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SPATIAL REPRESENTATION OF THORACIC SOUNDS

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Abstract - **Simultaneous multi-microphone recordings of thoracic sounds on the chest wall contain spatial information of potential diagnostic value. To begin to access this information, an algorithm was developed to spatially represent these sounds. For every point within the thorax, the algorithm tests the hypothesis that it contains the only relevant acoustic source. A hypothetical source signal is calculated by a least squares estimation procedure to explain a maximum of the signal variance in all microphone signals. The explained fraction of the total microphone signal variance is then displayed as a function of space in a 3-dimensional, gray-coded image. The algorithm was preliminarily evaluated using 16-microphone recordings from two healthy male subjects. Inspiratory and expiratory breath sounds as well as first and second heart sounds were analyzed separately. The images show distinct patterns for inspiratory breath sounds, expiratory breath sounds and heart sounds and similar images were obtained for a given sound category for both subjects. These representations are consistent with the assumed origin of the analyzed sounds. Specifically, the images support the concept that inspiratory sounds are produced predominantly in the periphery of the lung, while expiratory sounds are generated more centrally.**

1. INTRODUCTION

Alterations in the structure and function of thoracic organs that occur in disease often give rise to measurable changes in lung sound production and transmission. Auscultation is a widely used clinical method to asses these changes. Thoracic sounds are known to contain spatial information, which can be accessed using multi-microphone recordings [1,2]. This additional information may contain diagnostic features which are not accessible with current methods. To begin to access this information, an algorithm for the spatial representation of thoracic sounds recorded with multiple microphones at the chest surface was developed. In earlier studies, the algorithm was tested using a gelatin model of the human lung, and the influence of different assumptions on the sound speed of damping within the thorax was investigated [3]. The aim of the current study is to investigate the consistency of the produced images (a) across a limited number of subjects, and (b) with current notions on the site of production of different physiological thoracic sounds

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II. SPATIAL REPRESENTATION ALGORITHM

The spatial representation algorithm consists of two parts: (A) the calculation of a three-dimensional data array and (B) the graphic representation of this array.

A. Calculation of a 3-dimensional data array

For any given point within the thorax, the algorithm tests the hypothesis that it contains the only relevant acoustic source. A hypothetical source signal is calculated by a least squares estimation procedure to explain a maximum of the signal variance in all microphone signal as follows. Let $\underline{x}_i$ (i=1...M) be the positions of M microphones on the thoracic surface and s_i (t) the signals recorded at these microphones, where t represents time. Assuming a uniform sound propagation throughout the thorax (sound speed c, damping factor per unit length d) the signal $r(\underline{y},t)$ emitted by this hypothetical source at the location $\underline{y}$ can be estimated by solving the linear system source signal

$$\begin{aligned}
s_1(t-|\underline{x}_1-\underline{y}|/c) &= d \cdot |\underline{x}_1-\underline{y}| \cdot r(\underline{y},t)/|\underline{x}_1-\underline{y}|^2 \\
s_2(t-|\underline{x}_2-\underline{y}|/c) &= d \cdot |\underline{x}_2-\underline{y}| \cdot r(\underline{y},t)/|\underline{x}_2-\underline{y}|^2 \qquad (1) \\
&\vdots \\
s_M(t-|\underline{x}_M-\underline{y}|/c) &= d \cdot |\underline{x}_M-\underline{y}| \cdot r(\underline{y},t)/|\underline{x}_M-\underline{y}|^2
\end{aligned}$$

using a least squares fit. In the above equations, the left hand side represents the microphone signals taking into account the time delay between hypothetical source and microphone, the right hand side represents the source signal including geometric and linear damping. Assuming different hypothetical source sites $\underline{y}$, the thoracic volume is scanned using a step size of 1 cm. From the hypothetical source signal estimated for each location, the portion of all microphone signals which could be explained by the given the hypothetical source only, i.e. a number between 0 and 1, is calculated and stored in a three-dimensional table, representing the thoracic volume.

B. Graphic Representation of the Data Array

The array calculated by the above procedure can be represented in different ways, including CT-like images and several 3-dimensional representations. In this paper, a gray-level-coded spatial representation (Fig. 1) is used. Each data point is represented using a sphere at the appropriate location. High data values, i.e. data points at which a hypothetical sound source is able to explain much of the total microphone signal variance, are depicted in dark colors, low data values in light colors. To avoid data points in the front to obscure data points in the rear, only the 30% of the data points with the highest values are represented with spheres, the rest of the volume remaining empty.

III. Evaluation of the Spatial Representation Algorithm: Materials and Methods

A. Experimental Apparatus

The subjects were seated in a sound proof room (Model 108192, Industrial Acoustic Co.) with 16 microphones (Sony ECM-T150) in optimized couplers [4] attached to the chest. The microphone signals were amplified and bandpass-filtered between 100 and 1000 Hz by 16 custom-built filter-amplifier units. Then the signals were digitized at a sampling rate of 10240 Hz using a PC-based analog-to digital converter (Data Translation DT-2831 G). The subjects breathed through a pneumotachograph (Fleisch No. 3) and observed their air-flow signal on an oscilloscope.

B. Experimental protocol

The 16 microphones were attached to the chest of the subjects as follows: 8 microphones were placed in the front, arranged in a regular pattern of 4 horizontal by 2 vertical microphones. Distances between adjacent microphones were 10 cm, both in the horizontal and vertical direction. The resulting rectangle was centered around the median plane of the subject, with the middle two microphones of the upper row being placed on the 2nd intercostal space. The remaining 8 microphones where placed on the back of the thorax, using the same 4 by 2 arrangement of the microphones and the same distances. Corresponding microphones in the front and the back of the subjects were at the same level. For the representation algorithm, microphone positions were measured in three dimensions using a stereotactic measuring device with an accuracy of 1 cm.

2 male non-smokers, ages 33 and 34 participated in this study. Their chest circumferences were 94 and 98 cm, their weights 68 and 70 kg. Respiratory sound data was acquired for at least 6 to 7 complete breath cycles at target airflows of ± 30 ml/s/kg (corresponding to approximately ± 2 l/s). Background noise and heart sounds were then measured while the subjects stopped breathing at end-expiration with their glottis open.

C. Signal Analysis and Spatial Representation

Signals were analyzed separately for inspiration, expiration, first heart sounds and second heart sounds. For inspiratory and expiratory sounds, only segments with flow rates within ±20% of the target flow were analyzed. For the heart sounds, segments from the breath-hold section of the recordings were used. For each spatial representation, time segments of 0.1 s were used. Each microphone/amplifier/filter unit was calibrated and the (small) differences between the frequency responses of the individual units were corrected in the frequency domain. To produce averaged images, data arrays from multiple segments containing the same sounds were averaged before graphic representation.

IV. Results

Fig. 1. depicts the spatial representations of the four different sound categories under investigation for the two subjects. The blocks represent a volume of 30 x 30 x 21 cm (subject 1) or 30 x 30 x 23 cm (subject 2) overlying the thorax of the subjects. The viewing angle is from the front, right side, from the same direction as shown for the thoracic outline in Fig. 2. The microphone positions are not shown. However, the represented volumes were chosen in such a manner, that anterior and posterior microphones are lying approximately in the front and rear plane of the depicted volume. In the vertical dimension, the volumes shown are centered around the center of gravity of all 16 microphones.

During inspiration, areas with high data values (i.e. areas in which were a hypothetical sound source explains a significant portion of the total microphone signal variance) are concentrated mainly in the front of the thorax. A major contribution is made by a dark spot in the upper half of the thorax, just left from the median plane. Another, smaller maximum, which is partly hidden by the front maxima, can be found in the back in both subjects.

During expiration, dark areas can be found more centrally in the thorax. For both subjects, there is a 'hot spot' around the 2nd intercostal space in the front, right hemithorax.

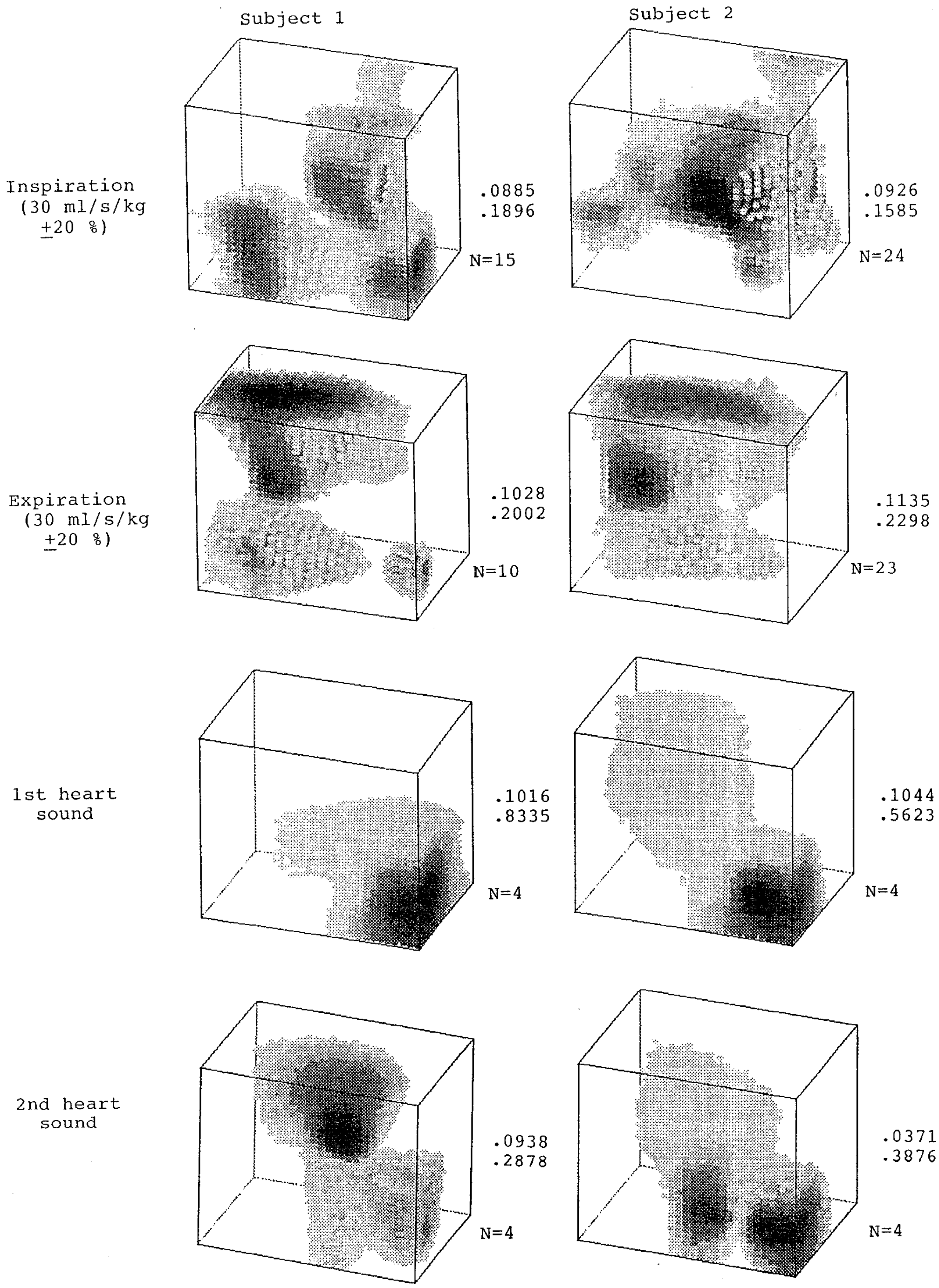

Fig. 1. Spatial representations of different thoracic sounds from two subjects. The boxes denote the thoracic volumes of the two subjects in a frontal view 30° from the right, as depicted in the thoracic outline in Fig. 2. N denotes the number of time segments of 0.1 s duration, over which the data was averaged. The numbers to the right of the depicted volumes give the range of the depicted data points (dark points = high values).

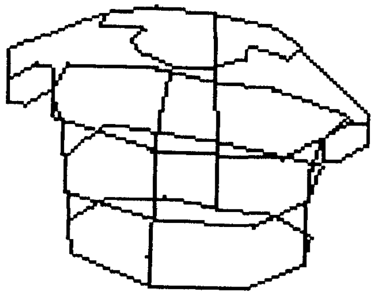

Fig. 2. Thoracic outline showing the viewing angle for the spatial representations in Fig.1

For first heart sounds, a major part microphone signal variance can be explained by assuming sources in the front left lower thorax, i.e. at the approximate location of the heart. Spatial representations from first heart sounds are similar for both subjects. For second heart sounds however, the differences between subject 1 and subject 2 are more pronounced. There are multiple centers with relatively high values, the absolute levels of which differ between the subjects.

V. Discussion

The spatial representations in Fig 2 show similar patterns for both subjects during inspiration, expiration and the first heart sound. Differences between the two subjects are greater for the second heart sound. This may be an actual difference between the two subjects, or an artifact due to the proposed spatial representation algorithm.

Images during inspiration and expiration confirm the hypothesis that inspiratory sounds are produced predominantly in the periphery of the lung, while expiratory are generated more centrally [1,5].

During expiration, a major sound source appears to lie close to the 2nd inter-costal space at the upper right anterior portion of the chest wall, confirming the findings of an earlier study [5].

The spatial representation algorithm locates heart sounds roughly at the expected location of the heart itself. Second heart sounds give rise to more complicated patterns with multiple centers, which may indicate that multiple, spatially separated sound sources contribute to the second heart sound.

VI. Future Research Efforts

In the near future, spatial reconstructions from more normal subjects as well as subjects with different lung diseases are planned. The influence of the assumed sound speed and damping in the thorax, which has been found to be small in a previous study using less microphones [3] will be evaluated with the current recordings. Also, the influence of the number and placement of microphones as well as the inherent assumptions of the algorithm will be investigated.

VII. Summary

The first spatial representations of thoracic sounds using a novel reconstruction algorithm have been presented. The method was evaluated preliminarily using simultaneous 16-microphone recordings in two human subjects. Images have been found to show distinct patterns for inspiratory breath sounds, expiratory breath sounds and first heart sounds that are similar in each case across the two subjects. The spatial representations are consistent with the assumed origin of the analyzed sounds. Specifically, the images support the concept that inspiratory sounds are produced predominantly in the periphery of the lung, while expiratory sounds are generated more centrally.

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