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Pressure Waveform Generator for Replicating Arterial Pressure Waveforms

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ABSTRACT

A device for replicating arterial pressure waveforms has been developed at the National Physical Laboratory and is being used to investigate the performance of Continuous Cardiac Output instruments. The device uses a low-force (10 N) electro-dynamic shaker to drive a piston that acts on a water-filled cavity and thereby generates the required pressure changes. Arterial pressure waveforms have been recorded from patients within the Intensive Care Unit at Guy's and St Thomas' NHS Foundation Trust; these digitized waveforms have been reproduced by the pressure generator with a typical RMS error of approximately 0.2 mmHg (the pressures of the tested waveforms ranged from 40 mmHg to 175 mmHg).

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Approved on behalf of NPLML by Dr Andrew Lewis, Science Area Leader,
Dimensional Metrology

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1 INTRODUCTION

The National Physical Laboratory (NPL) has developed a Pressure Waveform Generator (PWG) that is capable of reproducing, in a water-filled chamber, arterial pressure waveforms from digitized recordings. Such waveforms, recorded from patients who are suffering from a range of clinical conditions in the Intensive Care Unit (ICU) at Guy's and St. Thomas' NHS Foundation Trust (GSTT), are being used with the PWG to evaluate the performance of different Continuous Cardiac Output (CCO) instruments.

2 PRESSURE WAVEFORM GENERATOR

Arterial pressure waveforms have been sampled (16-bit, 2 kSs^{-1}) and recorded from patients in the ICU at GSTT. These waveforms are reproduced by the PWG in the manner now described. Figure 1 shows the main components of the PWG. The pressure in the water-filled chamber is controlled by a computer using the analogue voltage output of a National Instruments RIO Card (type NI PCI-7830R). This voltage is converted to a current by the voltage-to-current converter (Figure 2) and the current is used to control the force exerted on a piston by the drive-coil of the electro-dynamic shaker (Bruel & Kjaer, type 4810). An aluminium shaft incorporating a section of wire rope connects the shaker 'table' to the piston which is in direct contact with the water in the chamber. The force applied to the piston will change the pressure within the chamber. This pressure is largely proportional to the voltage generated by the computer and is measured with a GE Sensing device (type PMP4010, identified as P_C in Figure 1) which has a 350 mbar gauge range. The voltage output from the pressure sensor is connected to an analogue voltage input of the RIO card via a 400 Hz low-pass RC filter. LabVIEW software is used to operate the PWG using a digital servo which utilises a proportional-integral-derivative (PID) algorithm to compare the instantaneous output from P_C with that of the recorded patient (input) waveform and then, dependent on the error, modify the voltage driving the shaker unit. This closed-loop circuit is able to overcome residual deficiencies in the system and thereby maintain good agreement between the generated and input waveforms, as demonstrated in Section 3.

Crucial to the performance of the PWG is the linear and angular alignment of the movement axes of the shaker and piston; any significant misalignment causes excessive friction between the piston and cylinder which cannot be compensated by the closed-loop circuit and gives rise to unacceptable distortion of the generated waveform. There are two mechanisms for achieving good alignment: 1) the shaker is mounted on a mechanical stage that provides both horizontal and vertical translation, and also tilt about both horizontal axes; 2) a section of the shaft connecting the shaker and piston is constructed from wire rope (shown in Figure 3) which provides enough compliance in the horizontal plane to accommodate any remaining misalignment between the axes. The wire rope is effectively rigid along its length as any compliance in this direction would make it difficult for the closed-loop circuit to maintain adequate control of the generated pressure.

The PWG was originally designed to operate with a small air gap of a few millimetres directly below the piston. The rationale for the air gap was to provide a means of determining the frequency response (*i.e.* dynamic calibration) of the pressure sensor P_C by measuring the piston displacement in the air. However, the relatively high compressibility of the air, which would make this approach feasible, also meant the control system was unable to maintain adequate control of the generated pressure. Consequently, the system is now used with the chamber completely filled with water and the piston acting directly on the water.

A pressure sensor of the type used by hospitals (*e.g.* an Edwards FloTrac or TruWave device) can be connected to the chamber as shown in Figure 1 and labelled P_H (multiple sensors can easily be accommodated by adding extra ports).

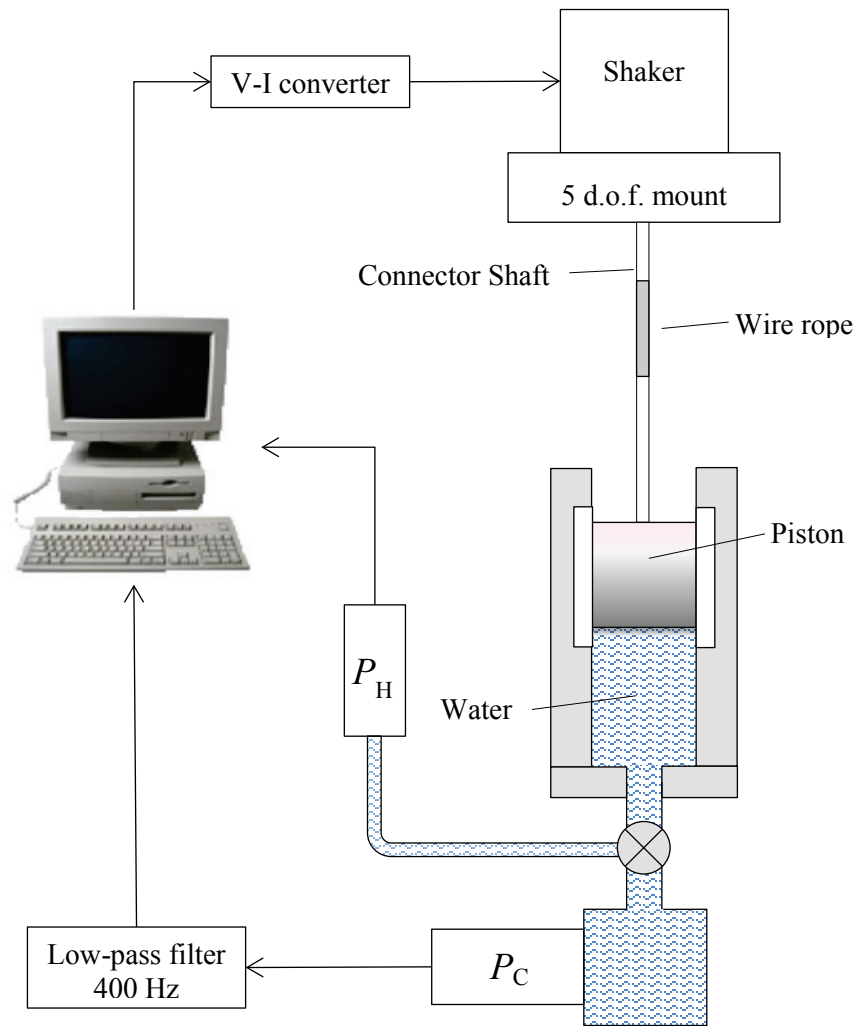


Figure 1 Components of the Pressure Waveform Generator.

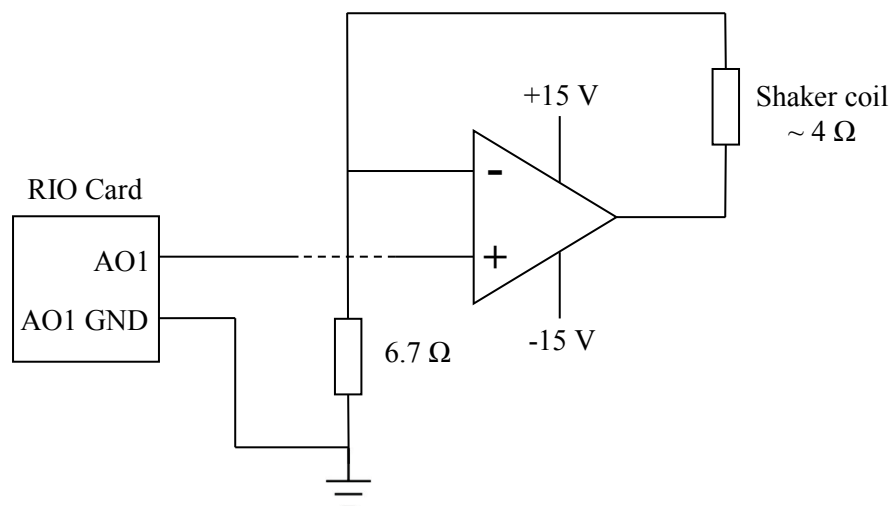


Figure 2 Voltage-to-current converter.



Figure 3 Wire rope and clamping mechanism.

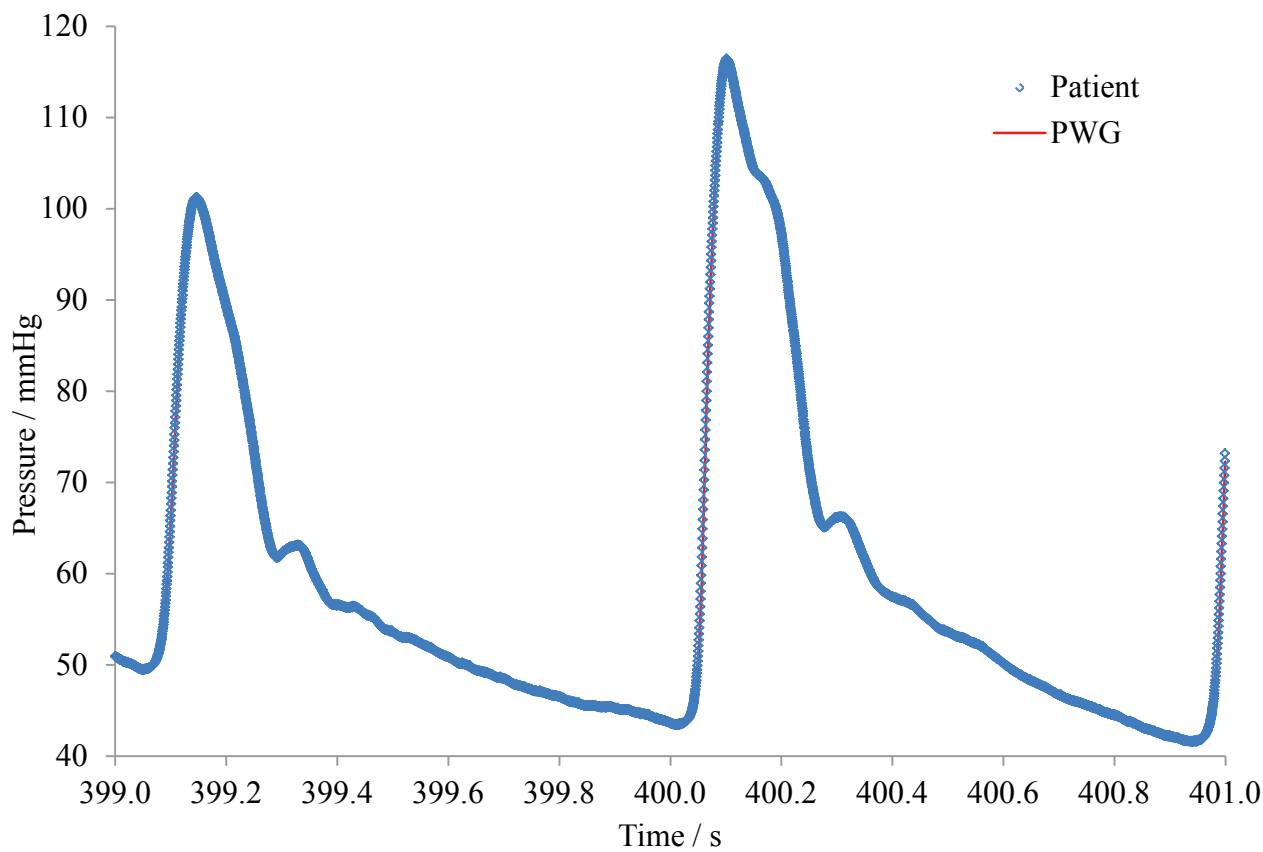


Figure 4 Part of a patient waveform overlaid with that generated by the PWG.

3 PRESSURE GENERATION

3.1 WAVEFORM DURATION AND FIDELITY

As part of the operating requirements, the device must be able to reproduce patient arterial pressure waveforms continuously for at least 1 hour. This duration enables the drift or ‘trend’ of the output of CCO instruments to be determined. The patient waveforms all have pressures exceeding that of the atmosphere and therefore water will leak past the piston during operation; this leak-rate will determine how long the PWG is able to generate a continuous waveform before refilling is required. Once correctly set up, the PWG is capable of continuously reproducing a waveform for an hour or more. The maximum duration depends on at least two factors: 1) the amplitude of the patient waveform; and 2) the accuracy of the alignment of the shaker’s movement axis with that of the piston.

Figure 4 is a plot showing a patient waveform recorded at GSTT overlaid with the waveform generated by the PWG and recorded from the control pressure sensor P_C . The full duration of the generated waveform was approximately 950 s and the data presented in the plot relates to the period from 399 s to 401 s. Figure 5 shows the same data but also includes the error (e_t) between the patient (p_t) and generated (g_t) waveform samples (*i.e.* $e_t = p_t - g_t$). The RMS value of error for the full duration of the waveform was 0.14 mmHg. When the error is expressed as a percentage of the pressure (*i.e.* percentage error = $100 \times e_t / p_t$) then its RMS value was 0.39 % (the waveform pressures have values ranging from 40 mmHg to 170 mmHg). The maximum error was 1.95 mmHg which corresponds to a percentage error of 4.1 %.

From Figure 5 we can see that the error at a given instant is dependent on the waveform profile and that the largest errors occur when the required pressure value stops decreasing and then rapidly increases - the generated pressures initially lag behind the demand until they catch up. As a turning-point in the pressure is generated by the piston coming to a halt and then reversing its direction of travel, this observed behaviour can be explained by the control circuit having to overcome significant static frictional forces that oppose the force driving the piston.

3.2 UNCERTAINTY

The PWG does not generate pressures that are traceable to the International System of Units (SI). Instead, its function is to be able to produce pressures that, when measured with a suitable device (*e.g.* a hospital pressure sensor), are a faithful reproduction of a recorded waveform (*e.g.* an arterial waveform recorded from a patient). As such, the uncertainties presented in this report apply to the PWG’s ability to reproduce a given waveform.

Figure 6 is a histogram of the errors generated when reproducing the patient waveform discussed in Section 3.1. An estimate of the uncertainty in the generated waveform can be calculated from the histogram by determining the limits which cover 95 % of the generated pressures taken about an error of 0.0 mmHg. So, for the example given here:

$$\text{Generated Waveform} = \text{Patient Waveform} \pm 0.56 \text{ mmHg}$$

It should be noted that a standard statement of uncertainty cannot be specified in advance to the performance of the PWG as this will depend on 1) the ‘on-the-day’ alignment of the shaker and piston axes and 2) the profile of the waveform to be generated. The uncertainty must therefore be estimated for each generated waveform.

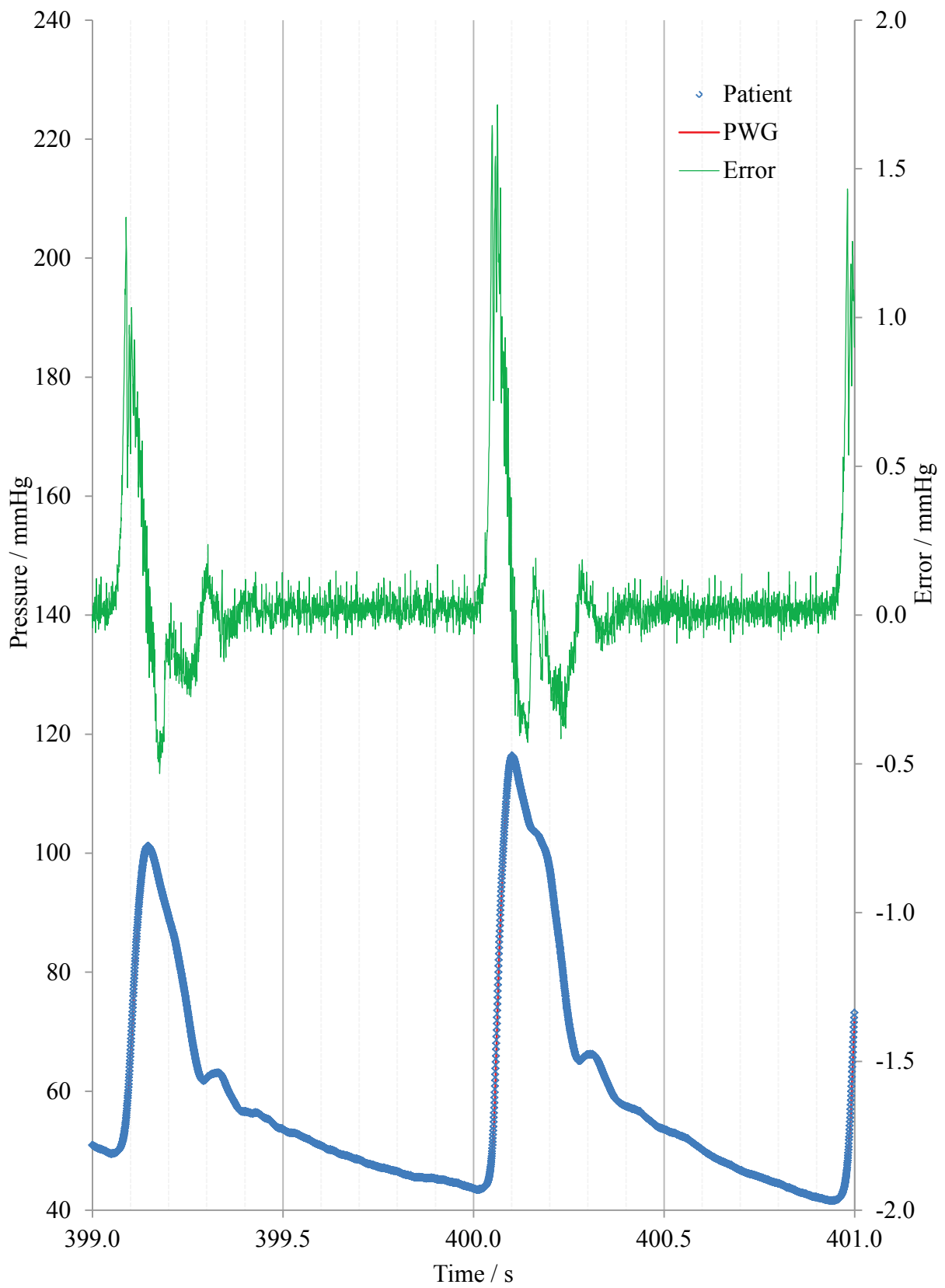


Figure 5 The error now included with the patient and generated waveforms.

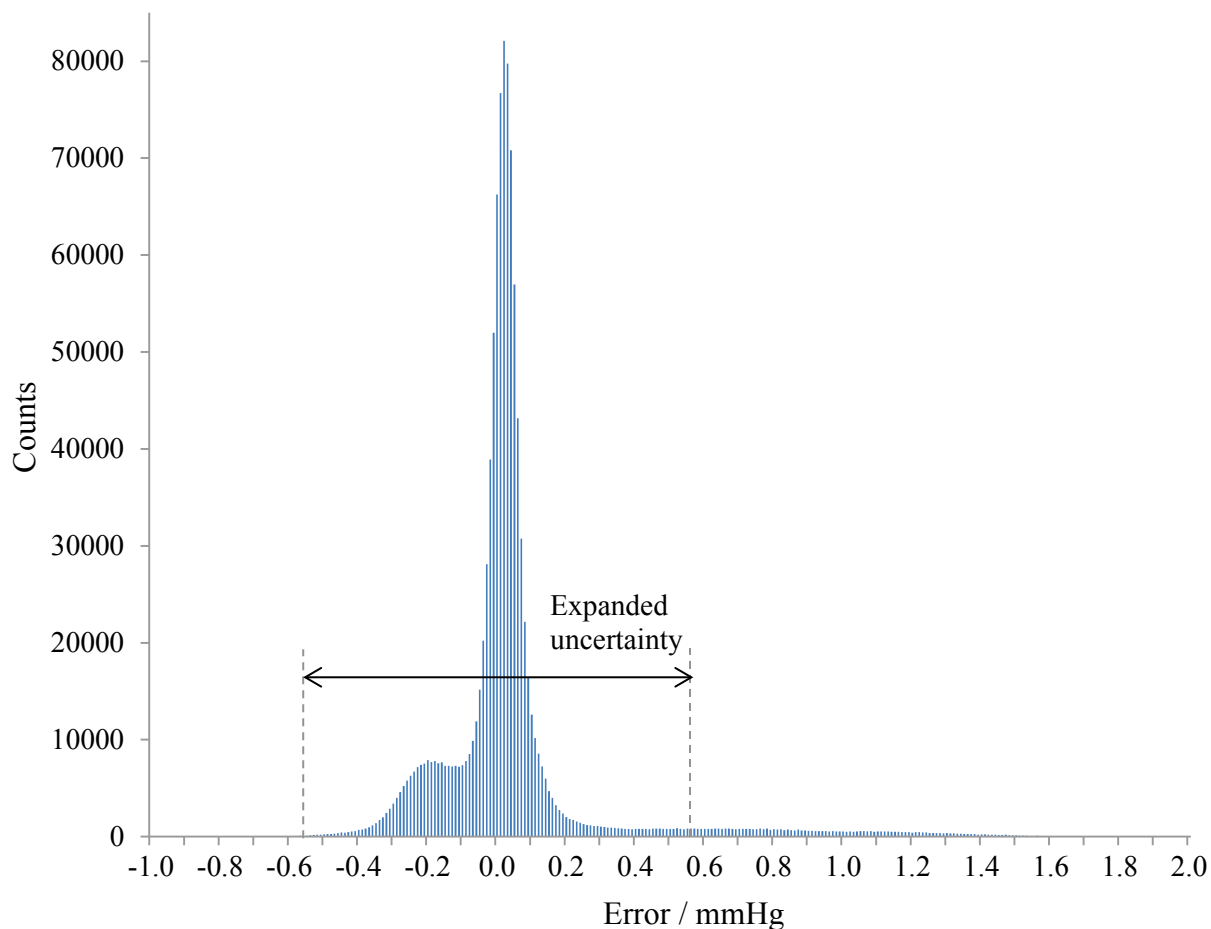


Figure 6 A histogram of the error shows its non-uniform distribution.

4 CONCLUSIONS

NPL has built a Pressure Waveform Generator that is capable of reproducing, in a water-filled chamber, recorded arterial pressure waveforms. The fidelity of these generated waveforms has been shown to be very good with typical RMS error values of approximately 0.2 mmHg. Furthermore, the PWG is able to generate a continuous waveform for a period exceeding 1 hour. A pressure sensor of the type used by hospitals can be connected to the water-filled chamber and its output connected to CCO instruments. In this manner, the PWG is being used to evaluate the performance of different CCO monitors when subjected to pressure waveforms derived from patients suffering from a wide range of clinical conditions.

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