Chest electrical impedance tomography examination, data analysis, terminology, clinical use and recommendations: consensus statement of the TRanslational EIT developmeNt stuDy group

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ONLINE SUPPLEMENT 1

Execution of EIT chest measurements

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Electrical impedance Tomography (EIT) calculates tomographic (i.e. cross-sectional) images of the chest using non-invasive electrical measurements at electrodes on the body surface. EIT measurement requires the placement of electrodes (either individual electrodes or as part of an electrode belt) onto the area of interest and connection of these electrodes to the EIT device. While acquiring data, an EIT device performs a sequence of current stimulations across sets of electrodes, while the resultant voltages are measured at the other electrodes. The currents used are imperceptible and below electrical safety norms for macroshock on the body surface. This electronic online supplement (EOS) 1 describes how EIT chest examinations are carried out. Figure E1.1 shows the sequences of all processes involved in EIT examinations and EIT data analysis for orientation. The process described in this EOS is highlighted.

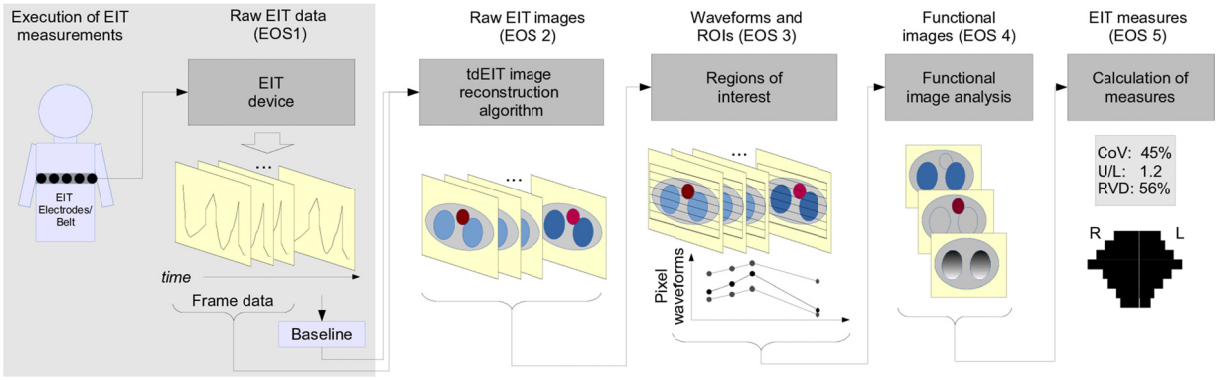

Figure E1.1. Sequence of processes involved in EIT chest examination and data analysis. EOS 1 (gray background) describes the process of raw image generation. Abbreviations: EOS, electronic online supplement; tdEIT, time-difference EIT; ROI, region-of-interest; CoV, center of ventilation; U/L, upper-to-lower ventilation ratio; RVD, regional ventilation delay; R, right; L, left.

General comment

We estimate that more than 50 different EIT devices have been developed since the invention of EIT, typically in university research labs. According to our knowledge, the last attempt to generate the list of the existing devices originates from the mid-nineties of the last century (1). In this supplement document, only a few EIT devices are mentioned which: 1) have most frequently been used under in-vivo conditions (i.e. in animal experimental and clinical studies), and/or 2) are currently commercially available. (Table E1.1 provides a list of

these devices with some basic characteristics.) The choice to mention a device is thus based on these criteria, and does not imply our recommendation. We describe the general features of EIT data acquisition that are common in EIT examinations of humans and only briefly refer to some device-specific characteristics. For other, detailed specific features of the EIT devices the users are advised to follow the instructions of use of the individual producers of EIT technology.

Table E1.1. List of commercial EIT devices frequently used in examinations of human subjects.

Manufacturer	EIT system	Electrodes (number, configuration)	Characteristics
CareFusion	Goe-MF II	16, individual electrodes	Pair drive (adjacent), serial measurement. Algorithm: Sheffield back-projection
Dräger Medical	PulmoVista 500 *	16, electrode belt	Pair drive (adjacent), serial measurement. Algorithm: FEM-based Newton-Raphson method
Maltron Inc	Mark 1 Mark 3.5 *	16, individual electrodes 8, individual electrodes	Pair drive (adjacent), serial measurement. Algorithm: Sheffield back-projection
Swisstom AG	BB^2 *	32, electrode belt	Pair drive (adjustable skip), serial measurement. Algorithm: GREIT
Timpel SA	Enlight *	32, electrode stripes	Pair drive (3-electrode skip), parallel measurement: Algorithm: FEM-based Newton-Raphson method

*, commercially available as of May 2016; FEM, finite element method.

EIT electrode array

EIT examinations require the placement of electrodes on the chest circumference usually in the mid or caudal part of the chest. The plane is chosen to be sensitive to the phenomena of interest. The electrodes are either single self-adhesive electrodes (e.g. ECG electrodes) that have to be placed on the chest individually with possibly equal spacing or they are integrated into one electrode belt or two self-adhesive electrode stripes. The latter solutions render the application more user-friendly.

- **Electrode plane**

The array of EIT electrodes is typically placed in one transverse plane, although oblique placement has also been described (2) and is used in one commercially available EIT device.

More than one plane has been used in a few studies to document the regional ventilation differences in two (3, 4) or three chest slices (5, 6). Acquisition of EIT data in more than one plane may offer the possibility to assess the lung electrical properties in a large section of the chest (7). However, true 3D EIT imaging has not achieved any relevant state of development.

The location of the electrode plane impacts the findings because EIT is most sensitive to nearby anatomical locations. The effective thickness of the studied slice of the chest is not uniform (8). It is the largest in the center of the chest and decreases toward the chest boundary (see EOS 2, Figure E2.2). Therefore, it is necessary to document the exact location of the electrode array to secure comparability of examinations performed on separate occasions. Typical anatomical landmarks should be used; when describing the EIT electrode plane we recommend specifying the exact intercostal space at the parasternal line. The distance relative to the internipple line has occasionally been used to describe the location of the electrode plane. However, we do not recommend this as the distance is impacted by body growth in children and not suitable in women.

Electrode placement in the 5^{th} to 6^{th} intercostal spaces at the parasternal line allows good representation of impedance changes mainly in the lower lobes of the right and left lungs as well as in the heart region. It is generally not recommended to place the electrodes below the 6^{th} intercostal space in supine subjects because the diaphragm may periodically enter the measurement plane (4, 5), and the sensitivity to abdominal conductivity increases. More cranial lung regions are assessed by EIT when the electrode plane is located in the 3^{rd} to 4^{th} intercostal spaces. In certain applications it is considered an advantage that less heart is represented in these parts of the chest (9, 10).

- **Placement of the electrode array**

The placement of the electrode array is easy in awake, cooperative upright subjects. However, patients are often sedated or anaesthetized and thus uncooperative. They usually lie in the supine position. Placement of the electrode array on the chest under these conditions usually requires two persons.

The placement of electrode belts on the chest is relatively straightforward. The patient needs to be turned to one side to partially expose the back and the belt is then moved below the body. Afterwards the patient is turned to the other side and the belt is pulled out and closed. Alternatively, the patient is slightly leaned forward and the belt is moved from above underneath the head towards the chest. When two electrode stripes are used, the preferred way of placement is to turn the lying patient at first to one and then to the other side and attach the stripes starting at the backbone.

With individual electrodes, we recommend placement of the electrode on the sternum, i.e. on the front part of the chest at first and then one electrode each in the left and right midaxilar lines. Afterwards, the electrodes in between these first three electrodes are attached. Then the patient is slightly turned to one side and an electrode is placed directly on the backbone. The remaining electrodes between the backbone and the midaxillar electrodes are attached after that. Finally, the patient is turned to the other side and the last remaining electrodes are attached.

Especially with individual electrodes, care must be taken that no electrical contact exists between the electrodes. This is seldom a problem in adults, but can be when preterm infants are examined. In this specific group of patients, the individual electrodes need to be trimmed to fit on the very small chests (Fig. E1.2). Nonetheless, it has been shown in a few clinical studies that even infants weighing less than 1000 g can be examined by EIT (11-14). Unfortunately, there exist no EIT electrode belts for the use in neonates and small infants at present.

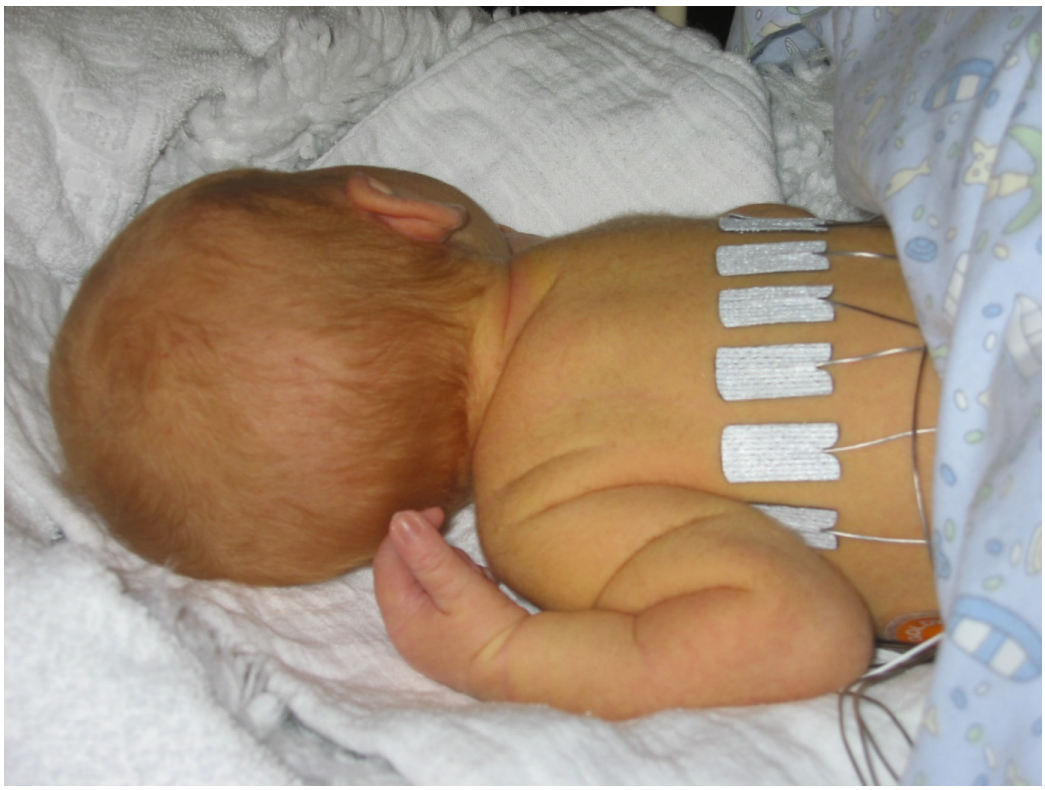

Figure E1.2. Placement of individual EIT electrodes in a 10-day old spontaneously breathing neonate. X-ray translucent electrodes were trimmed to fit on the small chest and placed on the chest circumference. The examination (Goe-MF II EIT device, CareFusion, Höchberg, Germany) was performed to assess the effect of prone position on ventilation distribution in the transverse plane with written informed consent of the parents (15).

- **Number of EIT electrodes**

The first commercially available EIT system, the Sheffield Mk1 device but also some of the more recently developed commercial (Goe-MF II, CareFusion, Höchberg, Germany or the PulmoVista 500, Dräger, Lübeck, Germany) or non-commercial devices operate with 16 electrodes. EIT systems with 32 electrodes (Enlight, Timpel, Sao Paulo, Brazil and Swisstom BB^2, Swisstom, Landquart, Switzerland) and 8 electrodes (Maltron Sheffield Mark 3.5, Maltron, Raleigh, UK) have also been developed.

The higher number of electrodes gives two advantages: an improved spatial resolution and a redundancy of data, from which the reconstruction algorithm can reject measurements at poorly connected electrodes. Because of the diffuse pattern of electric current flow, image resolution in the interior of the thorax does not improve in proportion to the number of electrodes (16).

The lower number of electrodes may simplify the placement of electrodes in preterm infants with very small chest dimensions (17), however, the spatial resolution deteriorates (16). Also, clearly, an additional advantage is the reduced cost of the EIT hardware production.

- **Numbering of EIT electrodes**

The image reconstruction algorithm needs to "know" the position of the electrodes on the chest circumference in order to generate proper chest EIT images. If electrode belts or the individual electrodes are placed on the chest in an arbitrary way, image orientation will be correspondingly arbitrary. Therefore, the instructions how the electrode belt is applied and where it is closed need to be exactly followed. Individual electrodes need to be connected with the leads in a specified order.

As mentioned above, in systems using individual electrodes like the Sheffield Mk1 or Mk3.5 or the Goe-MF II devices, one of the electrodes is located directly in the middle of sternum and one on the backbone. This is not the case with the electrode belts and stripes of other EIT devices, where the electrodes are to each side of the sternum and backbone and not directly on them.

In some cases, it is necessary to adjust placement of electrodes, in order to work around body surface wounds, bandages or catheters. When individual electrodes are used, the electrodes can be placed above or below the correct site. Such off-plane placement should be recorded.

- **Electrode contact**

Good electrode contact (with low electrical impedance) is essential to the recording of high quality data. To improve the skin contact of the electrodes some producers of EIT technology recommend the use of electrode gel or spray. In the specific group of preterm and term neonates, where very small individual EIT electrodes close to each other need to be applied on the chest, the use of skin lotions immediately before the measurement may affect the EIT measured data. This has been observed with EIT systems using the adjacent pattern of current applications and voltage measurements (see also EOS 2), therefore, we do not recommended excessive use of body lotion prior to examination in this patient group.

Generally, EIT measurements can be performed even when the impedance at the body-electrode interface is high (e.g. when the skin is dry) or non-uniform, however, it should be aspired to keep the body-electrode impedance low, stable and similar among the electrodes. It is recommended that no electrical contact is formed by conductive fluid (i.e. saline or excessive sweat) between electrodes.

With modern EIT devices, an EIT examination can be initiated almost immediately after the electrode belt or the individual electrodes have been attached on the chest and the patient has been connected with the device. However, it is known that the electrode contacts improve with time (18, 19); therefore, whenever possible, a delayed onset of the measurement by approx. 5-10 minutes is recommended. This time period may be beneficial for some devices to stabilize after the power-on. Passive or active movement of patients or touching of electrodes or leads during EIT data acquisition should be avoided. Large chest wounds or multiple chest tubes may preclude the measurement. The best quality of EIT images is achieved when the EIT signal quality is good at all electrodes. However, even with missing or faulty electrodes EIT images can be generated (20, 21), albeit of slightly lower quality. With this respect, it is important that the signal quality at individual electrodes is monitored and that low quality and/or missing data are taken into account during EIT image reconstruction. Modern commercial EIT devices automatically warn the investigator when the signal quality is low and a schematic drawing highlighting the faulty electrodes is displayed. An automatic compensation is offered by some devices.

EIT measurement and data acquisition

During an EIT measurement, very small alternating electrical currents are applied through pairs of electrodes, and the resulting voltages measured on the remaining passive electrodes. The electrical currents used by EIT are imperceptible and safe for body surface application. (The use of EIT in patients with cardiac pacemakers and with electrically active implants like cardioverter-defibrillators is not recommended). The frequency and the

amplitude of the current should be specified. The most widespread spatial pattern of current applications and voltage measurements is through adjacent electrode pairs. Because of its prevalence, this pattern will continue to be broadly used. However, other patterns of current applications and voltage measurements can be expected to replace the adjacent electrode pattern in the future because they offer technical advantages (22). Most commercial EIT devices do not offer the user the choice of measurement patterns, but select an appropriate pattern compatible with the vendor-specific image reconstruction algorithm. It is important to mention the measurement pattern used, if it is not determined by the choice of EIT device used.

Each set of EIT data from which an image can be reconstructed is called a frame, and the rate at which data are acquired is the scan (or frame) rate. Modern EIT devices are capable of high scan rates with respect to the physiological processes of interest (for more information see EOS 2). The scanning period of the first EIT devices was limited by the performance of at that time existing hardware and computers. Nowadays, continuous scanning is possible enabling long-term examinations.

Factors affecting or interfering with EIT measurements

- **Patient-related factors**

Since posture (3, 23-25) and the type of ventilation (26-31) affect the findings they need to be taken into account and stated in the measurement description. Specific ventilation maneuvers performed during either spontaneous or mechanical ventilation also need to be documented. The ventilation mode (assisted or controlled) and the settings should also be provided during mechanical ventilation.

Body movement (either active or passive) and speech may affect the acquired EIT data. Restricted thoracic movement has also been shown to exert an effect on the EIT findings (32). Other patient-related factors typically encountered in the medical environment either impact the electrode contact (presence of fresh blood or other body fluids, electrolyte solutions, wet compresses) or the propagation of the electrical current in the chest (metal sutures, breast implants, chest tubes, electrically active implants). Rapid changes in body fluid volumes induced, e.g. by massive bleeding of quick administration of crystalloid or colloid fluids modify the electrical properties of the chest. This may affect the interpretation of EIT results, especially regarding the end-expiratory lung volume, ventilation distribution findings seem not to be affected (33).

- **Other factors**

Some medical devices may interfere with EIT examinations (34). Typical potential sources of interference are devices using the same measuring principle as EIT like impedance pneumography or impedance cardiography, especially when operating with drive currents of a similar frequency as the EIT excitation currents. Modern EIT devices allow automatic or manual change of the EIT drive frequency when this type of electrical interference is detected, thus, this effect may be eliminated when present.

Continuous cardiac output monitoring has also been identified as a possible source of interference with EIT measurements (34). Online or offline frequency filtering of the EIT signals may enable meaningful interpretation of the acquired data (see also EOS 3). However, it is generally recommended to eliminate the sources of interference before EIT data acquisition whenever possible.

Pulsating air suspension mattresses, typically used in patients treated in intensive care units, may induce periodic changes in electrode contact. In supine subjects, these are mainly located on both sides of the dependent part of the chest (34). At low rates of pulsation, the interference may not be easily identified, nevertheless, it may impact the interpretation of EIT findings, especially when end-expiratory lung volume is assessed in mechanically ventilated patients.

Document preparation

The first draft of this online document was prepared by I. Frerichs with collaboration of A. Adler and V. Torsani. It was reviewed and approved by all other authors and collaborators.

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