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eitprocessing: a Python package for analysis of Electrical Impedance Tomography data

Peter Somhorst [1*], **Dani L. Bodor** [2*], **Juliette Francovich** [1], **Jantine J. Wisse** [1], **Walter Baccinelli** [2], and **Annemijn H. Jonkman** [1]

1 Department of Adult Intensive Care, Erasmus MC, Rotterdam, The Netherlands **2** Netherlands eScience Center, Amsterdam, The Netherlands ***** These authors contributed equally.

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Reviewers:

- @ajbaird
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Summary

Electrical Impedance Tomography (EIT) is a promising non-invasive, radiation-free technology for monitoring the respiratory system. EIT is mostly used to optimize ventilator settings to the respiratory mechanics of mechanically ventilated patients in the Intensive Care Unit. While EIT is gaining popularity, the complexity of data processing, analysis and interpretation hampers standardization, validation and widespread adoption. Commercial software is closed and opaque, while custom research software is often ad-hoc, single use, and unverified. `eitprocessing` offers a standardized, open, and highly expandable pipeline for the processing and analysis of EIT and respiration related data.

State of the field

Acute respiratory failure is the most common reason for admission to the intensive care unit (ICU), and can be caused by e.g., infection, trauma, heart failure, or complications during elective surgery. Patients with severely injured lungs and critically low levels of arterial oxygen require life-saving breathing support with mechanical ventilation (Tobin & Gardner, 1998). Although mechanical ventilation is the cornerstone of supportive therapy in the ICU, it is a double-edged sword: inadequate mechanical ventilator assist exacerbates lung injury and inflammation, and worsens outcomes (Amato et al., 2015; Slutsky & Ranieri, 2013). ICU mortality for patients with acute respiratory failure remains high (~40%, Bellani et al., 2016); these numbers increased drastically during the COVID-19 pandemic. To ameliorate the risk of death and long-term morbidity of the critically ill, we need mechanical ventilation strategies that are lung-protective and tailored to the individual patient's respiratory physiology (Goligher, Dres, et al., 2020; Goligher, Jonkman, et al., 2020). However, there are currently no simple, reliable, and readily accessible tools available to clinicians at the bedside to identify the beneficial and harmful effects of adaptations in mechanical ventilator support (Jonkman et al., 2022).

A very promising technology to change clinical practice in ICU patients is EIT (Frerichs et al., 2016). EIT is gaining worldwide popularity as a bedside non-invasive radiation-free tool for lung imaging. Using a belt fitted with electrodes placed around the chest, it continuously visualizes real-time changes in lung volume. These changes reflect tidal ventilation, changes in lung volume due to ventilator settings, and adaptations due to variations in lung characteristics caused by improved or worsening lung mechanics. In contrast to static anatomical imaging techniques such as computed tomography scan, EIT provides dynamic information on lung ventilation. As such, EIT can monitor at the bedside the direct impact of mechanical ventilation on the lung, help with personalizing mechanical ventilation, and assist in clinical decision-making. Personalizing mechanical ventilation using EIT monitoring and diagnostics may ameliorate the risk of death and long-term morbidity, and may substantially reduce the burden on our healthcare system.

Statement of need

The perspective that EIT will become an important standard monitoring technique is shared by international experts (Frerichs et al., 2016; Wisse, Scaramuzzo, et al., 2024). Both Frerichs et al. (2016) and Wisse, Scaramuzzo, et al. (2024) emphasize the importance of standardized techniques, terminology, and consensus regarding the application of EIT. Validated methods to implement EIT-based parameters in routine care are still lacking. Standardized implementation of EIT-based parameters is further limited as the availability of both bedside and offline analysis tools depends on the type of EIT device used. Advanced image and signal analysis could overcome certain challenges but also requires complex post-processing (including detection/removal of common artifacts) that is time-consuming and requires specific technical expertise that is often not present in clinical practice. This currently hampers reproducibility of research findings and clinical implementation. The current limitations of EIT analysis stresses the importance of close collaboration between physicians, clinical researchers and engineers in order to identify clinical needs, to develop and validate new algorithms, and to facilitate clinical implementation (Scaramuzzo et al., 2024).

Currently, some open source EIT software packages are available (Adler & Lionheart, 2005; Liu et al., 2018). These, however, all focus on reconstruction of voltage data to images, bypassing the clinically used reconstruction algorithms implemented in CE-approved devices, and don't include tools for the analysis of reconstructed EIT image data.

`eitprocessing` offers a standardized, open, and highly expandable library of tools for loading, filtering, segmentation and analysis of reconstructed EIT data as well as related waveform or sparse data. The package is written in Python to ensure accessibility without the requirement for commercial software. `eitprocessing` is compatible with data from the three most-used clinically available EIT devices, as well as from related data sources, such as mechanical ventilators and dedicated pressure devices. It includes commonly used methods for filtering and segmentation. The authors continuously develop and implement further algorithms for analysis. The international community has been invited to use and contribute to the software.

Key features

`eitprocessing` aims to simplify and standardize loading, pre-processing, analysis and reporting of respiration-related datasets. Notebooks demonstrating these features are available in the repository.

Loading

`eitprocessing` supports the loading of EIT data exported from the Dräger Pulmovista (`.bin` files), Timpel Enlight (`.txt` files) and Sentec LuMon (`.zri` files) devices. Non-EIT data — such as pressure, flow and volume — saved in the data files are also loaded.

Data containers

The main data container in `eitprocessing` is the `Sequence`. A sequence represents a single continuous measurement of data in a single subject, and can contain data from different sources. Sequences can be sliced — by time or index — and concatenated. All data contained in the sequence are sliced and concatenated accordingly.

`eitprocessing` currently supports four types of dataset. The most important type is `EITData`, which contains the electrical impedance of individual pixels as three-dimensional data — (generally) 32 rows by 32 columns over time. Each frame of 32 by 32 pixels represents the impedance in a transverse plane through the thorax at the corresponding time. `ContinuousData` has one-dimensional data points at predictable intervals with a fixed sample frequency. Examples are airway pressure measured by a mechanical ventilator or a global impedance signal. `SparseData` has one-dimensional data points at unpredictable intervals and no set sample frequency. An example is the tidal volume measured by a mechanical ventilator, registered at the end of each breath. `IntervalData` has one-dimensional data points that are valid for a time interval. An example is the position of a subject, e.g., supine for the first part of a measurement and prone for the second part.

Pre-processing

`eitprocessing` currently has implementations for the following pre-processing steps:

- high-pass, low-pass, band-pass or band-stop Butterworth filters, as well as a Multiple Digital Notch filter (Wisse, Somhorst, et al., 2024);
- calculation of the global or regional impedance as the sum of the impedance of all or a subset of pixels;
- a moving averager using convolution with a given window;
- region of interest selection using predefined or custom masks;
- functional lung space detection using the tidal impedance variation, amplitude, or the Watershed method;
- automatic detection of the start, middle (end-inspiration) and end of breaths on a global/regional and pixel level;
- automatic detection of the respiratory and heart rate from pixel impedance values.

Analysis

`eitprocessing` currently has implementations for the following parameters:

- end-expiratory lung impedance on a global/regional and pixel level;
- tidal impedance variation on a global/regional and pixel level.

Visualization

`eitprocessing` includes several visualization methods to simplify and standardize visual output. Examples are:

- showing pixel maps, e.g., tidal impedance variation, changes in EELI, pendelluft, etc.;
- show the effect of filtering methods in the frequency domain.

Future perspective

`eitprocessing` is ready for use in offline analysis of EIT and respiratory related data. Our team is actively working on expanding the features of the software.

Several features are in active development. Examples are:

- provenance tracking of data processing steps;
- more advanced filtering methods, e.g., empirical mode decomposition and wavelet transforms;
- quantification of pendelluft;
- expansion of visualization methods.

Moreover, we plan to extend `eitprocessing` with standardized workflows to summarize and report analysis results.

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