A NEW OPTICAL TRANSDUCER FOR ARTERIAL PRESSURE MEASUREMENT


SUMMARY

A new optical pressure transducer system (Viggo) has been assessed and compared with a standard P10 transducer (Spectramed) using a similar 20-gauge cannula, both in vitro in terms of linearity and frequency response and in vivo using an animal model. The linearity of the transducers was comparable; the resonant frequencies were 106 Hz and 75 Hz, respectively. However, the resonant frequency of the complete Spectramed system including 150-cm tubing was 11 Hz. The frequencies at which the output amplitude error exceeded 10% of the initial amplitude for the Viggo and for P10 with and without 150-cm tubing were 32 Hz, 24 Hz and 4 Hz, respectively. The principal advantage of the new transducer is that it is sufficiently compact to be mounted directly in the cannula at the wrist, so obviating the use of connecting tubing between the transducer and the cannula.

KEY WORDS


The accuracy of clinical invasive arterial pressure monitoring is often compromised by the use of long lengths of connecting tubing, large volume transducer domes and a transmission liquid saturated with air. These factors greatly reduce the frequency at which resonance becomes significant. Appropriate damping devices may extend the range of accuracy, but are not used widely. A new disposable optical transducer (Viggo) is sufficiently compact to be mounted in the cannula hub, thus increasing the resonant frequency to a point at which accurate recording is possible even without measures to reduce the effects of resonance in the recorded signal.

Studies of the dynamic response of modern catheter–transducer systems have tended to omit the intravascular cannula from the system under test. Such studies are inapplicable to the clinical situation. In practice, a narrow gauge cannula is always used and this is one of the main sources of resistance, causing a substantial reduction in the sine wave frequency components of a signal at which errors become significant.

In this study, five prototypes of a new optical cannula–transducer system (Viggo, U.K.) were evaluated by laboratory methods and compared, in vitro and in vivo, with a conventional clinical strain gauge transducer, the P10 (Spectramed, U.K.) attached to a standard pressure monitoring kit (Spectramed, U.K.). Cannulae of similar diameter and length (4440-4, Viggo, U.K.) were used in both systems.

The optical transducer was compared with the Spectramed system in terms of linearity, frequency response and damping factor. The effect of the presence of manometer tubing on the Spectramed system was evaluated also.

MATERIALS AND METHODS

The transducer systems

Viggo group. Five were studied. The system contains a disposable element consisting of a 4440-4 20-gauge arterial cannula (Viggo, U.K.), the transducer and the fibreoptic connection to a preamplifier interface. The transducer consists of a reflective membrane 1 mm in diameter and three
optical fibres mounted in a row a short distance from the membrane (figs 1, 2). The two outer fibres are linked to photodiodes mounted in the connector and the middle fibre terminates in the connector so as to receive a light input from the preamplifier interface. Application of pressure to the transducer deflects the light reflected from the centre fibre and hence alters the proportion of light received by the two outer fibres. The preamplifier interface is designed to connect to the transducer remotely via a fibreoptic cable.

The power requirements of the Viggo preamplifier interface are designed to be run from any standard operating theatre monitor. The preamplifier also provides an oscilloscope output which was used for all measurements.

**P10 group.** Five were tested. Each comprises a P10 transducer (Spectramed, U.K.) and a standard disposable pressure monitoring kit (Spectramed, U.K.) consisting of a transducer dome with integral flush device, 150 cm of manometer tubing and a three-way tap. In all tests, the P10 transducer was connected to a 4440-4 (Viggo, U.K.) 20-gauge arterial cannula. The P10 transducer was tested in two forms, with and without manometer tubing. In this study, “Spectramed system” refers to the complete transducer system described above and “P10 transducer” refers to the transducer tested without flush device and manometer tubing. The space behind the dome membrane was flushed with saline to remove all visible bubbles before the transducer was fitted and the whole system was flushed repeatedly with saline until there was no further visible evidence of bubbles.

**Laboratory test design.** Each Viggo system was paired with a Spectramed system. Each system
was connected to one of two ports of the dome of the pressure generator. The diameter of the 20-gauge cannula was narrower than the port diameter of the dome and a rigid, saline-filled plastic extension tube was incorporated between the port and the hub of the cannula and sealed to ensure a good fit. The tip of the cannula was inside the chamber of the dome (fig. 3). Thus in both systems the same pressure was applied to the tip of the cannula and the presence of the extension tube was of no consequence to the measurement. Following assembly, the entire apparatus was flushed meticulously with saline to prevent retention of bubbles.

**Linearity and reproducibility**

Five Viggo optical and two P10 transducers were tested for linearity against a mercury manometer over the range 0–250 mm Hg. The preamplifiers used were the Viggo optical transducer interface for the Viggo system and the transducer preamplifier of a two-channel chart recorder (Lectromed Multitrace 2, Ormed Engineering U.K.) for the Spectramed system. The outputs of both preamplifiers were recorded on two channels of the chart recorder. This recorder was selected as it had been tested previously with a sine wave frequency generator and no evidence of resonance or fade was seen at frequencies less than 60 Hz. The chart recorder was considered, therefore, to have a response adequate for the studies.

**Frequency response**

The two types of transducer were compared by the pure sine wave method [1–3]. The sinusoidal pressure waveforms were produced by driving a Biotek 601A pressure transducer calibration unit (Bio-Tek Instruments Inc., Winooski, VT 05404, U.S.A.) with an electrical sine wave generated by a TG150DM transistor oscillator (Levell Electronics, U.K.). The Biotek 601A pressure transducer calibration unit is referred to as the pressure generator and the Levell TG150DM transistor oscillator is termed the frequency generator.

**Testing of the pressure waveform generator.** The sinusoidal pressure produced by the pressure generator and the frequency generator was tested against four different transducers: the Viggo optical, the P10, the disposable type TNF (Gould Medical, U.K.), and the Bell and Howell type 4-422-0001 (Devices Ltd., U.K.), connected in turn without cannula or tubing to a port of the pressure waveform generator. In the case of the Viggo optical transducer, this was detached from its cannula and sealed into a male Luer connector with epoxy resin so that the transducer membrane was flush with the tip of the fitting.

The sine frequency of the frequency generator was varied while keeping the amplitude constant. The frequency and amplitude of the outputs of the four transducers were measured using a two-channel digital oscilloscope (1602, Gould Medical, U.K.). At the same time the oscilloscope output was checked for possible deviation from a pure pressure sine wave by Fourier analysis.

The output signal showed an increase in amplitude at frequencies greater than 32 Hz, although resonance occurred at much greater frequencies for each of the four transducers—130 Hz for the Viggo optical, 125 Hz for the Spectramed P10, 100 Hz for the TNF Disposable and 120 Hz for the Bell and Howell transducer. This showed that the pressure generator itself was not resonating at a particular frequency and that the output signals were relevant to each of the transducer systems. However, the pressure generator itself may not give a constant amplitude at frequencies greater than 32 Hz in spite of a constant input amplitude, as the output amplitude increased with the increase in frequency. For this reason it was considered appropriate to apply a correction factor for frequencies greater than 32 Hz, using the ratio of the observed amplitude to the amplitude at 1.5 Hz (the initial amplitude) for subsequent tests with a cannula attached to the transducer.
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Testing of the transducer systems. The paired systems were connected to the pressure generator as described above. The frequency was varied while keeping the amplitude constant and the displayed oscilloscope output was recorded.

In addition, the step-response of each system was measured and the undamped natural frequency and degree of damping calculated according to the method of Hansen and Warburg [4] using a 1.5-Hz pressure square wave generated by the pressure waveform generator. The amplitude of the first overshoot was not used for the subsequent calculations, to avoid errors arising from possible imperfections in the square wave.

Fourier analysis of arterial pressure signal

Two greyhound dogs (mean weight 24 kg) were used for arterial pressure signal analysis. The animals had been prepared for another study and were anaesthetized with thiopentone 20 mg kg\(^{-1}\); anaesthesia was maintained with 1% \(\alpha\)-chloralose 1 ml kg\(^{-1}\) h\(^{-1}\).

A previously tested Viggo optical transducer with 20-gauge arterial cannula was used to cannulate the left femoral artery. The right femoral artery was cannulated with a similar 20-gauge arterial cannula, to which was attached a Spectramed system also tested previously. Both transducers were kept at the same level with reference to the heart.

The outputs from both transducer preamplifiers were connected both to the two-channel chart recorder and to a TM 7002 computer (Tandon, U.S.A.) running under MSDOS and a CED 1401 Data Acquisition System (Cambridge Electronic Devices, U.K.). Measurements of systolic, diastolic and pulse pressure were made from the chart recorder trace and Fourier analysis of pressure waveforms was performed by the CED 1401 controlled by the "Waterfall" programme (CED, U.K.). The accuracy of the Fourier analysis system was confirmed first by applying a pure sine wave from the frequency generator and comparing the displayed graph of amplitude against the sine wave frequency with an oscilloscope trace and, second, by repeating the comparison with a mixture of two pure sine waves.

RESULTS

Linearity

For both systems linearity over the range 0–250 mm Hg is presented in figure 4, which shows a near perfect correlation with physical calibration against a mercury manometer.

Frequency response

Frequency response of pressure generator with bare transducers. The relative increase in the amplitude of the output signal with the increase in frequency and the resonant frequency at which the amplitudes were maximal varied considerably for the four transducers. The output signal amplitude remained constant up to 32 Hz, after which it increased with the increase in frequency. Therefore a correction factor was derived, as stated in the Methods section.

Frequency response of the transducer systems. The results of the Viggo optical and the Spectramed systems, the latter with clinically used manometer tubing, are presented in figure 5. The resonant frequencies of the cannula-mounted Viggo optical transducer and the P10 transducer attached directly to a cannula were 106 Hz and 75 Hz, respectively. Increases in amplitude gain of more than 10% were observed at approximately 32 Hz and 24 Hz, respectively. However, when the P10 transducer was attached to the cannula by 150 cm of standard Spectramed manometer tubing, greater than 10% increase in gain occurred at only 4 Hz and its resonant frequency was found to be only 11 Hz (fig. 5). The mean amplitude gain ratio with increase in the applied frequency, for five sets each of the cannula-mounted Viggo optical transducer and the Spectramed system with tubing, showed a gain of more than 10% (i.e. 10% error) at a significantly

Fig. 4. Linearity testing of transducers. Comparison of output signals of Viggo (○) and P10 (●) against a mercury column.
greater frequency with the Viggo optical (32 Hz) than with the Spectramed (4 Hz). The degree of damping for both transducers without manometer tubing and Spectramed system with tubing was 0.16 (Viggo), 0.24 (P10) and 0.42 by the step-response method, and the resonant frequencies were similar to those obtained by the sine wave method.

Fourier analysis of the dog femoral artery waveform showed that more than 99% of the energy of the pressure waveform was contained in the frequencies up to the 10th harmonic (fig. 6).

Even when the heart rate was 180 beat min\(^{-1}\) (i.e. a fundamental frequency of 3 Hz) no harmonic components were detectable at frequencies greater than the 10th harmonic (30 Hz) for both systems.

**DISCUSSION**

The results show good correlation between the two transducers in terms of linearity on static testing.

Testing of the frequency response in the clinical range was performed by the sine wave method because this method does not depend on a perfect theoretical single degree of freedom system for its interpretation [4, 5]. However, as the resonant frequency of the Viggo system was 106 Hz and as we were unable to show a flat response for the pressure waveform generator itself beyond 32 Hz when the four transducers were connected directly to the pressure generator chamber, the step-response method, rather than the measured amplitude at sine wave frequencies, was used to calculate the undamped natural frequency and degree of damping. The results of in vitro dynamic testing indicate that the presence of the saline-filled dome and tubing in the complete Spectramed system degraded its dynamic response by decreasing the resonant frequency from 75 Hz to 11 Hz and by decreasing the frequency at which 10% increase in gain occurred from 24 Hz to 3 Hz (fig. 5). Under such conditions, accurate recording of systolic and pulse pressures would not be likely. Fourier analysis of the pressure waveform in the
dog shows the importance of frequencies up to 20 Hz at a heart rate of 120 beat min⁻¹. Even in the resting animal with a heart rate of 120 beat min⁻¹, most of the energy is represented by frequencies greater than 4.5 Hz because resonance starts to occur. The Spectramed system would be expected to over-read by at least 20%.

The frequency response of clinical catheter-transducer systems has been reported for test apparatus which has not included a cannula [6, 7] or connecting tubing [8]. This grossly underestimates the resonance effects produced by the complete system in the routine clinical setting. Such effects are produced by the compliance of the transducer membrane, which should be small for a well-designed transducer, but are caused predominantly by the compliance of the tubing and the compressibility of the fluid and any bubbles it may contain. However much the system is flushed, there are always microscopic bubbles in the fluid unless this has first been de-gassed by boiling [1, 8–11]. This is probably impractical clinically. As a general rule, the larger the volume of the tubing, the less is the natural frequency of the system. In contrast, the narrower the tubing, the greater is the damping, and this also limits the frequency response [4, 5].

Adequate frequency characteristics of devices for measuring arterial pressure have been described by Gardner [6]. Based on comparisons with clinical recordings, Gardner suggested that an adequate dynamic response for all pressure waveforms was possible with a natural frequency as little as 13 Hz, provided damping was adjusted carefully. However, the Spectramed P10 system, which is one of the best known non-disposable systems, has a resonant frequency of only 11 Hz when connected with 150 cm of manometer tubing.

If optimal damping of the Spectramed system were achieved by the use of a suitable adjustable parallel-damping device [9] (whether a hydraulic device or its electronic equivalent) in conjunction with routine step-response testing to check adjustment, its response could be made adequate for clinical purposes unless the arterial waveform was unusually demanding. However, a fixed damping device may well not be satisfactory in practice, as there is great variation between individual systems and the amount of gas present in the system varies during use.

To eliminate these problems under all clinical circumstances, it is logical to remove the tubing and keep the transducer dome as small as possible. Unfortunately, the commonest site for the placement of an arterial cannula is the radial artery at the wrist. A bulky, rigid device attached to the cannula at this site is cumbersome and may cause kinking or even withdrawal of the cannula during unwarranted movement and even a short length of compliant and flexible connecting tubing, which is sometimes used to overcome the problem of fixation and movement, may nullify the potential improvement in frequency response.

The Viggo optical system uses a sensing element only 1.4 mm in diameter and 4 mm in length, mounted on a flexible fiberoptic cable. In its present form it is supplied mounted in the side of the slightly extended hub of a standard Viggo arterial cannula which incorporates a miniature tap. It is therefore practicable for use without even a short length of saline-filled tubing at the wrist. There is, nevertheless, a problem with mounting the transducer system at the wrist: the zero reference point changes with the level of the wrist. Therefore, it may be necessary to incorporate an offset adjustment on the pressure channel amplifier in which the user could enter the vertical distance between the transducer and mid heart level. Also, the highly undamped characteristics of the Viggo transducer may require some form of fixed damping device to improve further its dynamic performance.

REFERENCES

