

Acoustic location of Bragg peak for Hadrontherapy Monitoring [†]

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Abstract: Hadron therapy makes possible to deliver high doses of energy on cancerous tumours by using the large energy deposition in the Bragg-peak. However, uncertainties in the patient positioning and or in the anatomical parameters can cause distortions in the calculation of the dose distribution. In order to maximize the effectiveness of heavy particle treatments, an accurate monitoring system of the deposited dose depending on the energy, the beam time and the spot size is necessary. The localized deposition of this energy leads to the generation of a thermoacoustic pulse that can be detected using acoustic technologies. This article presents different experimental and simulation studies of the acoustic localization of thermoacoustic pulses by generating similar signals that have been captured with a set of sensors around the samples. In addition, numerical simulations have been done where thermoacoustic pulses are emitted for the specific case of proton beam of 100 MeV.

Keywords: Hadrontherapy; Acoustic Localization; Bragg Peak, Thermoacoustic, Piezoelectric Ceramic.

1. Introduction

The processes by which a source is located, recording the propagation signals received in several sensors and analysing them to determine the source position is known as the location of a source [1]. There are many localization techniques proposed for wireless sensor networks [2] [3]. However, in this article is introduced a three-dimensional localization to solve the estimation of an acoustic source in a homogeneous medium. The use of acoustic sensors to locate sound sources in such practical systems is of great interest to develop quiter and improved performance systems. The research has significant potential for many applications in medicine, physics, engineering and underwater acoustic. Actually, the method to locate tumour tissue is based in computed tomography scan to find the area that will then be radiated by heavy particles in the Bragg peak region [4]. However, uncertainties in the patient positioning and or in the anatomical parameters can rise the uncertainty during the radiotherapy. In these cases, acoustic source localization in medical applications has gained a lot of interest in recent years owing to the necessity of improving the monitoring of tumour tissue in hadron therapy treatments. Linear sensors can be employed for acoustic source localization in a noise environment using time delay estimation. The method presented here is based on TDOA (Time Difference of Arrival) [5] technique that performs very well in localization of an acoustic event in both two dimensional and three-dimensional space decreasing the error while increasing the number of sensors. The acoustic signal is generated and detected by piezoelectric sensors in known

positions and using a DAQ system to record the signal. Differences in signal propagation path from the source leads to different phases in the detected signal. Therefore, cross-correlation analysis is used to estimate the delays of arrivals accurately.

Pressure source localization of the Bragg peak in hadrontherapy will also allow to identify the regions of local heat released due to energy deposition. This pressure is related with the beam energy, the temporal pulse width and the number of protons by pulse. For this reason, the source assessed in this article, presents a pressure above the threshold of detection [6].

2. Overview of Approach

Techniques based on cross-correlation and generalized correlation (GCC) [7] have been employed to determinate the time difference of arrival of the signals (TDOA) given its computational cost and accuracy of the results. To obtain a better estimate of the TDOA $\hat{\tau}$ is convenient to filter the signal before its integration as shown in figure 1.

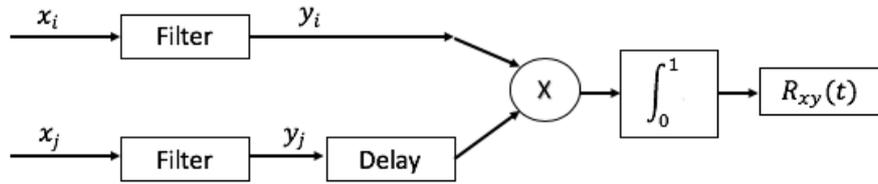


Figure 1. Scheme for obtaining time of arrival (TOA)

The cross-correlation $R_{x_i x_j}$ between the signal x_i and x_j filtered by the filters H_i and H_j , is expressed as a function of the power spectral density $G_{x_i x_j}$ as:

$$R_{x_i x_j}^{GCC}(t') = \int_{-\infty}^{+\infty} H_i(f) H_j^*(f) G_{x_i x_j}(f) e^{i2\pi f t'} df = \int_{-\infty}^{+\infty} \varphi^{GCC}(f) G_{x_i x_j}(f) e^{i2\pi f t'} df \quad (1)$$

where $\{*\}$ indicates conjugated complex and $\varphi^{GCC}(f)$ is a frequency-dependent weight function. Due to finite observations we can only obtain an estimate of $G_{x_i x_j}(f)$. Therefore, to obtain the TDOA the following expression will be used:

$$\hat{R}_{x_i x_j}^{GCC1}(t') = \int_{-\infty}^{+\infty} \varphi^{GCC}(f) \hat{G}_{x_i x_j}(f) e^{i2\pi f t'} df \quad (2)$$

For each pair of sensors, the TDOA is taken as the time delay that maximizes the cross-correlation between the filtered signals of both sensors, that is: $\hat{\tau}_{ij}^{GCC} = \arg(\max_{t'} \{\hat{R}_{x_i x_j}^{GCC1}(t')\})$. A general model for three dimensional (3-D) estimation of a source using M receivers is developed. To obtain the location of the source, we start by knowing the spatial position (x_i, y_i, z_i) of a certain number of sensors N ($i = 1, 2, \dots, N$). Let (x_s, y_s, z_s) , the position of the source to be located, the distance between the source and the i -th sensor will be:

$$d_i = \sqrt{(x_i - x_s)^2 + (y_i - x_s)^2 + (z_i - x_s)^2} \quad (3)$$

The range difference between receivers with respect to the first receiver is:

$$d_{i1} = c \cdot \tau_{i1} = d_i - d_1 = \sqrt{(x_i - x_s)^2 + (y_i - y_s)^2 + (z_i - z_s)^2} - \sqrt{(x_1 - x_s)^2 + (y_1 - y_s)^2 + (z_1 - z_s)^2} \quad (4)$$

where c is the sound velocity in the medium, d_{i1} is the range difference distance between the first receiver and the i -th receiver, d_1 is the distance between the first receiver and the source, and τ_{i1} is the estimated TDOA between the first receiver and the i -th receiver.

There are different methods to solve this type of systems of equations. In this case, a generalized Newton-Raphson method have been used. Particularly, the location of the source in each simulation and experiment has been computed by defining a maximum error volume for each coordinate of 0.1 mm. The robustness of similar studies for the localization of transient acoustic pulses can be found in the literature [8].

3. Studies and Results

In this section the results of the applications of the localization method are described. Studies about simulations, experimental measures with harmonic, sine sweep signals and bipolar pulses, closer and closer to the temporal shape of the acoustic pulse from the Bragg peak have been done. The measurements were evaluated in a water tank with a water volume of 0.64 m³. A TC4014 sensor with receiving sensitivity -186 ± 3 dB @ 1 V/ μ Pa and a frequency response from 15 to 480 kHz was used. The positions of the sensors are shown in table 3. The transmitter was a ring piezoelectric ceramic with a transmitting sensitivity 120 ± 4 dB (typical) @ 1 μ Pa/V @ 1 m at 100 kHz and a vertical directivity omnidirectional ± 5 dB at 300 kHz. The external and internal radius of the ring are 15 mm and 6 mm, respectively, with 3 mm in thickness shape. Figure 2 shows the Transmitting Voltage Response (TVR) and directivity of the piezoelectric transmitter.

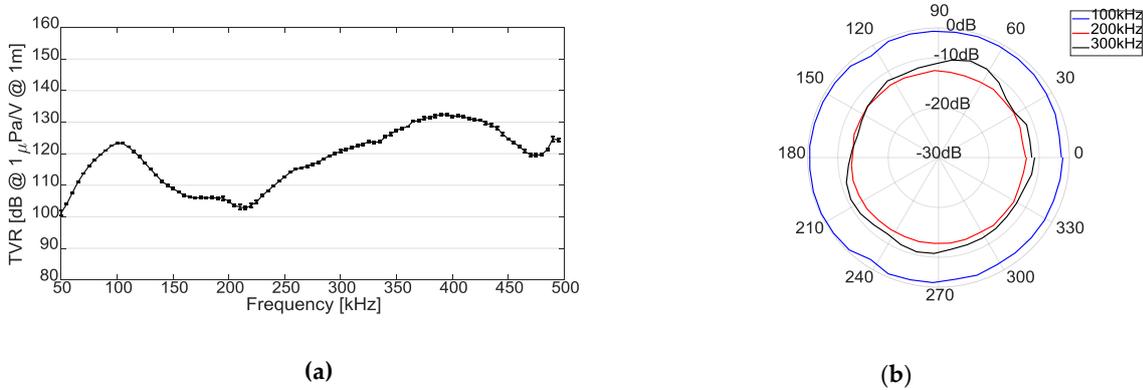


Figure 2. (a) Transmitting Voltage Response (TVR) for the piezoelectric ring transmitter; (b) Directivity at 100, 200 and 300 kHz.

3.1. Numerical simulation

To evaluate the localization algorithm described, the reconstruction of the location of a Gaussian pulse source of 50 μ s is simulated from the reception of 4 sensors located on the lateral surface of different coordinates. Figure 3 shows the position of the sensors and source in the space for the simulated model. In this simulation, the sources are always into the volume described by the coordinates of the sensors.

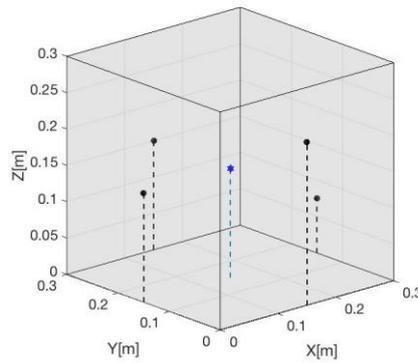


Figure 3. Volume proposed to evaluate the localization algorithm. In this case 4 sensors (black points) have been situated on the faces around the cube. Inside, three events will be simulated in different positions. The positions of the sensors and sources are shown in table 1. This figure shows 1 point of source (blue point).

To evaluate the algorithm, the volume of the cube has been modified between $27.0 \cdot 10^{-3}$ to $512.0 \cdot 10^{-3} m^3$. The positions of the sensors are shown in the table 1 where H represents the size of the edges, that is, values of edges were 200, 300, 400, 500 and 600 mm.

Table 1. Positions of the sensors and the source in the simulated.

Axis	Sensors				Source [mm]		
	1	2	3	4	1	2	3
X	H/2	0.0	H/2	H	150	100	80
Y	0.0	H/2	H	H/2	150	180	100
Z	3H/4	H/2	H/2	H/4	150	150	180

The results of the reconstructed position obtained by the algorithm for the 4 source positions are shown in table 2. These were evaluated by a computer with Core i5 2.4 GHz processor, 16 Gb in ram memory and a 500 Gb in SSD. To solve the reconstructed position the algorithm needed a mean time of 0.4 s , so it could be implemented for real time applications.

Table 2. Real and estimated positions of three different sources depending on the increase of the volume.

Volume [m^3]	Real position [mm]	1	2	3	4	5
		27^{-3}	64^{-3}	125^{-3}	216^{-3}	343^{-3}
X	100	100.10±0.11	100.10±0.10	100.10±0.10	94.00±0.42	100.0±0.01
Y	100	100.10±0.10	98.00±0.14	100.10±0.11	96.00±0.28	100.0±0.01
Z	100	100.10±0.10	96.00±0.28	101.20±0.14	94.00±0.42	100.0±0.01
X	100	100.00±0.01	100.0±0.01	100.0±0.01	100.0±0.01	102.0±1.4
Y	180	100.20±0.56	100.20±0.56	181.2±1.4	150±21	163±12
Z	150	100.10±0.32	100.1±0.35	147.4±1.8	146±21	145.8±3.0
X	80	80.00±0.01	78.0±1.4	85.0±4.5	71.0±8.0	87.0±4.9
Y	100	100.00±0.01	98.0±2.2	106.0±5.2	93.0±6.4	105.0±3.5
Z	180	180.10±0.10	178.0±1.4	186.0±5.3	168±12	189.0±6.4

Table 2 also shows the deviation of the position of the simulated source with respect to the position of the source. These reconstructed positions do not exceed 12 mm the real position for all the studied cases. Once satisfactory results of the localization algorithm have been obtained by simulating different source points in know sensor positions, the localization method has been evaluated experimentally as described below.

3.2. Experimental localization with armonic signals

The piezoelectric transmitter was situated in two different positions inside the tank with four sensors. The positions referred to the left-corner of the tank are shown in the table 3.

Table 3. Positions of the sensors and the source inside the tank.

Axis	Sensors [mm]				Source [mm]	
	1	2	3	4	1	2
X	600	500	400	500	410	450
Y	550	450	540	650	450	540
Z	380	280	340	340	350	330

Three different signals were emitted: a 100 kHz sine signal, a 150 kHz sine signal, both with five cycles per signal, and a sweep signal from 50 to 400 kHz during 150 μs. The signal has been filtered previously with a pass-band filter from 30 to 410 kHz and the cross-correlation method has been used to detect the start time of arrival on the sensors. An example is shown in Figure 4.

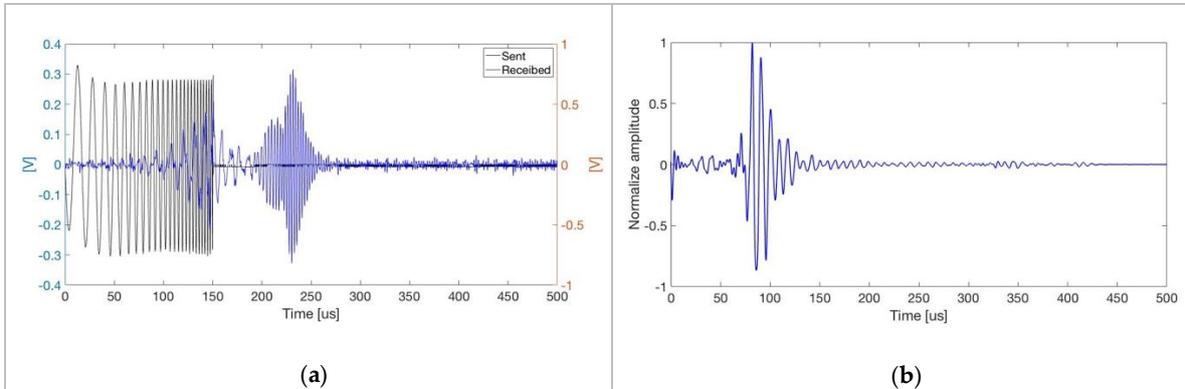


Figure 4. (a) Example of sine sweep signal emitted and received; (b) Cross-correlation between the emitted and received signals.

The results of the reconstructed positions are shown in table 4 where real position of the emitter and the resulting position after applying the localization algorithm can be observed.

Table 4. Real and estimated positions of two different harmonic sources inside the tank.

	Real position [mm]	Sine 100kHz	Sine 150kHz	Sweep signal
X	450	459.0±9.0	460.0±9.3	460.0±9.2
Y	540	540.00±0.72	540.00±0.55	540.00±0.43
Z	330	340.0±9.2	330.00±0.18	330.00±0.32
X	410	401.0±8.9	416.0±5.7	418.0±7.0

Y	450	448.0±1.3	450.00±0.44	450.00±0.56
Z	350	352.0±1.8	350.00±0.36	350.00±0.65

3.3 Experimental localization with thermoacoustic signals

To simulate the behaviour of the Bragg peak on a large scale, a bipolar pulse was generated by a thermoacoustic model [9] following characteristics in energy 100 MeV, beam time, spot size and number of protons per pulse that are the usual parameters involved in hadrontherapy treatment. This signal is the results of proton interactions with tissue [10]. Also, this pulse was compared with different studies about Bragg peak behaviour in experimental analysis [6] [10] [11] to determinate the frequency and pressure of the signal generated. Figure 5 shows the signal emitted by the piezoelectric ceramic and the recorded signal in one of the sensors.

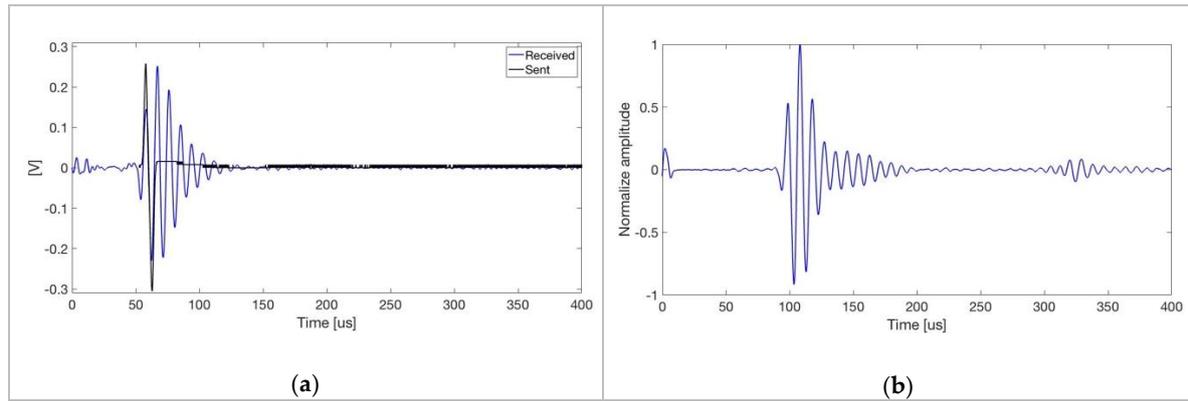


Figure 5. (a) Signal generated (sent, black) by the piezoelectric ring ceramic and received signal (blue) from TC4014 sensor in one of the measurement positions. The bipolar pulse generated by the thermoacoustic model are characteristics as 100 MeV, temporal profile 5 μs and $5.6 \cdot 10^6$ protons per pulse; (b) Cross-correlation of the emitted and received signal.

The time of arrival in each sensor was obtained with the correlation method. The spectrum of the bipolar pulse signal has a main component around 128 kHz [6]. The signal recorded has been filtered with a 110 to 140 kHz pass-band filter. Table 5 shows the results of the localization algorithm.

Table 5. Real and estimated positions of bipolar pulse signal in two different positions.

	Real position [mm]	Sine 100 kHz
X	450	459.0±8.8
Y	540	540.00±0.52
Z	330	330.00±0.12
X	410	414.0±3.3
Y	450	450.00±0.52
Z	350	350.00±0.49

4. Conclusions

The proposed localization method for the Bragg peak location in hadrontherapy has been tested in different numerical simulations and experiments using different kind of signals. In all of them the results of time of arrival were successful using the cross-correlation method and the uncertainty in the reconstructed position is small and close to the one needed for the application. Moreover, the computational cost of the method is low, as shown for the case of the four sensors studied. So, to have a computational time smaller than 1 s should not be an issue even for the case that the number of sensors will be increased. Thus, the technique is valid for the real time application.

Conflicts of Interest: The authors declare no conflict of interest.

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