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Mk3.5: a modular, multi-frequency successor to the Mk3a EIS/EIT system

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Abstract

This paper describes the Sheffield Mk3.5 EIT/EIS system which measures both the real and imaginary part of impedance at 30 frequencies between 2 kHz and 1.6 MHz. The system uses eight electrodes with an adjacent drive/receive electrode data acquisition protocol. The system is modular, containing eight identical data acquisition boards, which contain DSPs to generate the drive frequencies and to perform the FFT used for demodulation. The current drive is in three sequentially applied packets, where each packet contains ten summed sine waves. The data acquisition system is interfaced to a host PC through an optically isolated high speed serial link (RS485) running at 2 Mbaud (2 Mbits s^{-1}). Measurements on a saline filled tank show that the average signal to noise performance of the system is 40 dB measured across all frequencies and that this figure is independent of frequency of measurement. These results suggest that the current system is 10 dB better in absolute terms than the previous Sheffield (Mk3a) system.

Keywords: impedance spectroscopy, instrumentation, modular

1. Introduction

The Sheffield Mk3a EIT system used 16 interleaved drive and receive electrodes (Brown *et al* 1994) unlike the earlier systems developed in Sheffield (table 1) which used adjacent drive and receive electrode combinations (Brown and Seagar 1987). The Mk3a system collected data at eight frequencies between 9.6 kHz and 1.2 MHz and the data acquisition rate was 33 frames s^{-1}. The use of separate drive and receive electrodes was to eliminate the problems of using multiplexers to switch electrodes between drive and receive modes. However, whilst this was clearly an advantage, the use of interleaved drive and receive electrodes produced problems in image reconstruction. One of the major uses of the Mk3a system was in modelling both adult and neonatal lung tissue with the objective of monitoring both regional ventilation and fluid changes (Noble *et al* 1999, Nopp *et al* 1997, Smallwood *et al* 1999). Placing 16 electrodes around the thorax of a neonate presents considerable difficulties. As a result of both the technical and ergonomic problems, a Mk3.5 EIT system has been developed.

Table 1. Characteristics of the impedance measurement systems developed in Sheffield.

Identifier	Electrodes	Drive pattern	Frequencies	Technology	Date
Mk1	16	adjacent	50 kHz	analogue	1987
Space/portable	16	adjacent	50 kHz	analogue	1989
Mk2	16	adjacent	20kHz	digital	1990
Mk3	16	interlaced	8: 9.6 kHz–1.2 MHz	analogue	1993
Mk3.5	*8*	*adjacent*	*30: 2 kHz–1.6 MHz*	*digital*	*2000*

2. Comparison with Mk3a system

The Mk3.5 system uses eight electrodes with adjacent drive and receive combinations. In this respect it is similar to the earlier 16 electrode systems developed in Sheffield (Brown and Seagar 1987), which are summarized in table 1. The system measures data at 30 frequencies between 2 kHz and 1.6 MHz at 25 frames s^{-1}. Like the Mk3a system, it uses triaxial cables to connect the electrodes to the electronics (Lu and Brown 1994). The outer screen is earthed to minimize capacitive coupling between electrodes whilst the inner screen is bootstrapped to the voltage on the central conductor in order to minimize capacitance to earth. However, unlike the Mk3a system, which used analogue demodulation, the Mk3.5 system uses digital signal processing for both the generation of the current drive frequencies and demodulation of the measured signals. Perhaps more importantly, the Mk3a system did not use programmable devices so any changes to the data acquisition protocol required significant changes to the electronics which led to version control and support problems. The Mk3.5 is designed to be a modular system that is based around programmable devices. The system contains eight data acquisition boards connected to a motherboard (figure 1). Each data acquisition board has been designed to be self-contained with two, externally controlled, modes of operation: a current drive mode and a voltage measurement mode. Therefore, each electrode must be connected to two data acquisition boards in order that every adjacent pair of electrodes can be utilized. Each data acquisition board has a single electrode cable connector mounted on the board itself and the links between electrodes are achieved using minimum length driven screen coaxial cables which link the data acquisition boards for adjacent electrodes.

Each data acquisition board contains a Texas Instruments '549 DSP, an analogue-to-digital converter for data capture and a digital-to-analogue converter for current drive (figure 2). The low number of components should produce high reliability whilst reducing the costs of replicating the system. The eight data acquisition boards are connected to a motherboard by high speed synchronous serial links. The motherboard contains a single microcontroller that controls both data transfer to and from the DSPs on the data acquisition boards and serial communication with the host PC. Current drive is achieved through a precision balanced voltage controlled current source (VCCS) which uses the modified Howland circuit described previously (Bertemes-Filho *et al* 2000). In current drive mode, the output of the balanced VCCS is connected to the differential amplifier of the voltage measurement circuit. Overdriving the inputs of high gain wide bandwidth amplifiers can result in charge retention, which limits the speed of response to subsequent signals within their normal dynamic range. This is potentially one of the limiting factors determining the data acquisition speed of the overall system. To prevent this, the gains of the amplifiers are reduced during current drive. In voltage measurement mode, the input to digital to analogue (DAC) converter connected to the balanced VCCS is set to zero. However, any noise at the output of either the DAC or the balanced VCCS itself will produce a current drive which will contribute to the measurement noise. To minimize this, electronic switches disconnect the balanced VCCS from the electrodes and connect its

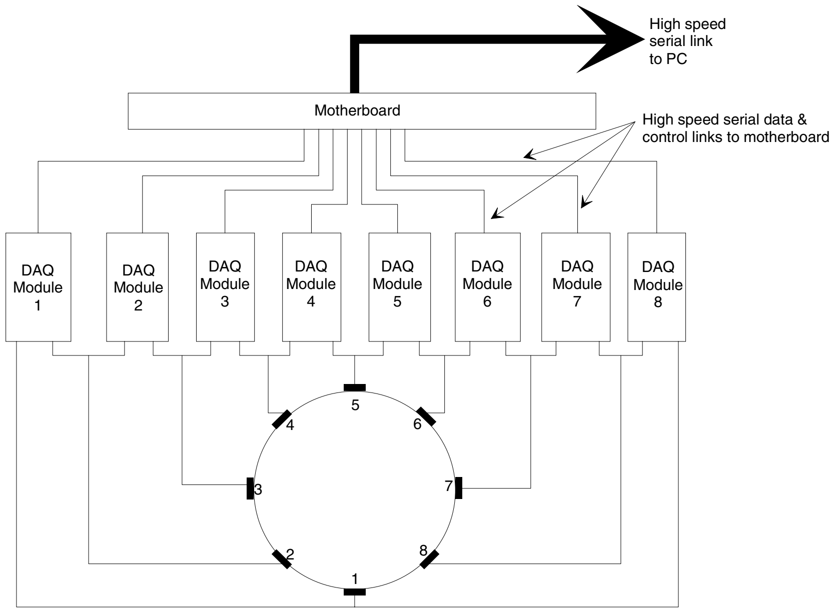

Figure 1. Block diagram of the Mk3.5 EIT data acquisition system.

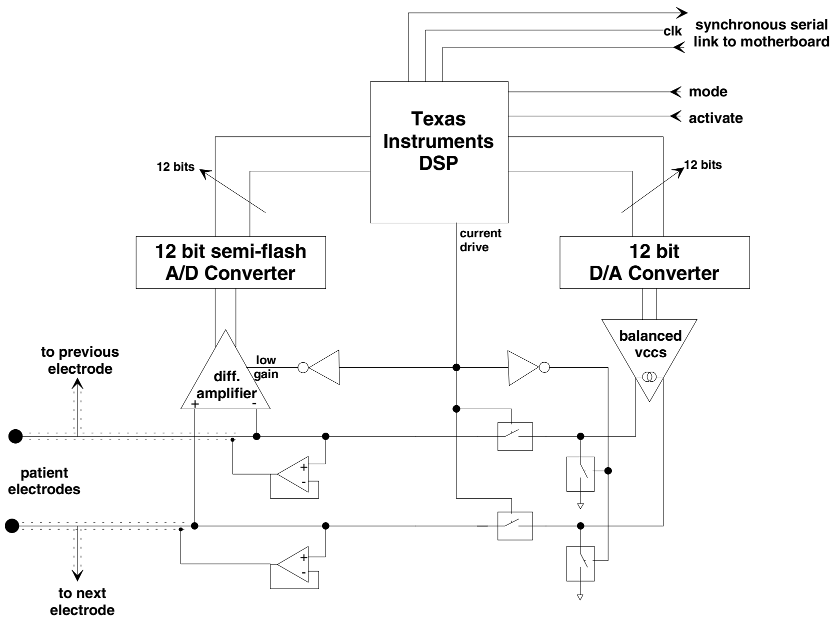

Figure 2. Block diagram of the data acquisition modules for the Mk3.5 EIT data acquisition system.

output to earth. All analogue signals in both the voltage measurement circuit and the current drive circuit are differential to minimize common mode noise.

Within the Mk3a system, the eight frequencies were delivered serially in order to make the multifrequency measurements. This approach becomes impracticable once the number of frequencies reaches 30 due to the time required to make the measurements. Demodulation in the Mk3.5 system uses an FFT algorithm. The 30 frequencies have been divided into three groups of ten. The measurement length for each of these groups of frequencies is different and is set so that each frequency within the group has an integral number of cycles to preclude the need for windowing prior to the calculation of the FFT. Each frequency in the ten-frequency set has an amplitude of 282 μA peak to peak. Taken together, the ten frequencies have a total amplitude of 300 μA rms. This is within the limits set by IEC601.

The analogue outputs from the demodulators in the Mk3a system required a high performance analogue to digital converter interfaced to a computer in order to capture the data for image reconstruction. Since the demodulation in the Mk3.5 system is digital, a direct digital link between the data acquisition system and a computer has been implemented. We wanted an interface that could be used with either a desktop or a notebook PC. The recent advances in high speed serial communication links make these an attractive proposition. With a data acquisition speed of 25 frames s^{-1} for 30 frequencies, the serial link needs to run at a minimum of 1.6 Mbaud (1.6 Mbit s^{-1}) if 16 bit values for both the real and imaginary components of the impedance measurement are to be transferred. For communication between a desktop PC and the Mk3.5 EIT data acquisition systems we have used one of the commercially available cards which support data rates up to 15 Mbaud (15 Mbit s^{-1}) using the RS485 protocol. As yet, comparable cards are not available for notebooks computers and the Mk3.5 system will be interfaced to these using an in-house developed serial-to-parallel converter which then connects to a commercially available PCMCIA parallel interface card. The advantage of using commercially available interface cards for both the desktop and notebook computers is that the manufacturers supply drivers which interface the hardware components of the interface to the Windows operating system. To ensure that the leakage current is below that required by IEC601, the Mk3.5 EIT system is optically isolated from the PC controlling it.

3. Software support

The micro-code required to run the DSPs in the Mk3.5 data acquisition system is downloaded each time the system is started. This offers the potential of using the same hardware for different data acquisition protocols whilst also simplifying the process of providing software maintenance and upgrades. The user controls the Mk3.5 system through a program with a GUI interface that runs on the PC. The system is written in MATLAB 5.2 with the data transfer code that controls the high speed serial link written in C and compiled into a dll. All data files are written in MATLAB format so that they are accessible for additional/specialist analysis. The MathWorks, who produce MATLAB, have recently announced a compiler which is capable of compiling GUI code. This should significantly increase the execution speed of the controlling software.

4. Performance assessment

The key performance characteristic of the EIT data acquisition system is the signal to noise performance. Parallel measurements are made from all adjacent electrodes pairs for each drive combination before moving onto the next drive combination. Measurements were made on a 15 cm diameter tank filled with saline having a conductivity of 2 mS cm^{-1}. The profile of measured values averaged over all frequencies is shown in figure 3. Measurements close to the drive electrode pair will produce a higher amplitude than those further away. The results show a 32 dB dynamic range in measured value if those values where drive and receive electrodes

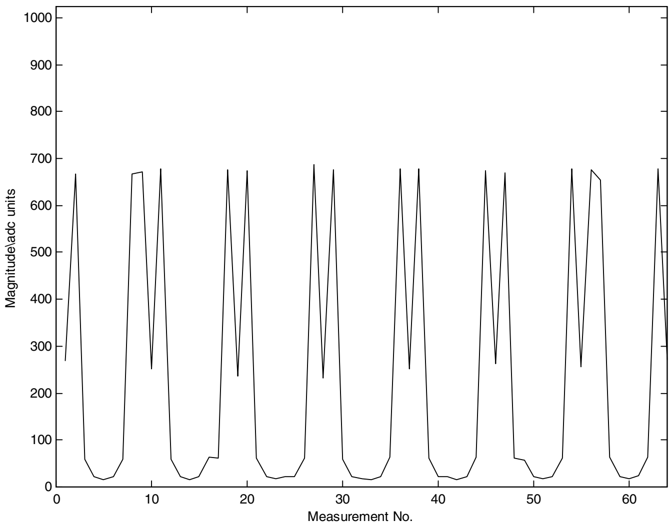

Figure 3. The profile of the magnitude of measured values in analogue to digital converter (adc) units against measurement number averaged over all frequencies. Each cycle in the profile results from the measurements using a single drive electrode pair. The drop in amplitude at the peak of the profile results from the reduction in gain of the input amplifier when the drive electrodes and receive electrodes coincide.

coincide are ignored. It has been proposed that the signal to noise measurement for an EIT system be defined as the ratio of the mean and standard deviation for a contiguous sequence of measurements (Lu 1995). Using this definition for the lowest amplitude signals gives a mean signal to noise performance of 40 dB measured across all frequencies ($N = 1500$; sd $= 1.6$ dB; range $=$ 35–43 dB). A Runs test showed the variation in signal to noise ratio to be independent of measurement frequency ($p > 0.05$).

5. Conclusions

The original specification for the Sheffield Mk3a system was that measurements could be made with a precision of 0.1% (corresponding to a signal to noise ratio of 60 dB). Measurements made on a saline filled tank with the new Mk3.5 system show that we can make measurements with a precision corresponding to 40 dB for the smallest amplitude signals. Similar measurements made with the Mk3a system obtained a signal to noise ratio corresponding to 55 dB for the smallest amplitude signals (Lu 1995). However, in the case of the Mk3.5 system, current is injected in packets of ten frequencies where the amplitude of each component within the packet is about 25 dB down on the amplitude of the single frequencies used in the Mk3a system. Thus, these results show that the measurement precision is 10 dB better in absolute terms than that obtained from the Mk3a system. The signal to noise performance of the Mk3a system decreased with increasing frequency (Lu 1995) whilst the results presented here for the Mk3.5 system show that the signal to noise performance is independent of frequency.

IEC601 requires that the auxiliary current be less than 100 μA rms for frequencies less than 1 kHz and less than 0.1 mA kHz^{-1} up to a maximum of 10 mA for frequencies above 1 kHz. The Mk3a system used a 1 mA peak-to-peak drive current. The total current drive is 300 μA rms, corresponding to a peak-to-peak current of approximately 850 μA. Thus our total applied current is 15% below what was used in the Mk3a system and is well within the limits allowed by IEC601. Clearly we could improve our signal to noise performance by increasing the current but we have deliberately adopted a conservative approach to the specification of the total applied current.

References

Bertemes-Filho P, Brown B H and Wilson A J 2000 A comparison of modified Howland circuits as current generators with current mirror type circuits *Physiol. Meas.* **21** 1–6

Brown B H, Barber D C, Leathard A D, Lu L, Wang W, Smallwood R H and Wilson A J 1994 High frequency EIT data collection and parameteric imaging *Innovation Technol. Biol. Med.* **15** 1–8

Brown B H and Seagar A D 1987 The Sheffield data collection system *Clin. Phys. Physiol. Meas.* **8** (suppl A) 91–7

Lu L 1995 Aspects of an electrical impedance tomography spectroscopy (EITS) system *PhD Thesis* University of Sheffield

Lu L and Brown B H 1994 The electrode and electronic interface in an EIT spectroscopy system *Innovation Technol. Biol. Med.* **15** (suppl 1) 98–103

Noble T J, Morice A H, Channer K S, Milnes P, Harris N D and Brown B H 1999 Monitoring patients with left ventricular failure by electrical impedance tomography *Eur. J. Heart Failure* **1** 379–84

Nopp P, Harris N D, Zhao T X and Brown B H 1997 Model of the dielectric properties of human lung tissue against frequency and air content *Med. Biol. Eng. Comput.* **35** 695–702

Smallwood R H, Hampshire A R, Brown B H, Primhak R A, Marven S and Nopp P 1999 A comparison of neonatal and adult lung impedances derived from EIT images *Physiol. Meas.* **20** 401–13