A.; Lindstedt, E.; Persson, H. W.; Hertz, C. H. On the mechanism of kidney stone disintegration by acoustic shock waves. *Ultrasound Med. Biol.* [1991].
- Ljung, L. *System identification: Theory for the user*. Englewood Cliffs, NJ: Prentice-Hall; 1987.
- Ljung, L. *System identification toolbox*.[®] S. Natick, MA: The Mathworks Inc.; 1988.
- Marple, S. L. Jr. *Digital spectral analysis with applications*. Englewood Cliffs, NJ: Prentice-Hall; 1987.
- Moler, C. *Matlab*[®] user's guide. S. Natick, MA: The Mathworks Inc.; 1989.