JOURNAL OF MODERN SCIENCE
SPECIAL ISSUE
3/57/2024
www.jomswsge.com

DOI: doi.org/10.13166/jms/191390

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ANALYSIS OF MEDICAL CORRELATION MODELS USING ULTRASOUND TOMOGRAPHY AND ELECTRIC IMPEDANCE TOMOGRAPHY

ANALIZA MEDYCZNYCH MODELI KORELACJI Z UŻYCIEM TOMOGRAFII ULTRADŹWIĘKOWEJ I ELEKTRYCZNEJ TOMOGRAFII IMPEDANCYJNEJ

Summary

The main goal of the work was to develop a method for the fusion of images from two different measurement techniques. A project has been designed to integrate electrical impedance tomography (EIT) and ultrasonic tomography (UST) data. The next stage was to analyze the correlation between the EIT results and the occurrence of lower urinary tract dysfunctions and establish boundary parameters for visualization and segmentation. Additionally, the relationships between UST data and the dysfunctions were examined, which also required defining parameters for segmentation. The work also involves establishing standards and methods for the arrangement of measurement electrodes, which is crucial for the precision of both techniques. The proposed approach and results constitute an essential step towards implementing more advanced diagnostic tools to improve patient's quality of life by diagnosing lower urinary tract dysfunctions faster and more precisely.

Streszczenie

Głównym celem pracy było opracowanie metody fuzji obrazów pochodzących z dwóch różnych technik pomiarowych. Opracowano projekt, który umożliwia integrację danych z elektrycznej tomografii impedancyjnej (EIT) oraz z tomografii ultradźwiękowej (UST). Kolejnym etapem była analiza korelacji między wynikami z EIT a występowaniem dysfunkcji dolnych dróg moczowych, a także ustalenie parametrów granicznych dla wizualizacji i segmentacji. Dodatkowo, badano związki między danymi z UST a samymi dysfunkcjami, co również wymagało określenia parametrów dla segmentacji. Praca zakłada także ustalenie standardów oraz metod rozmieszczenia elektrod pomiarowych, co jest kluczowe dla precyzji obu technik. Proponowane podejście i wyniki stanowią istotny krok w kierunku implementacji bardziej zaawansowanych narzędzi diagnostycznych, które mogą przyczynić się do poprawy jakości życia pacjentów poprzez szybsze i bardziej precyzyjne diagnozowanie dysfunkcji dolnych dróg moczowych.

Keywords: *image fusion, electrical impedance tomography, ultrasonic tomography, lower urinary tract dysfunctions*

Słowa kluczowe: *fuzja obrazów, elektryczna tomografia impedancyjna, tomografia ultradźwiękowa, dysfunkcje dolnych dróg moczowych*

Introduction

Medical image fusion is an advanced technological process that involves registering and combining images from one or different imaging methods, such as magnetic resonance imaging (MRI), computed tomography (CT), or ultrasound. This process aims to improve image quality by increasing its resolution and contrast and supplementing image information by integrating data from various modalities. Such synergy allows for obtaining a more comprehensive picture of the structure and functions of the examined tissues or organs, which is crucial in precise medical diagnostics (Rymarczyk et al., 2021).

In clinical practice, medical image fusion significantly increases the diagnostic usefulness of test results, enabling better interpretation of pathological changes and more precise planning of therapeutic procedures. Multi-modal image fusion algorithms that integrate data from various sources enrich clinical knowledge with morphological and functional aspects, which is particularly important in oncological, neurological, and cardiological diagnostics (Rymarczyk et al., 2021).

Advances in hybrid devices such as PET/CT and SPECT/CT have also contributed to the development of image fusion techniques. These modern devices combine various imaging methods to enable the simultaneous acquisition of high-resolution anatomical images and functional data, which significantly shortens the examination time and increases patient comfort.

The benefits of medical image fusion include improving the quality and quantity of available diagnostic data and significantly improving the accuracy of clinical decisions. This, in turn, translates into better treatment results and reduced time needed to make a diagnosis (World Population Prospects, 2022; Kozłowski et al., 2021).

Electrical impedance tomography (EIT) and ultrasonic reflection tomography (UTR) are different imaging methods used in medical diagnosis. EIT is a technique that allows you to visualize electrical conductivity distribution in the tested object by analyzing electrical impedance measurements at its periphery. On the other hand, UTR uses ultrasound waves to generate images based on differences in the acoustic impedance of tissue, which allows for observing its mechanical properties.

Both techniques, as noted in the work of (Steiner et al., 2008), are examples of soft-field tomography, which means that they generate images based on subtle differences in the physical properties of the object under examination. However, their diagnostic effectiveness is sometimes limited due to insufficient data and problems related to the mathematical modeling of reverse processes, which are crucial for image reconstruction. These limitations negatively impact the accuracy and resolution of image reconstruction, which is particularly problematic when detecting minor anomalies such as early-stage tumors.

In response to these challenges, the authors of the mentioned work proposed an approach of integrating both these methods within a dual system of bio-electromechanical tomography. Combining information obtained from both EIT and UTR is possible thanks to data fusion techniques. This combination allows the data to complement each other, which increases the ability to detect even small changes in the tissue and improves the accuracy of locating changes in deeper layers.

Simulations conducted by the research team showed that this hybrid technique significantly improves the detection of minor anomalies and the precision of determining their depth compared to single-modal methods. This improvement opens new perspectives for early diagnosis and precise monitoring of pathological conditions, which is crucial in effective therapy planning and increasing the chances of effective treatment.

The research conducted by (Duan et al., 2020) concerns the development of advanced tomography systems combining the electrical impedance method (EIT) with ultrasonic transit time tomography (UTT). As part of this research, an experimental system was built consisting of an integrated sensor that connects two 32-electrode sensor arrays: one dedicated to EIT and the other to UTT. This configuration makes it possible to use both imaging techniques simultaneously in one examination.

The UTT sensor was designed and manufactured in the laboratory and then integrated with the EIT system by mounting the EIT electrodes directly above the UTT electrodes. This design allows for synergy between the two modalities, increasing the complexity and accuracy of the obtained images.

The UTT system has a specially designed power supply, control module, and computer. The control module coordinates the measurement process, including switching between different operating modes and generating the excitation signal and amplification. Additionally, this module manages the received signals to determine time of flight (TOF) values, which are crucial for ultrasonic time-of-flight tomography. In turn, the computer, an integral part of the system, is responsible for image reconstruction based on the collected data, providing final images for analysis (Rymarczyk et al., 2021; Tchórzewski et al., 2020).

This combination of EIT and UTT technologies in one system not only increases diagnostic accuracy by using two different types of data but also allows for a more detailed assessment of the examined area, which is important in various medical applications, including the diagnosis of cancer (Duan et al., 2020).

Development of methods for rapid processing of measurement data

As part of this work, a regression model is developed to estimate the level of bladder filling based on data obtained from transmission ultrasound tomography. Various regression methods are considered to achieve the highest precision while minimizing model complexity.

These include linear regression, which offers simplicity and speed of calculation but may not cope with more complex dependencies in the data. SVM regression is an alternative that better handles nonlinearities using various kernel functions, allowing for better modeling of complex patterns in the data. Additionally, neural networks are being considered for their ability to learn deep representations of data, which can significantly increase estimation accuracy.

The selection criteria for the final model is based on the principle of balance between cost and accuracy, emphasizing providing the most accurate results possible while maintaining low model complexity. This strategy is crucial in applying the model to embedded devices, where hardware constraints require computational efficiency without compromising accuracy. The model's performance under actual operating conditions is also critical to its practical utility in a medical production environment.

The data used in the project comes from a simulation specially prepared to analyze a regression model. This simulation generates transmission ultrasound tomography images that reproduce single elliptical inclusions symbolizing the urinary bladder in various filling degrees. The size of these inclusions varies to simulate natural conditions where the bladder may be filled to varying degrees.

The degree of bladder filling, a key parameter estimated by the model, was defined as a continuous value ranging from 0 to 1, where 0 means an empty bladder and 1 means completely filled. Each image from the simulation was assigned a specific value of this parameter, which allows training and verification of regression models in the context of their ability to estimate precisely.

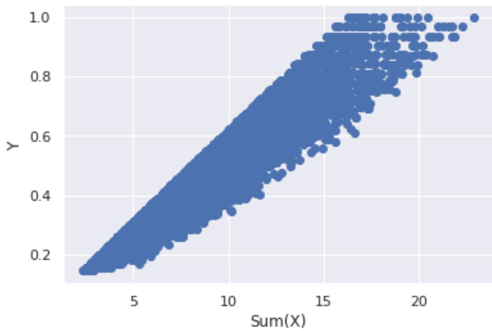
The data set consists of 256 elements, where each component of the data frame contains a UST image (marked as X) and its corresponding bladder filling level (marked as Y). The data structure was designed to enable efficient training and testing of various regression models, emphasizing their ability to interpret and process ultrasound images in the context of bladder filling estimation. This methodology allows for an in-depth study of the potential and limitations of individual modeling approaches in realistically simulated medical conditions.

Data cleaning is a crucial stage in preparing a regression model to improve the training process and increase the accuracy of predictions. In the case of the analyzed data set, this strategy involves selecting only those matrix elements that are above the main diagonal. This choice is dictated by the fact that variables located on opposite sides of the diagonal show a strong correlation, which may lead to the problem of multicollinearity in the model. Reducing the number of predictors by eliminating correlated variables speeds up the model's runtime and improves its generalization by reducing the risk of overfitting. In the case of UST images, variables located symmetrically about the diagonal represent similar information, and eliminating them from the training set helps focus on more meaningful and unique attributes in the data. Focusing on elements above the main diagonal also allows you to reduce the dimensionality of data, which is particularly important in the context of embedded devices with limited computing resources. Such optimization can contribute to more efficient and faster data processing in production conditions, which is crucial in medical applications requiring fast and reliable diagnostics.

Construction of models

When beginning to analyze the relationship between aggregated data and bladder filling status, it is essential first to understand the characteristics of the data set. The data comes from an ultrasound imaging simulation, where each image represents an elliptical inclusion of different sizes, simulating a urinary bladder at various degrees of filling (Fig. 1).

Figure 1. *The data set contains 256 data frame elements from the UST measurement (X) and the degree of bladder filling (Y)*



In this case, the aggregated data primarily includes values from ultrasound images, which are processed to reduce dimensionality and eliminate redundancy. The key in this aggregation is to focus on the matrix elements above the main diagonal, which helps eliminate the repetition of information resulting from symmetry concerning the diagonal.

When analyzing the relationship between the data processed in this way and bladder filling, the first step is to examine the correlation between the features and the target variable, i.e., the degree of bladder filling. This is important because solid correlations indicate the most predictive features and may be crucial in further regression modeling.

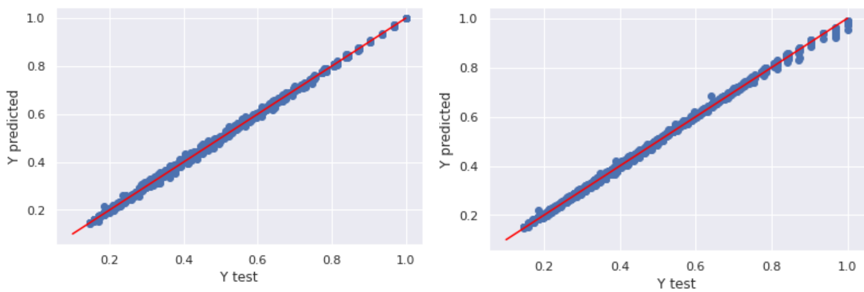
This analysis may reveal potential patterns, such as specific image features specific to certain bladder filling levels. For example, larger elliptical areas may correlate with a higher degree of infill, which could be used for more precise modeling.

As a result of this analysis, it is also possible to identify and eliminate features that will not provide significant predictive value, which is crucial to maintaining the computational efficiency of the model, especially in applications running on embedded devices. Reducing the number of features can speed up the modeling process and improve the model's ability to generalize to unknown data, increasing its usefulness in practical medical applications.

Based on the data analysis and observation of the graph showing the relationship between the summed measurement values and the degree of bladder filling, a clear linear relationship can be noticed. This observation is crucial because it indicates the possibility of effectively using a relatively simple regression model to estimate the level of bladder filling.

The linear relationship between the variables suggests that simple linear regression may be an appropriate choice for modeling these data. In this model, the dependent variable, i.e., the degree of bladder filling, can be predicted directly from a linear combination of independent variables, i.e., summed measurement values, without introducing more complex non-linear transformations (Fig. 2).

Figure 2. *(a) Linear regression has excellent predictive ability; (b) SVM regression*

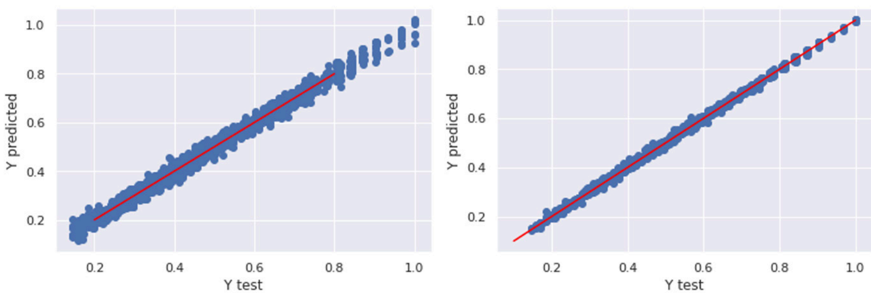


(a) (b)

Adopting a linear model has many advantages, including simplicity in interpreting results, lower computational power requirements, and faster convergence during the training process. Moreover, this approach allows easy verification of model assumptions, such as homoscedasticity of residuals or the absence of autocorrelation, which is essential to ensure the reliability and accuracy of the model in practical applications.

However, although linear regression appears to be appropriate in this situation, it is essential to perform additional validation of the model, including diagnostic testing and checking its performance on a test set, to ensure that the model adequately reflects the relationships in the data and is robust to a variety of conditions operational. Additionally, if any anomalies or exceptions in the data are identified, it may be necessary to consider more complex modeling methods, such as regularized regression or machine learning-based methods (Fig. 3).

Figure 3. *(a) Neural network – sklearn; (b) Neural networks – Tensorflow*



(a) (b)

Correlation analysis between electrical impedance tomography parameters and lower urinary tract dysfunction

Determination of critical parameters for effective data visualization and segmentation

The study focuses on analyzing the possibility of using electrical impedance tomography (EIT) in the diagnosis of lower urinary tract dysfunction. The main goal is to assess the effectiveness of EIT as a diagnostic tool for this type of disorder and to establish parameters that are critical for adequate visualization and segmentation of data obtained using this technology. The study used advanced statistical approaches, including statistical hypothesis testing, to evaluate associations between EIT data and specific urinary tract dysfunctions.

The research methodology includes several vital stages. The first is collecting and processing EIT data from patients diagnosed with lower urinary tract dysfunction. This data is then analyzed to identify patterns or characteristic features that could differentiate between different types and degrees of these dysfunctions. Data visualization and segmentation are crucial elements of the process because they enable a better understanding of the structural and functional aspects of the disorders being studied (Fig. 4-5).

Figure 4. *Visual checking of data correctness – displaying one case from each set*

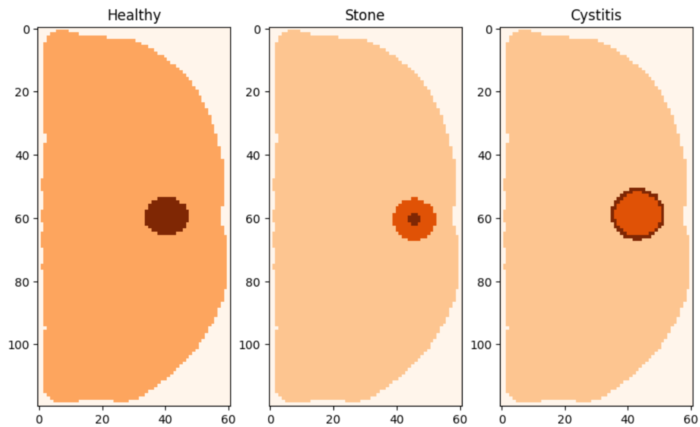
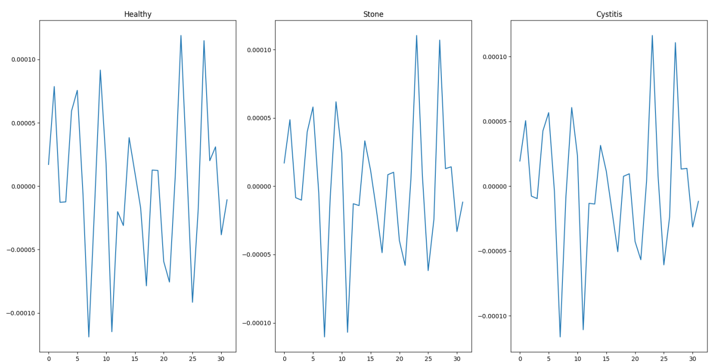


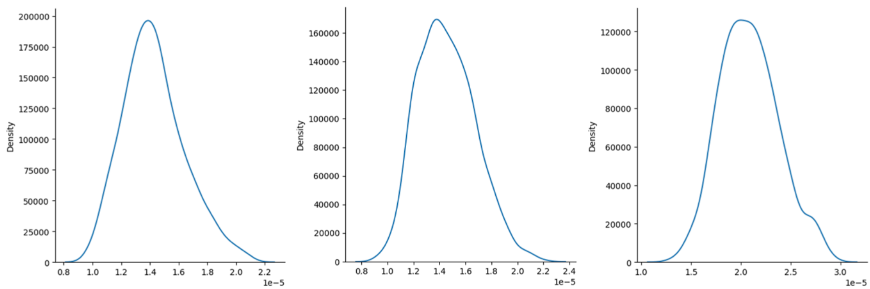
Figure 5. *Overview (visualization) of measurement vectors*



Hypothesis testing in these studies involves checking whether the observed differences in EIT parameters are statistically significant in the context of the diagnosed conditions. The null hypothesis (H0) assumes no considerable difference in EIT data between groups of patients with different lower urinary tract dysfunctions. In contrast, the alternative hypothesis (H1) suggests the existence of such a difference. Appropriate statistical tests are used to test hypotheses, such as the Student's t-test for independent samples when the data are typically distributed or nonparametric tests when assumptions of normality are not met.

The research results presented in the report provide knowledge about EIT's effectiveness in diagnosing lower urinary tract dysfunctions. Statistical analysis allows to assess which EIT parameters are the most promising in differentiating between specific pathological conditions, which is crucial for the further development and optimization of this diagnostic method (Fig. 6).

Figure 6. *Review of descriptive statistics of collections on aggregated measurements EIT: (a) Healthy patient, (b) Disease – Stones, (c) Disease – Cystitis*



(a) (b) (c)

A comparison of descriptive statistics and naked-eye distributions shows that measurements of a diseased bladder can be distinguished from those of a healthy one. However, this needs to be proven objectively and quantitatively.

We are determining the correlation between measurement data obtained by ultrasound tomography and diagnosed lower urinary tract dysfunctions

Determining boundary parameters for visualization (segmentation)

The correlation between measurement data obtained using ultrasound tomography and diagnosed lower urinary tract dysfunctions is a crucial area of research that allows for a better understanding of the mechanisms of these disorders and the potential improvement of diagnostic methods. Advanced statistical techniques are used to analyze the relationship between various measurement data and clinical diagnosis to accurately determine this correlation. One approach is regression analysis, which assesses the strength and nature of the relationship between variables. Thanks to regression, it is possible to determine which variables significantly impact the diagnosis and how the risk of the disease changes depending on the specific values of ultrasound parameters. Alternatively, clustering can identify patterns in the data that group patients with similar ultrasound profiles, which may suggest common pathological pathways or similar stages of disease progression. Determining these parameters and applying appropriate statistical methods allows for a more accurate interpretation of the data ultrasound, directly translating into diagnostic accuracy and treatment effectiveness. Precisely tailored boundary parameters for visualization and segmentation enable better differentiation of anatomical and pathological structures, which is particularly important in the rapidly developing field of medical imaging applications. This approach increases diagnostic efficiency and opens the way to personalized medicine, where diagnostic parameters and treatment methods are individually adjusted to the patient's condition and needs, which can significantly affect the treatment results (Fig. 7-8).

Figure 7. *Displaying one random case from each set to check the data type we are dealing with*

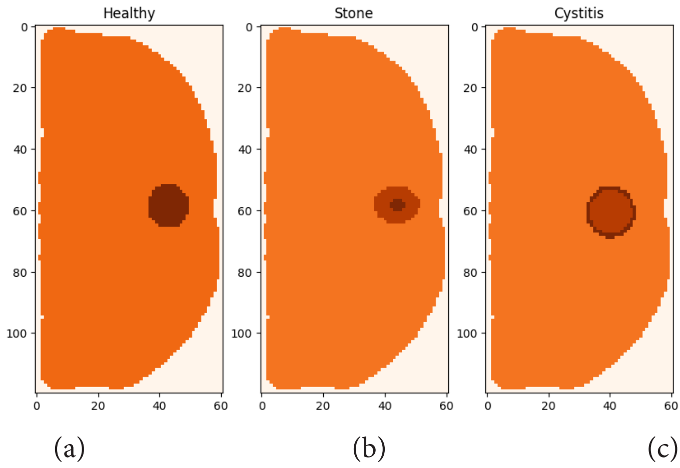
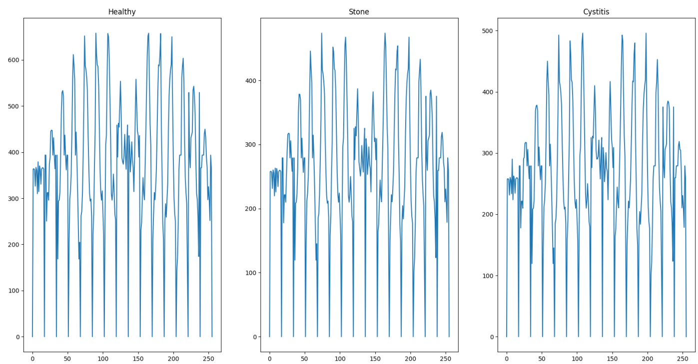


Figure 8. *Overview of UST transmission tomography measurement vectors: (a) Healthy patient, (b) Disease – Stones, (c) Disease – Cystitis*



The measurements look very similar; finding a clear difference in shape is difficult. However, when we look at the Y-axis, size differences are visible.

Some channels have zero variance. This means that the sound wave beam does not pass through the tested area; therefore, each measurement's value is the same. In such a case, these channels should be filtered out, and only those with non-zero variance should be considered (Fig. 9).

Figure 9. *Descriptive statistics for a healthy patient*

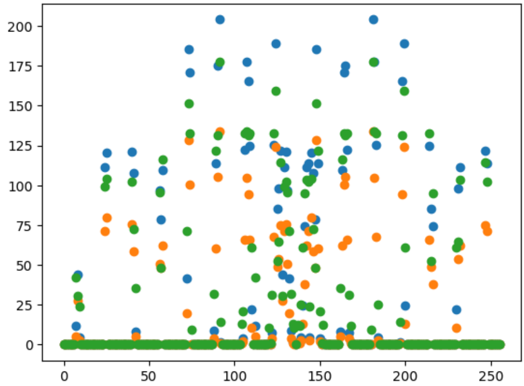
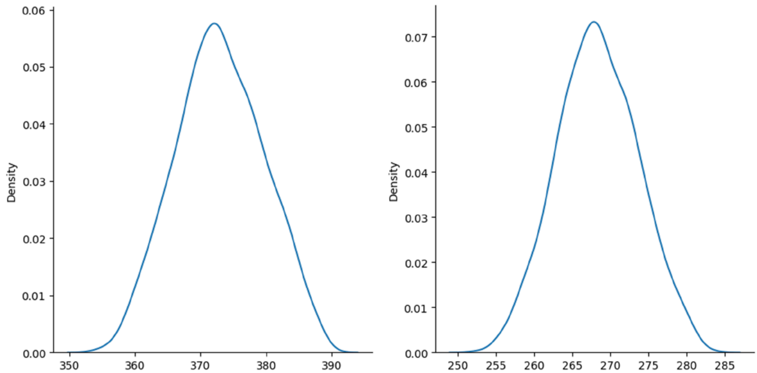


Figure 10. *Review of descriptive statistics of collections on aggregated measurements UST: (a) Disease – Stones, (b) Disease – Cystitis*



(a) (b)

The distribution of features can be considered normal, so tests assuming normality will be performed. All considered channels are significantly different, with a significance level of over 99.99% (Fig. 10).

Conclusions

The ultrasonic transmission tomography (UST) channel analysis, which corresponds to the flight times of the sound wave passing through the urinary bladder, showed a statistically significant difference between the discussed data sets. The computer considers the calculated p-values practically zero, so the data from a healthy and sick patient can be regarded as entirely distinguishable with high probability.

Analysis of EIT measurements in three groups, healthy bladder, bladder with stones, and bladder with inflammation, showed statistically significant differences between the groups. Statistical evidence for the difference between these data was performed at significance levels of 99, 95, and 90. In the case of the distinction between healthy vs. with stones, a significant difference appears on several EIT channels. From a physical point of view, this is justified because only some channels can measure the presence of scale. No difference is visible for other channels that do not have insight into the space where the stone is located.

The situation is completely different when comparing a healthy bladder with an inflamed one. The calculated p-values on all channels are less than numerical zero (10 do potęgi, minus 16 koniec indeks górny), indicating almost certainty in distinguishing between the two cases. Physically, this is also justified—all channels *have insight* into the bladder area, and changes taking place there are recorded.

Further exploration with larger data sets and the possibility of using more advanced statistical and computational methods, such as principal component analysis (PCA) and machine learning, may contribute to a better understanding and use of EIT in medical diagnostics. Long-term clinical studies are also recommended to assess the actual usefulness and accuracy of EIT as a diagnostic tool in actual clinical conditions.

References

Duan, X. (2020). Electrical impedance tomography: methods and applications. Doctoral Thesis, PhD. Published on 24 June 2020.

Kozłowski, E., Gołabek, M., Guzik, M., Wójcik, D., Rymarczyk, T. (2021). Ultrasound Tomography for Monitoring the Lower Urinary Tract. Proceedings of the 19th ACM Conference on Embedded Networked Sensor Systems (SenSys ,21), Association for Computing Machinery, New York, NY, USA, 2021, 388–390.

Rymarczyk, T., Kosior, A., Tchórzewski, P., Vejar, A. (2021). Image reconstruction in electrical impedance tomography using a reconfigurable FPGA system. Journal of Physics: Conference Series, 1782, 1 (Feb 2021), 012033. https://doi.org/10.1088/1742-6596/1782/1/012033

Rymarczyk, T., Polakowski, K., Sikora, J. (2021). PDE-solved by boundary element method for electrical impedance tomography. Journal of Physics: Conference Series, 1782, 1 (Feb 2021), 012030. https://doi.org/10.1088/1742-6596/1782/1/012030

Rymarczyk, T., Wójcik, D., Cieplak, T., Gołąbek, P., Mazurek, M., Kania, K. (2021). Implementation of Block-Wise-Transform-Reduction Method for Image Reconstruction in Ultrasound Transmission Tomography. IEEE INFOCOM 2021 – IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), 2021, 1–2.

Rymarczyk, T., Wójcik, D., Kozłowski, E., Rzemieniak, M., Gudowski, J., Gauda, K., Majerek, D. (2021). Machine Learning and Deterministic Approach to the Reflective Ultrasound Tomography. Energies, 14(2021), 7549.

Steiner, G., Soleimani, M., Watzenig, D. (2008). A bio-electromechanical imaging technique with combined electrical impedance and ultrasound tomography. Physiological Measurement, 29(6), S63. Published 10 June 2008. 2008 Institute of Physics and Engineering in Medicine. https://doi.org/10.1088/0967-3334/29/6/S06

Tchórzewski, P., Kłosowski, G., Adamkiewicz, P., Rymarczyk, T., Kozłowski, E. (2020). Applying the logistic regression in electrical impedance tomography to analyze the conductivity of the examined objects. International Journal of Applied Electromagnetics and Mechanics, 64, S1 (2020), S235–S252. https://doi.org/10.3233/JAE-209520

United Nations Department of Economic and Social Affairs. [n.d.]. World Population Prospects 2022: Summary of Results. UN DESA/POP/2022/TR/NO. 3.