Validation and Management of Data Quality Metrics on ICU Patients

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Abstract: Real-time monitoring of lung function is one of the most promising applications of electrical impedance tomography (EIT). There are however some technical challenges that require validating diagnostic information extracted from EIT images. Two new data quality metrics are proposed and are applied on EIT and ventilator data acquired in an intensive care unit (ICU) setting. Their interpretation and usefulness in a clinical context is discussed.

1 Introduction

Real-time monitoring of mechanically-ventilated lung function at the bedside of intensive care unit (ICU) patients represents one of the most promising applications for electrical impedance tomography (EIT). Some technical challenges remain however before EIT could become a routinely used clinical tool in the ICU [1]. Most of these challenges are related to the long-term monitoring of patients for durations of hours or days. Maintaining high-quality EIT data then becomes difficult due to variations in quality of electrode contacts with the patient, instrumentation drift as well as patient's movement and manipulation by clinical staff. Some data quality metrics (DQM) have been proposed in the literature [2] to assess EIT data quality and therefore ensure the quality of any diagnostic or therapeutic information extracted from EIT images.

From reviewing and validating previous DQM definitions from the literature, two new simple and efficient DQM are presented. They are applied and validated on EIT and ventilator data previously acquired on ICU patients [3]. A discussion follows on how clinical staff should interpret and manage the information provided by these two new DQM.

2 Methods

Most EIT systems used for monitoring lung function reconstruct time difference images representing a change of conductivity relative to a reference state: $\mathbf{m} = (\boldsymbol{\sigma} - \boldsymbol{\sigma}_\mathrm{r})/\boldsymbol{\sigma}_\mathrm{r}$, where $\mathbf{m}$ is a vector, whose elements correspond to the element of a mesh or the pixels of an image, that represents the change of conductivity between the latest conductivity distribution $\boldsymbol{\sigma}$ and a reference conductivity distribution $\boldsymbol{\sigma}_\mathrm{r}$. Such images are typically reconstructed from normalized voltage difference data $\mathbf{d} = (\mathbf{v} - \mathbf{v}_\mathrm{r})/\mathbf{v}_\mathrm{r}$, where $\mathbf{v}$ is the latest voltage measurement vector and $\mathbf{v}_\mathrm{r}$ is the voltage measurement vector corresponding to a reference state.

The relationship between $\mathbf{d}$ and $\mathbf{m}$ is typically obtained from the linearization of a physics model:

$$\mathbf{d} = \mathbf{J}\mathbf{m} \tag{1}$$

where $\mathbf{J}$ represents the Jacobian or sensitivity matrix. Since, EIT is an ill-posed problem, some optimization algorithms combined with regularization techniques are used to obtain the following linear relationship:

$$\mathbf{m} = \mathbf{R}\mathbf{d} \tag{2}$$

where $\mathbf{R}$ is called the reconstruction matrix which can be derived from different optimization methods such as, for instance, the *maximum a posteriori* (MAP) estimate.

From (1) and (2), reconstruction error $\boldsymbol{\varepsilon}_\mathrm{reconst}$ can be defined as:

$$\boldsymbol{\varepsilon}_\mathrm{reconst} = \frac{1}{P_\mathbf{d}}(\mathbf{I} - \mathbf{J}\mathbf{R})\mathbf{d} \tag{3}$$

where $P_\mathbf{d}$ is the average signal $\mathbf{d}$ obtained for a spherical conductivity located in the medium center with 2:1 contrast and 20% medium radius.

Reciprocity error $\boldsymbol{\varepsilon}_\mathrm{recip}$ can be defined as:

$$\boldsymbol{\varepsilon}_\mathrm{recip} = \frac{1}{P_\mathbf{v}}(\mathbf{I} - \mathbf{K}(\mathbf{K}^\mathrm{t}\mathbf{K})^{-1}\mathbf{K}^\mathrm{t})\mathbf{v} \tag{4}$$

where $P_\mathbf{v}$ is the average of signal $\mathbf{v}$ and $\mathbf{K}$ is a matrix representing the relationship $\mathbf{v} = \mathbf{K}\mathbf{v}_\mathrm{ind}$ between voltage measurement vector $\mathbf{v}$ and a reduced-size version $\mathbf{v}_\mathrm{ind}$ containing only a set of independent voltage measurements mainly due to the reciprocity principle. Using (4) implies that the EIT acquisition system performs some reciprocal measurements or else $\mathbf{K}$ would be equal to the identity matrix $\mathbf{I}$ and $\boldsymbol{\varepsilon}_\mathrm{recip}$ would be equal to the zero vector $\mathbf{0}$ and become useless. In practice, most systems perform reciprocal measurements.

Finally, DQM q_reconst and q_recip are defined by respectively substituting $\boldsymbol{\varepsilon}_\mathrm{reconst}$ and $\boldsymbol{\varepsilon}_\mathrm{recip}$ from (3) and (4) into

$$q = \frac{1}{M}\sum_{i=1}^{M}\left(\frac{1}{2}\right)^{|\varepsilon_i|} \tag{5}$$

where M represents the length of $\boldsymbol{\varepsilon}_\mathrm{reconst}$ or $\boldsymbol{\varepsilon}_\mathrm{recip}$ depending on which DQM is being computed. Following this definition, any computed q value will be constrained between 0 and 1 to respectively indicate poor or good data quality.

3 Discussion

DQM were computed on data acquired on ICU patients from a previous study [3] and validated with the corresponding ventilator data. It was found that 1) DQM show abrupt changes, which often correspond to known events, and 2) DQM behave differently and are sensitive to different effects. q_recip indicates the quality of a particular voltage measurement vector $\mathbf{v}$ while q_reconst is useful to assess the quality of reconstructed images. q_reconst is affected by several parameters: mainly, reference voltage measurement vector $\mathbf{v}_\mathrm{r}$, physics model geometry and reference conductivity distribution $\boldsymbol{\sigma}_\mathrm{r}$ used to compute Jacobian $\mathbf{J}$. q_reconst can be used to assist clinicians in selecting the best model geometry and reference conductivity distribution for a given patient and in assessing how long a reference state ($\boldsymbol{\sigma}_\mathrm{r}$, $\mathbf{v}_\mathrm{r}$) is valid before a new one should be selected or acquired.

References

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