TECHNOLOGY

A new system for ambulatory pulmonary artery pressure recording

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Abstract

Objective—To develop a complete system for the measurement, recording, and analysis of ambulatory pulmonary artery pressure.

Design—The new system consists of a pulmonary artery catheter, an ambulatory recorder, and a desktop computer. Pulmonary artery pressure is measured by a micromanometer tipped catheter with an in vivo calibration system to allow correction for zero drift. This catheter is plugged into a small battery powered recorder. The recorder has two input channels, one for pressure and one for an event marker. The pressure wave is sampled 32 times/s, processed by an in built computer, compressed, and stored in semi-conductor memory. On completion of a recording, data is transferred from the ambulatory recorder through a serial data link to an Acorn Archimedes desktop computer on which further data processing, statistical analysis, graphics, and printouts can be obtained.

Results—The system has been used in 18 patients, with technically successful recording in 14, less than 15 minutes of data loss in three, and 12 hours of data loss in one.

Conclusions—A new system for ambulatory pulmonary artery monitoring has been developed and used clinically with success. It may provide new perspectives on the pathophysiology of disease as it applies to everyday life.

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The pulmonary circulation is somewhat inaccessible for haemodynamic measurements, but this should not belittle its importance in the pathophysiology of cardiovascular and pulmonary disease. As pulmonary artery pressure undergoes large changes with alterations in posture and activity, ambulatory recordings provide more information than single measurements made in a catheter laboratory.

Ambulatory pulmonary artery pressure has been used to investigate pathophysiological aspects of heart failure,¹⁻³ coronary artery

disease,⁴⁻⁶ and pulmonary hypertension.⁷ It may be used to study the effects of medical and surgical treatments. Because pulmonary artery diastolic pressure is a good estimate of left ventricular end diastolic pressure in the absence of mitral valve disease or raised pulmonary vascular resistance,^{8,9} this technique may be used to assess left ventricular function in ambulant patients.^{10,11} Ambulatory monitoring of the pulmonary artery has been used in a few cases both in our own studies and by others to guide clinical decisions.¹²

The application of ambulatory monitoring of pulmonary artery pressure has been limited because of the lack of a suitable catheter for long-term pressure recording and a data recording and analysis system specialised for pulmonary artery pressure. To make this technique practical we have developed a complete system for measurement and recording of ambulatory pulmonary artery pressure.

Patients and methods

DESCRIPTION OF NEW SYSTEM

The new system consists of a pulmonary artery catheter, an ambulatory recorder, and a desktop computer.

Catheter

Pulmonary artery pressure is measured by a 7F NIH catheter (Type 7F/B, Gaeltec Ltd, UK) designed for making continuous long term recordings. The catheter is intended for multiple use and is sterilised either in activated glutaraldehyde (Cidex, Surgikos Ltd, UK) for at least 10 hours, or ethylene oxide.

A pressure transducer is located at the tip of the catheter thus making the tip its own zero reference point and overcoming the difficulty of levelling an external transducer with the catheter tip. As zero drift is an unpredictable property of micromanometer tipped catheters during prolonged recordings, the special feature of this catheter is that it is fitted with an in vivo calibration system to allow correction for zero drift.¹³ The calibration is simple to perform: it takes 10 to 15 s and can be performed by medical or nursing staff.

During normal recording the back of the pressure transducer is in contiguity with atmospheric pressure through a luer fitting on the end of the catheter outside the patient (fig 1).

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Figure 1 Pulmonary artery catheter showing a 1 ml syringe attached to the external luer fitting as required for calibration. The stainless steel tip houses the transducer.

The catheter is calibrated during recording by injecting 0.4 ml air from a 1 ml syringe into the luer fitting. This causes a pressure of about 124 mm Hg to be applied not only to the back of the pressure transducer, but also to a second lumen which connects with the opposite side of the transducer and causes the elastomer covering the transducer at the tip of the catheter to be lifted off its surface. The high and equal pressure that now exists either side of the transducer restores it to its zero state. During calibration, pulmonary artery pressure is transiently interrupted by a calibration line (fig 2). When the syringe is removed from the luer lock, pulmonary artery pressure recording restarts automatically.

Because zero drift tends to be largest during the early part of the recording,¹³ we calibrate the catheter every 10 minutes for the first two hours, every 20 minutes for the next six hours, and one to two hourly thereafter.

Ambulatory Recorder

The catheter is plugged into a battery powered ambulatory recorder (Type 7MPR, Gaeltec Ltd, UK) which is carried by the patient on a shoulder strap. The dimensions are 188 × 137 × 67 mm and it weighs 850 g including its four size AA batteries that provide sufficient power for 24 hours of recording.

The recorder (fig 3) has three buttons that are used for setting it up at the beginning of recording and one of which is used as an event

Figure 3 The new ambulatory recorder. Note the three function buttons and the liquid crystal display on the front of the box, and the socket for the serial link to the desktop computer on the side.

button during recording. A liquid crystal screen displays the clock time and the amount of memory used. A socket on the side of the box is used to connect it to the desktop computer through a serial link and the catheter connection socket is at the rear of the box.

Figure 4 shows a schematic diagram of the ambulatory recorder. Pulmonary artery pressure can be recorded in the range -30 mm Hg to 223 mm Hg. The analogue pressure signal from the catheter is received by the analogue input board, amplified, filtered to limit the highest frequency to 16 Hz to prevent aliasing, and sampled 32 times/s. This data is processed to reduce the amount of data that has to be stored and then held in a semiconductor memory. This data reduction is important to enable long recordings to be made. Sufficient memory is provided for roughly 12 hours of recording. The memory used for storage of data has a back up power source separate from the main batteries, so that these can be changed without loss of data.

The desktop computer can be connected to the ambulatory recorder through the serial link, which for patient safety is optically isolated. This link is used for three purposes. Firstly, it is used to download recorded data for analysis and storage on magnetic disk. Secondly, it allows the desktop computer to be used to interrogate the recorder and alter its recording parameters before and during recording. Thirdly, it allows the desktop computer to display pulmonary artery pressure in real time. This real time display, which does not undergo any data compression, can be saved on disk and compared later with the compressed data stored in the recorder.

We used an Archimedes desktop computer (Acorn Computers, UK) which is multitasking and particularly suited to this type of application. A minimum of two megabytes of random access memory and a 20 megabyte hard disk are required.

The reference pressure port includes an industrial standard pressure transducer and is used for calibration purposes.

Calibration of Ambulatory Recorder

The ambulatory recorder is calibrated with the catheter immediately before catheterisation. The catheter is connected to the recorder and

Figure 2 Pulmonary artery pressure recording showing transient interruption by a reference calibration.

Figure 4 Schematic diagram of the ambulatory recording system. EPROM, electronically programmable read only memory; EEPROM, electronically erasable and programmable read only memory.

set to zero, the catheter output being stored in memory. Negative pressure is then applied simultaneously to the catheter transducer through the external luer fitting and to the recorder's own reference standard. When the reference transducer measures a pressure of -100 mm Hg, the catheter output is stored. The system is then ready to use.

Compression of Pressure Data

Data compression presents a particular problem because of the irregular nature of pulmonary artery pressure waves during large amounts of respiratory variation. One consequence of this is that the diastolic pressure of one wave may exceed the systolic pressure of the next.

Figure 5 shows pressure waves composed of equally spaced samples marked by crosses. The number of samples stored may be reduced by using only those marked by circles. If the circles are linked by straight lines, the maximum deviation of the other points from the lines is very small. The algorithm that we have used identifies such data points. The important features of this algorithm are that all recorded points lie on the original curve, and that it tends to select points of inflection so that errors in the subsequent calculation of systolic and diastolic pressure are less than 1 mm Hg. The amount of data stored is further reduced by dynamically varying the number of points recorded with the amplitude of the pressure wave. Over 24 hours this algorithm will typically store between 800 000 and 1 million data points.

As the amount of irregularity of the pulmonary artery pressure waveforms varies between patients, we have validated this algorithm for individual patients by comparing real time recordings made from non-compressed data over the serial link, with the same record compressed within the recorder and replayed later.

Data Analysis and Presentation

With a menu driven programme on the desktop computer, pressure recordings can be analysed, printed, and stored on hard or floppy disks.

Firstly, pressure recordings are corrected for zero drift. This requires the operator to validate recorded data visually and identify catheter calibrations. The computer will then automatically recalculate the whole recording by linear interpolation between calibrations. Secondly, heart rate is automatically derived by measuring the distance between pressure wave peaks. Thirdly, event markers, which appear as short vertical lines on the screen display of the pulmonary artery pressure, can be annotated with comments concerning posture and activity from a diary kept during the recording period.

Presentation graphics allow the display of any period of recording from 15 seconds to 48 hours with a summary of the average systolic, diastolic, and mean pulmonary artery pressure as well as heart rate during the specified period. The value of individual data points can be obtained with the aid of a screen cursor.

Patient Studies

We have performed ambulatory recordings with the new pulmonary artery catheter in 36 patients of whom the ambulatory recorder and analysis system described here was used in 18. The age range was 16–68 years and recordings have been made from 10 to 48 hours in duration. Twenty four patients with chronic heart failure, 10 with pulmonary hypertension, and one with breathlessness of unknown aetiology were investigated.

Patients were not given premedication. The catheter was inserted into a subclavian or internal jugular vein through an 8F sheath under local anaesthesia, and positioned in the proximal right or left pulmonary artery under fluoroscopy. The sheath was then withdrawn from the vein and the catheter sutured to the skin and covered with a sterile dressing. All catheterisations were performed by one of us (JSRG). All patients went about unrestricted activities within the confines of the hospital and underwent symptom limited exercise testing during the period of recording.

An ambulatory electrocardiogram was performed simultaneously with two bipolar leads, an anterior lead CM5, and an inferior lead. Recordings on to magnetic tape were made by a

Figure 5 Schematic representation of the data compression algorithm. See text for explanation.

Figure 6 Comparison of compressed (top panel) and non-compressed (middle panel) pulmonary artery pressure recording showing good agreement between systolic and diastolic values when the traces are superimposed (bottom panel).

frequency modulated dual channel recorder (Oxford Medilog II) to detect arrhythmias.

The results of these studies were scrutinised for complications related to catheterisation and technical problems related to the catheter and recording system. Recordings were considered technically satisfactory if no data loss was caused by the catheter or ambulatory recorder during the intended recording period (minimum 24 h). The results of the studies on patients with heart failure have been published elsewhere.²³

Figure 7 An example of display of a region of interest. The horizontal axis represents 32 min. Heart rate is displayed in the top panel and pulmonary artery pressure in the lower panel. Pulmonary artery pressure is shaded: the upper border is systolic pressure and the lower border is diastolic pressure. Event markers indicating the beginning and end of exercise appear as short vertical lines at the top of the figure. Pulmonary artery pressure rises with exercise and falls rapidly after the end of exercise.

Results

VALIDATION OF DATA COMPRESSION ALGORITHM Figure 6 shows the result of comparing a recording of non-compressed data with compressed data. This typical excerpt from a recording includes a catheter calibration. Despite data compression the pulmonary artery waveform, shown in the middle panel, is still clearly recognisable. When the non-compressed trace (top panel) is superimposed (bottom panel) on the compressed trace there is a good match and the maximum error between the two traces is < 1 mm Hg. This good match was confirmed in multiple comparisons in different patients.

PATIENT STUDIES

No complications were encountered because of catheterisation. In particular, no pneumothoraces, inadvertent arterial punctures, or local or systemic sepsis occurred. There was no clinical evidence of pulmonary embolism or infarction. Some patients had a mild ache at the site of catheter insertion, but this was always relieved by paracetamol and did not restrict their activities. One patient had the catheter removed after 10 hours because of discomfort. Continuous recording of the electrocardiogram showed no sustained disturbance of rhythm during recording of pulmonary artery pressure.

Seven catheters were used in the 36 patients. The maximum recording time for a single catheter was 240 hours. Catheters were discarded if there was any evidence of damage to the shaft or the tip.

Of the 18 patients assessed with the complete system, recordings were technically satisfactory in 14. Data loss occurred because of disconnection of the catheter from the lead connecting it to the recorder in two patients causing data loss of < 5 minutes; inadvertent calibration of the recorder after downloading data after 12 hours of recording in one patient resulted in subsequent data loss; and loss of battery power in one patient caused the loss of 15 minutes of data. None of these causes of data loss can be blamed on the recording system itself. As catheter tip impaction in a pulmonary arteriole causes distortion or loss of the pulmonary artery pressure wave, it can be concluded that no such impaction occurred. During exercise tests the pulmonary artery pressure waveform remained undistorted.

Figure 7 shows how a particular region of interest, in this example a treadmill exercise test performed by our patient with unexplained breathlessness, can be displayed. The rise in pressure occurred at the beginning of exercise and there is a rapid fall when exercise stops. Figure 8 shows a 48 hour recording in a patient with chronic heart failure. This patient was investigated as part of a single blind study in which he received placebo during the first half of the recording and xamoterol during the second half. The time the patient was in bed at night is indicated by the horizontal lines. Note how the nocturnal pressure rise on placebo was abolished while the patient was taking xamoterol.

Figure 8 A 48 hour recording of ambulatory pulmonary artery pressure in a patient with chronic heart failure. Heart rate is displayed in the top panel and pulmonary artery pressure in the lower panel. Pulmonary artery pressure is shaded: the upper border is systolic pressure, the lower border is diastolic pressure, and the measured mean is shown as a white line in between. The patient was given placebo during the first 24 hours and xamoterol during the second 24 hours. The horizontal lines indicate the time spent by the patient in bed at night.

Discussion

PULMONARY ARTERY PRESSURE MEASUREMENT

Reliable assessment of pulmonary artery pressure requires catheterisation. It was the partnership of Cournand and Richards and their coworkers who, experimenting first on animals and then on humans, perfected right heart catheterisation and used it to sample blood and measure cardiac output.¹⁴⁻¹⁶ The first recorded pressure tracings in the pulmonary artery of humans were taken in 1944 and thus opened a new era for the study of the pulmonary circulation in health and disease.¹⁷

Catheterisation of the pulmonary artery and the measurement of the oxygen saturation in blood taken from the pulmonary capillary "wedge" position was achieved by Dexter *et al* and Hellems *et al* while they were investigating congenital heart disease.¹⁸⁻²⁰ The close relation between the pressure measured in the "wedge" position, the pulmonary venous and left atrial pressure, and the pulmonary artery diastolic pressure was also reported.^{11 12 21} It was only a short time before catheterisation was used to investigate physiological problems and to guide medical treatment.²²⁻²⁴ The value of measuring pulmonary artery pressure in acutely ill patients was recognised,^{25 26} and a simple method for catheterising the pulmonary arteries without the need for fluoroscopy was described in 1970.²⁷ Fluid filled balloon flotation catheters have since remained the standard method for measurement of pressure in the pulmonary artery for research on haemodynamics. Whereas these catheters provide the simplest method of bedside monitoring, the difficulty of levelling an external pressure transducer with the catheter tip during totally unrestricted activities is impractical

AMBULATORY PULMONARY ARTERY PRESSURE MEASUREMENT

Different methods of ambulatory pulmonary artery monitoring have been reported by four other groups. Three of these have used micromanometer tipped catheters,^{1 28 29} but only one has attempted to measure zero drift, and published data on their technique is limited.²⁹ The two methods that have not measured zero drift, including one published by our own laboratory,²⁸ have not been pursued further.

The fourth group have reported a method in which pressure was measured for 10 to 25 hours with a 5F Goodale Lubin catheter with one end hole and two side holes.³⁰ The external pressure transducer was calibrated once near the beginning and once near the end of each study. The catheter was linked to a portable transducer-perfusion unit. The investigators experienced difficulties with the catheter clotting despite administration of heparin at a rate of 20 000 IU a day. Twenty per cent of the recordings were affected by artefacts that presumably originated from the fluid filled catheter.

Various recording systems have been employed. The originators of the technique used a digital recorder that averaged systolic and diastolic pressure over consecutive 30 second intervals.¹ The system was unable to record pressure waves and neither visual validation of the recorded data nor beat to beat changes in pressure could be measured. Two groups favoured a miniature tape recorder. One used their own custom written computer programme to digitise and analyse the data,^{30 31} and the other an optical writer to playback the data for visual analysis.²⁸ Our own experience of visual analysis is that it is immensely time consuming.

All of these systems were developed by research workers for their own use. Without a commercially available system ambulatory pulmonary artery pressure recording has been unable to find general application.

The principal application of long-term continuous monitoring of ambulatory pulmonary artery pressure is as a research tool to investigate the natural history and pathophysiology of cardiovascular and pulmonary disease. It may be used to investigate diurnal variation, and the effects of daily activities and specific interventions, such as exercise tests, cold pressor tests, and drug administration, on pulmonary artery pressure. We have recently used ambulatory recordings for spectral analysis.³²

THE NEW SYSTEM

The purpose of developing a new system for monitoring ambulatory pulmonary artery pressure was to make this technique generally available while overcoming the technical difficulties that have dogged previous investigators. Pressure measurement is accurate and data analysis rapid. Patients do not require anticoagulation.

The limitations of the technique are those of all invasive investigations, but in particular operators should have previous experience of

right heart catheterisation and not simply the insertion of flotation catheters. Care should be taken not to advance the catheter too far into the pulmonary artery to a position from which it could migrate and become wedged. Like most invasive investigations the patients require careful monitoring as catheter calibrations should be performed frequently. With the need for more calibrations early in the recording we perform our catheterisations in the morning. Despite the frequent need for calibrations during recording, the brevity of this procedure hardly interferes with the daily activities of patients. During recording a doctor need only be in attendance during specific manoeuvres such as exercise tests. Although our patients were limited to the confines of the hospital, we do not believe that this is strictly necessary. For the foreseeable future we shall continue to investigate patients on an inpatient basis. The ambulatory recorder has enough memory for about 12 hours of recording. Although it might be more convenient to store 24 hours of data, 24 hour recordings will not fit on to a single floppy disc for data storage, and it is assumed that investigators will want to archive their data.

In conclusion, a new system for measurement of ambulatory pulmonary artery pressure, recording and analysis has been developed with a micromanometer tipped catheter, an ambulatory digital recorder, and a desk top computer. A data compression algorithm designed to contend with large fluctuations in pulmonary artery pressure has been validated. Measurement of ambulatory pulmonary artery pressure is safe and well tolerated. It may provide new perspectives on the pathophysiology of disease as it applies to everyday life.

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