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Technical Note

A new technique for monitoring Central Venous Pressures and determining Cardiac Index in adults

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*Paper honouring the memory of Tim de Dombal**

1. Introduction

The EIMC Unit of the University of Bradford, in conjunction with the Bradford Royal Infirmary, is carrying out research using a new technique for monitoring Central Venous Pressures (CVP) and the determination of Cardiac Index (CI). There are patents pending on certain, non-disclosable aspects of the research, and much industrial interest has been developed as a result.

CVP equates with Right Atrial Pressures (RAP) and the Jugular Venous Pressure (JVP). CVP is the core of the empirical formulation used, and use is made of other physiological parameters that can be easily measured by medical and nursing staff.

Cardiac Output (CO) is defined as the amount of blood passing through the heart, measured in litres per minute, Cardiac Index (CI) is measured in litres of blood delivered to the body tissues per square metre per minute. It is the latter which is commonly used in clinical practice to assess a patient's haemostatis. The Dubois formula for calculating Body Surface Area (BSA), which is measured in square metres, is given by

$$\text{BSA } (m^2) = 0.16\sqrt{WH}, \text{ where H = height in metres, and W = weight in kg.}$$

In practice the BSA is assessed by a nomogram, this measurement being used to derive the index values of many of the haemodynamic parameters in order to calculate drug therapy regimes, etc.:

$$CI = \frac{CO}{BSA}.$$

*Professor T. de Dombal was a close colleague at our neighbouring University of Leeds.

CO and CI determinations are performed using a number of both invasive and noninvasive methods in cardio-respiratory departments within hospitals. These determination measurements come within the definition of physiological measurements, usually producing a single set of results. However, in the management of a critically ill patient who has haemodynamic complications, the above techniques are limiting because they cannot perform constant monitoring on demand, simply and quickly. This is crucial where intravenous fluid replacements and inotrophic therapy is a continuous regime.

In the early 1970s, Swan and Ganz developed the technique whereby a catheter with a connecting transducer is inserted via a peripheral vessel into the right atria, floated through the septum and up into the Pulmonary Artery (PA) [1]. This type of catheter is manufactured with single or multiple lumens, depending upon the pressure measurements to be made and recorded. The Swan–Ganz system delivers the following information:

1. Cardiac Output (CO) & Cardiac Index (CI).
2. Mean Arterial Pressure (MAP).
3. Pulmonary Arterial Pressure (PAP).
4. Pulmonary Capillary Wedge Pressure (PCWP).
5. Central Venous Pressure (CVP).
6. Heart rate per minute (Hmb).
7. Total Vascular Resistance (TVR) and Index (TVRi).
8. Stroke Volume (SV) and Indexed (SVi).
9. Systemic Vascular Resistance (SVR) and Index (SVRi).
10. Pulmonary Vascular Resistance (PVR) and Index (PVRi).
11. Left Ventricular Stroke Work (LVSW) and Index (LVSWi).
12. Right Ventricular Stroke Work (RVSW) and Index (RVSWi).
13. Left Cardiac Work (LCW) and Index (LCWi).
14. Right Cardiac Work (RCW) and Index (RCWi).
15. Body and Injectate Temperatures in degrees Celsius.

In 1995 the Intensive Therapy Unit of Bradford Royal Infirmary took on trial the Abbott Laboratories Oesophageal Doppler Method (ODMII). This was compared with the standard Swan–Ganz procedure. It requires a considerable amount of accurate positioning of the probe in the oesophagus of the patient to line up behind the aorta, in order to obtain a measurement comparative in accuracy to the Swan–Ganz thermodilution method.

All of these techniques are based upon algorithms which tend to loose accuracy when high and low cardiac outputs are encountered, or pyrexial clinical conditions exist. Ongoing scientific research continues to seek a physiologically-based formula which could circumvent the invasive techniques. The CVP catheter lies in the Superior Vena Cava (SVC) or the Right Atrium (RA) of the heart. The Swan–Ganz balloon catheter is wedged in the Pulmonary Artery (PA) in the right side of the heart. Both systems are not without complications and/or risk to the patient, though the greater risk lies with the latter [2].

Mathematical models are employed in a wide range of techniques to emulate and understand haemodynamic principles. Many of these models tend to diverge away from hydraulic processes, with the consequence that the observations made do not actually correlate with clinical practice. As mentioned earlier, in the work reported here, an empirical formula has been developed which more closely represents the physiological performance of the heart action by use of known parameters. Those parameters used in this approach, when conducting the current clinical trials, are: Haemoglobin (Hb),

Weight (kg), Height (cm), Mean Arterial Pressure (MAP/mmHg), Mean Pulmonary Arterial Pressure (MPAP/mmHg), Central Venous Pressure (CVP/mmHg), Heart rate (Hbm) and body temperature (°C). The physiological parameters register and change with clinical conditions, which in turn affect the haemostatis. Other clinical conditions, such as anaemia and pyrexia, have marked effects on the viscosity of the blood. These, in turn, affect the forces acting upon blood flow in the greater and microcirculation of the body, which has corresponding affects on various pressures. It is not generally appreciated that changes in body temperature affect the CVP [3]. The empirical formula utilised in the research described has not been published at this time, due to the laws of patenting and disclosure procedures.

2. Central Venous Pressure (CVP) monitoring

The study of blood flow (haemodynamics) is a specialised subject in cardiovascular physiology. Measuring of CVP can be traced back to the early 1800s, starting with Fick [4], as is true of the mathematical formulations of Stewart & Hamilton in the late 1800 and early 1900s. They began to be used in clinical practice to measure cardiac output and cardiac index in the 1930s. These systems were further advanced by Fegler in 1953, who combined the algorithms of both of the above systems to produce the common and well-established thermo-dilution technique currently used [5].

The manual manometry technique for the determination of CVP came into modern clinical practice in the late 1960s, when companies such as Travenol Laboratories (within the Baxter Health Care Company) produced and marketed the inverted 'T' shaped which is now used by the majority of clinicians. This has been used in the control of intravenous fluid therapy and infusions of blood and saline, etc. CVP is considered an indirect method of assessing the haemostasis of the left side of the heart. It is well understood that venous pressure has an immediate effect upon CO and CI, respectively [6]. Other haemodynamic parameters are affected by changes such as heamorrhaging, dehydration, polycythaemia and shock, for example. The normal range, using the manual method of monitoring CVP, is between 0 to 10 cm of water in the right atria of an adult. Negative readings indicate hypovolaemia, and that a transfusion may be required, whereas readings above 13.6 require some form of inotrophic therapy, etc. (see Table 1). Long-term CVP monitoring is now carried out using electronic methods such as those previously discussed, measured in mm of mercury.

There are a number of anatomical sites on the chest, such as the mid-axillary line, which are chosen as the zero reference point. Medical literature demonstrates that CVP has been thoroughly investigated from many different perspectives, such as the reference point, position of the patient, complications of the technique and the value of CVP measurement. Certainly, prior to the introduction of the

Table 1
Range of pressures (normal) at different sites

Median basilic vein	Mean	Range
Children, 3–5 years	3.4 cms	2.2–4.6 cms
5–10 years	4.3 cms	2.4–5.4 cms
Adult males	7.4 cms	3.7–10.3 cms
Adult females	6.9 cms	4.4–9.4 cms
Dorsal metacarpal veins	9.6 cms	5.2–12.5 cms
Femoral vein	8.2 cms	7.2–9.4 cms
Abdominal veins	8.5 cms	5.2–11.8 cms
Long saphenous vein	11.0 cms	8.1–14.0 cms
Dorsal digital veins of foot	12.9 cms	9.1–15.4 cms

Swan–Ganz system, CVP was only considered a means of arbitrarily assessing the volaemic status of the patient. The Swan–Ganz system has clarified the close relationship that CVP has with other haemodynamic parameters, for example, in calculating Systemic Vascular Resistance (SVR), defined by

$$\mathrm{SVR} = \frac{(\mathrm{MAP} - \mathrm{CVP}) \times 80}{\mathrm{CO}}.$$

However, there has been relatively little work undertaken, when it comes to comparing manual techniques employed for calibrating CVP using the desired anatomical zero reference point. In practice, the zero level has to be transferred from the patient's chest to the scale on the drip stand beside the patient's bed, maintaining a horizontal line to zero on the scale. None of the papers written on the subject describes how the manual system has been zeroed, nor have they compared the accuracy of any one of the following methods:

1. Mounted gunsight to the scale.
2. Telescopic spirit level mounted to the scale.
3. Tape measure or rule.
4. Piece of string.

It is this relatively simple aspect of CVP monitoring that introduces the greatest errors in recordings. The manual method of CVP monitoring is based, primarily, upon the laws of physics appertaining to the hydraulic principles of a "U" tube manometer. Correspondingly, it follows that any form of calibrating system should follow the same rationale, one example of which was patented in 1970 [7].

3. New developments

It would appear from all the research so far that the omission of this fundamental point must invalidate many of the findings and conclusions drawn by many working in the field. However, in trials, the "U" tube method has been tried and tested extensively by anaesthetists, nurses and technicians, fully familiar with the manual method of CVP manometry. Twenty six surgical cases have been monitored using the Baxter BR5 CVP giving set, in operating theatres immediately after induction. Each patient had ten measurements performed during the time they remained in the operating theatre and/or recovery room. Apart from the scrub team, each member of the medical, nursing and technical staff was "calibrated for zero", using one of the four options stated above. The operating theatre environment places greater difficulties on the team, insofar as the patients are often in predetermined positions demanded by the type of operation and the surgeon's individual requirements. Therefore, patients undergoing surgical procedures which required the Trendelumburg or Supine position were chosen. Of the 26 cases investigated, 6 cases were emergencies, the remainder being cold list cases. Overall, a total of 249 measurements were made, the mean errors per patient ranging from 18% to 78%. The catheter, usually an Intracath, was checked immediately prior to any measurement, that it was not occluded and the meniscus followed the respiratory pattern. A further 22 cases were monitored in the ITU over a range of medical conditions, and again the same checking procedures were employed. However, in many cases, X-rays confirmed the position of the catheter in the Superior Vena Carva or Right Atrium. The measurements were performed by ITU staff. However, it was not always possible to carry out 10 measurements per patient. In the 22 patients, a total of 183 measurements were made, the mean error per patient varying from 17% to 81%. This range of error is clearly unacceptable, and

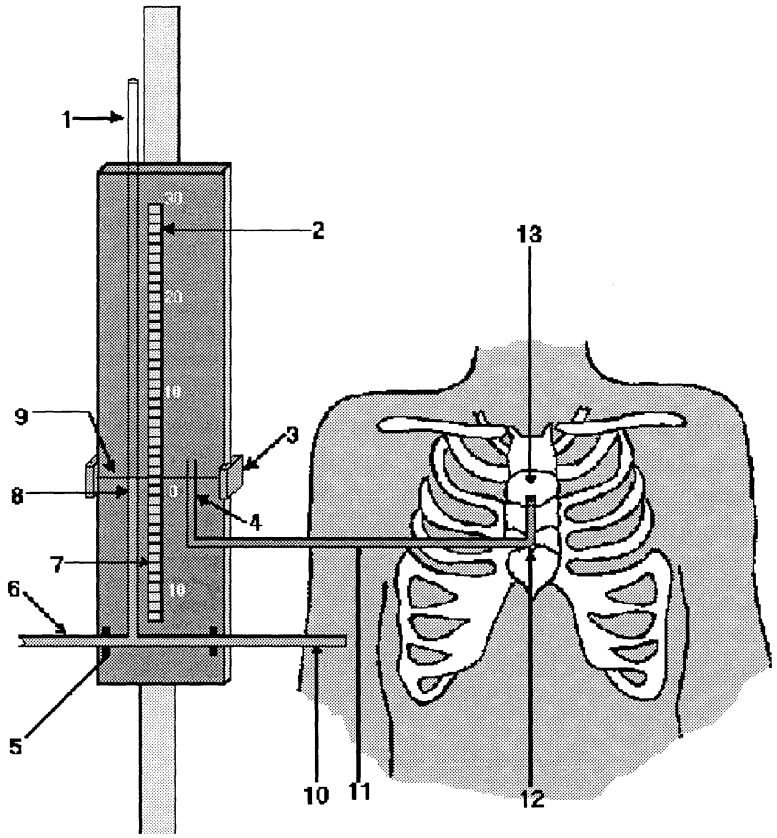

Fig. 1. Calibration of Central Venous Pressure manometer zeroing device in ward use. 1. Central Venous Pressure measuring manometer open to atmosphere. 2. Positive cm/mm scale rule. 3. Level slider in position for reading patient's Central Venous Pressure. 4. The measuring zero meniscus on the zero line of the measuring scale. 5. Three-way stopcock for control of direction of intravenous infusion fluid. 6. Intravenous infusion from the drip bottle. 7. Negative cm/mm scale. 8. Zero demarkation line on the scale. 9. Patient's Central Venous Pressure. 10. Intravenous infusion to the patient, e.g., medial casilic vein. 11. Zero manometer from measuring scale to patient's chest or desired position. 12. Position of patient zero meniscus in the zero manometer, e.g., menubriosternal junction. 13. 20 ml syringe 'B' open to atmospheric pressure.

the positional difficulties raised for anaesthetists and ODAs (Operating Theatre Department Assistants) in such cases as the Nephrectomy are virtually insurmountable.

The instrumentation used in the new procedure, designed as a part of this project, is not affected by the vagaries of eyesight. It gives audible and visual indications when the system is correctly zeroed at the chosen anatomical reference zero point. Only then is the system permitted to give a measurement. The instrumentation also provides the haemodynamic data in the conventional manner.

In the same way the Wood took the mathematics of Ohm's Law, and applied it to the cardiovascular system [8], in this research Poiseuille's Law (or, as it is more often described, the Hagen–Poiseuille Law) has been adapted:

$$Q = \frac{\Delta P \pi r^4}{8 l \beta},$$

where Q is the flow per unit of time in litres per minute, ΔP is the head of pressure in mmHg, r is the radius of the tube, l is the length of the tube, β is the viscosity of the fluid.

Other considerations are given to Newtonian and non-Newtonian fluid characteristics. These are combined with the effects of viscosity, and the way blood flows through small vessels such as the microcirculation, being directly proportional to the diameter of the vessels. This affects the shape of red cells (erythrocytes) against the vessel wall, known as the Fabraeus–Linquist Effect.

This research project has currently examined 90 patients (620 measurements) undergoing haemodynamic monitoring via the Swan–Ganz Thermodilution method.

4. Conclusions

The initial results are very encouraging, being well with the acceptable standards of error. Thus, it is now possible to postulate that haemodynamic monitoring will be carried out noninvasively. In the future, such a technique will have immense benefits to cardiac patients, as the paramedics or physicians at the scene could commence the appropriate IVI therapy immediately, and optimise the "golden hour" of survival. Because the system can be cheaper, and certainly safer than previous methods, then third world countries would be able to employ the system much more widely than currently is the case. The technique also opens up two other fields where the other techniques cannot be used without patient danger: pediatrics and veterinary medicine. These are significant market sectors where previous techniques have proved entirely inappropriate. As a result of this work, it is believed that understanding of cardiovascular physiology in the field of haemodynamics will be greatly increased.

Acknowledgements

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