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Design, confection and calibration of a flow phantom with ultrasound applications

DP Oliveira¹, WCA Pereira², RPB Costa-Félix¹,a
¹ Laboratory of Ultrasound, Inmetro, Duque de Caxias, RJ, Brazil
² Ultrasound Laboratory, COPPE-UFRJ, Rio de Janeiro, RJ, Brazil

E-mail: debora_poliveira@hotmail.com

Abstract. Ultrasound phantoms are standardized biological tissue models with well-defined acoustic properties, dimensions, and internal characteristics. Despite blood flow is a relevant factor in heat transfer in biological tissues, flow phantoms applied to therapeutic ultrasound are scarce in the literature. Therefore, this work aims to develop an ultrasound flow phantom capable of generating continuous flow with values similar to brachial artery. The phantom was made of agar based material with a tube of 4.6 mm of inner diameter inserted within, including a region of interest. The flow was produced with a linear flow propulsion system, generated by a peristaltic pump and an equalizing pressure system of milimetric graduated columns. The phantom was capable of generating adjustable and continuous flow rate. The flow rate generated by flow phantom propulsion system range between $20.85 \pm 0.95$ m³.s⁻¹ and $118.36 \pm 1.18$ m³.s⁻¹. Those values are similar to flow rate values in the brachial artery. We expect to apply the ultrasonic flow phantom to therapeutic ultrasound safety evaluation in testing houses.

1. Introduction
Phantoms are standardized biological tissue models with well-defined properties, developed to behaviour as a simplified biological organism. In order to better mimetize biological system for ultrasound phantom some acoustic properties as speed of sound and acoustic attenuation equivalent to human tissues are required.

Ultrasound phantoms are intended to many applications, such as calibrating ultrasound diagnostic and therapeutic equipment, training medical personnel in ultrasound imaging, evaluating heating generated by ultrasonic transducers, and others.

The bioheat transfer equation is a model of heat exchange in biological tissues [1]. The bioheat equation describes that the temperature elevation in a biological tissue is due to the energy offered by the source of heat and metabolism, and heat dissipation due to blood flow. Ultrasonic phantoms that mimic blood flow applied to diathermy or hyperthermia assays were not found in the literature. In spite of being an important variable on tissues heat exchange with direct influence on heating pattern, blood flow has been actually neglected on experimental models to assess therapeutic ultrasound safety. This work reports the confection and calibration of an ultrasound flow phantom with continuous flow range values and dimensions compatible with brachial artery [2-3].

E-mail: debora_poliveira@hotmail.com

¹ rpfelix@inmetro.gov.br.
2. Metodology
The flow phantom (figure 1) consists of three elements: a pressurization system, the fluid (1000 mL of degassed distilled water), and a region of interest (ROI).

The components of the phantom are: (a) A peristaltic pump (102FD / R , Watson Marlow Bredel, USA) activated by a continuous electric motor (6215A Power Supply, HP, USA), the pump is connected with a silicone tube (a-b) of 5.1 mm inner diameter and 550 mm length; (b) Two cylindrical reservoirs (B1 and B2) with connections located at their bases, which are plastic beakers of 1000 ml with 64.5 mm inner diameter and 420 mm height; (c) Two silicone interconnecting tubes (c-d, e-f) with 7 mm internal diameter and 600 mm length; and (d) Fluid.

The ROI consists of an acrylic frame (160 mm × 160mm × 52 mm) filled with agar based tissue mimic material [4] with a thin walled (0.2 mm) silicone duct of 4.6 mm internal diameter compatible with brachial artery inner diameter. The ROI is connected to rest of pressurization system with two connectors of 3.9 mm inner diameter with internal angle of approximately 6° minimizing turbulence ensuring a smooth flow transition between interne and external ROI ducts. Thermal sensors were positioned in the connectors and on surface of ROI.

The peristaltic pump flow rate (m³·s⁻¹) was calculated weighing the mass of water in grams ejected by the pumped in one minute with a calibrated balance model Adventure AR 3130 (Ohaus, Parsippany, New Jersey, USA), with expanded uncertainty (p = 0.95) of 0.001g. The elapsed time was measured using a digital timer with a resolution of ± 0.05 seconds.

The pressure (Pa) in the flow phantom pressure system was obtained by measuring the level difference between the fluids of columns B1 and B2 using millimeter scales fixed to the columns with 1 mm resolution and a stainless steel ruler of 300 mm with 0.5 mm resolution calibrated with an expanded uncertainty of 0.03 mm (p = 0.95).

All experiments were repeated five times in repeatability conditions for each voltage of the pump power supply (3V to 12V) monitored with a digital multimeter model 33410A (Agilent Technologies, Santa Clara-CA, USA) calibrated with U = 0.04 V (p = 0.95). The ambient temperature was monitored with an analogic thermometer (Thermo Shneider, Wertheim, Germany) calibrated with U = 0.02°C (p = 0.95).

The measurement uncertainties for all experimental setup were assessed according to JCGM 100:2008 [5].
The following sources of uncertainty were considered in measuring the driven voltage to the peristaltic pump electric motor power supply: type A (standard deviation between the five repetitions of the experiment); type B was obtained from the digital multimeter calibration certificate (0.04 V).

Furthermore, the following sources of uncertainty were considered for the flow rate within the phantom: type A (standard deviation of the mean); type B evaluation of the mass uncertainty was obtained from the balance calibration certificate (0.001 g) and type B uncertainty was obtained by evaluation of the time the chronometer resolution (0.05 s).

The following sources of uncertainty were considered in measuring the pressure in the phantom: type A (standard deviation of the mean) for the level difference between the fluids on reservoirs B1 and B2 in the five repetitions of the experiment; type B evaluation of the the level difference between the fluids on reservoirs B1 and B2 uncertainty was obtained from the ruler calibration certificate (0.03 mm).

The expanded uncertainty (U) of pressure, flow rate, resistance and tension were calculated by multiplying the combined standard uncertainty (uc) and the coverage factor (k) based on a t-distribution for a level of confidence interval of 95%.

The Reynolds number (Re), the theoretical system pressure (∆P) and theoretical system resistance (Rc and Ra) in ROI were expressed by equations (1) to (4) [6]. The theoretical fluid dynamics properties in the phantom were calculated to better evaluate fluid behavior in ROI.

\[ Re = \frac{4 \cdot \rho \cdot Q}{\mu \cdot \pi \cdot D}, \]  
\[ \Delta P = Q^2 \cdot (R_c + R_a), \]  
\[ R_c = \frac{128 \cdot \mu \cdot L}{\pi \cdot D^2 \cdot Q}, \]  
\[ R_a = \frac{K \cdot 8 \cdot \rho}{\pi^2 \cdot D^4}, \]

In which \( \rho \) is density, \( Q \) is the flow rate, \( \mu \) is the fluid dynamic viscosity and \( D \) is the tube internal diameter.

In which the difference in pressure (\( \Delta P \)) between the reservoirs (B1 and B2) is equal to the flow rate squared (\( Q^2 \)) multiplied by the circuit intrinsic resistance (\( R \)), which can be defined as the resulting resistance from the continuous straight pipe (\( R_c \)) and the accessories (\( R_a \)) that connect them.

In the laminar flow case, \( R_c \) can be calculated by equation (3) which expresses the pressure fall in a horizontal tube.

In which \( \mu \) is the fluid dynamic viscosity, \( L \) is the tube length, \( Q \) is the flow rate, and \( D \) is the tube internal diameter.

In which \( K \) is the dimensionless loss coefficient, \( \rho \) is density, and \( D \) is the tube internal diameter.

The experimental flow resistance value (\( R_c + R_a \)) was calculated using equation (2). The measurement uncertainty was estimated in accordance with JCGM 100:2008 [5] and the following sources of uncertainty were considered in measuring the resistance in the phantom: the standard uncertainty of experimental pressure due to the level difference between the fluids of columns B1 and
B2; type B evaluation of the mass uncertainty was obtained from the balance calibration certificate (0.001 g) and type B uncertainty was obtained by evaluation of the time the chronometer resolution (0.05 s).

The theoretical fluid dynamics properties calculations were done assuming a K of 0.35[6], a density (ρ) of 1000 kg.m⁻³ and a dynamic viscosity (μ) of 10⁻³ kg.(m.s)⁻¹ for the fluid (deionized water).

3. Results

The flow phantom was calibrated by means of the voltage (V) applied to the peristaltic pump motor, flow rate (m³.s⁻¹) and pressure (Pa) with their respective uncertainties as shown in table 1. Furthermore, experimental flow resistance (Pa.s².m⁻⁶) and theoretical values of flow resistance (Pa.s².m⁻⁶) with respective uncertainty were also calculated as seen in table 2.

Table 1. Experimental values of average flow rate (ml.min⁻¹) with expanded uncertainty, average peristaltic pump tension (V) with expanded uncertainty and average pressure (Pa) with expanded uncertainty.

| Nominal tension (V) | Voltage (V) | uᵣ (V) | k | Flow rate (10⁻⁷·m³.s⁻¹) | uₑ (10⁻⁷·m³.s⁻¹) | k | Pressure (Pa) | uₑ (Pa) | k |
|---------------------|-------------|--------|---|------------------------|------------------|---|----------------|---------|---|
| 12                  | 12.017 (±0.207) | 0.103  | 2 | 19.727 (±3.883) | 1.942       | 2 | 201.037 (±6.053) | 2.402  | 2 |
| 11                  | 11.000 (±0.204) | 0.102  | 2 | 17.841 (±3.538) | 1.769       | 2 | 172.597 (±3.010) | 1.387  | 2 |
| 10                  | 10.013 (±0.064) | 0.031  | 2 | 15.851 (±3.156) | 1.578       | 2 | 158.868 (±5.526) | 2.193  | 2 |
| 09                  | 8.980 (±0.077) | 0.036  | 2 | 14.092 (±2.784) | 1.392       | 2 | 139.255 (±5.526) | 2.193  | 2 |
| 08                  | 7.977 (±0.033) | 0.016  | 2 | 12.353 (±2.452) | 1.226       | 2 | 119.641 (±5.526) | 2.193  | 2 |
| 07                  | 7.003 (±0.033) | 0.016  | 2 | 10.549 (±2.098) | 1.049       | 2 | 104.931 (±3.489) | 1.551  | 2 |
| 06                  | 5.977 (±0.031) | 0.015  | 2 | 8.907 (±1.781)  | 0.890       | 2 | 95.125 (±3.489)  | 1.551  | 2 |
| 05                  | 4.970 (±0.029) | 0.014  | 2 | 7.154 (±1.449)  | 0.725       | 2 | 74.531 (±6.876)  | 2.595  | 3 |
| 04                  | 3.993 (±0.024) | 0.012  | 2 | 5.404 (±1.087)  | 0.543       | 2 | 57.859 (±3.010)  | 1.387  | 2 |
| 03                  | 2.963 (±0.027) | 0.013  | 2 | 3.475 (±0.698)  | 0.349       | 2 | 42.169 (±3.489)  | 1.551  | 2 |

Table 2. Experimental average resistance (Pa.s².m⁻⁶) with expanded uncertainty and theoretical resistance – Ra and Rc (Pa.s².m⁻⁶).

| Nominal Voltage (V) | Experimental Resistance - (Ra + Rc) (10⁻¹⁴·Pa·m⁻⁶·s²) | uₑ (10⁻¹⁴·Pa·m⁻⁶·s²) | k | Theoretical Resistance - Ra (10⁺¹³·Pa·m⁻⁶·s²) | uₑ (10⁺¹³·Pa·m⁻⁶·s²) | k | Theoretical Resistance - Rc (Pa·m⁻⁶·s²) |
|---------------------|-----------------------------------------------------|---------------------|---|-----------------------------------------------|---------------------|---|--------------------------|
| 12                  | 0.517 (±0.018)                                      | 0.006               | 3 | 0.672                                          | 2.580·10⁻⁶           |   |
| 11                  | 0.542 (±0.012)                                      | 0.004               | 3 | 0.743                                          | 2.580·10⁻⁶           |   |
| 10                  | 0.632 (±0.025)                                      | 0.009               | 3 | 0.836                                          | 2.580·10⁻⁶           |   |
| 09                  | 0.701 (±0.032)                                      | 0.011               | 3 | 0.941                                          | 2.580·10⁻⁶           |   |
| 08                  | 0.784 (±0.041)                                      | 0.014               | 3 | 1.073                                          | 2.580·10⁻⁶           |   |
| 07                  | 0.943 (±0.040)                                      | 0.014               | 3 | 1.256                                          | 2.580·10⁻⁶           |   |
| 06                  | 1.199 (±0.056)                                      | 0.019               | 3 | 1.488                                          | 2.580·10⁻⁶           |   |
| 05                  | 1.456 (±0.145)                                      | 0.051               | 3 | 1.853                                          | 2.580·10⁻⁶           |   |
| 04                  | 1.981 (±0.136)                                      | 0.047               | 3 | 2.453                                          | 2.580·10⁻⁶           |   |
| 03                  | 3.492 (±0.368)                                      | 0.128               | 3 | 3.814                                          | 2.580·10⁻⁶           |   |

The number following the symbol ± is the numerical value of expanded uncertainty (U), obtained by multiplying the combined standard uncertainty (uₑ) and the coverage factor (k) based on a t-distribution for a coverage probability of 0.95.
Flow phantoms are hydraulic circuits capable of generating known and adjustable flow pattern providing a controllable experimental system against which hypotheses can be tested or measurements validated [7]. A flow phantom will typically consist of a vessel (generally confectioned in a rubber based material) suspended in a tissue mimic material and a fluid, which is pumped through the phantom. An important consideration in the flow phantom design is that the vessel should be similar in size and position to those of the vessel in vivo [8]. In the present work a phantom with similar dimensions and capable of generating continuous laminar flow values similar to those observed in brachial artery was designed and built.

The measurement of flow rate and pressure in ROI covers the entire range of voltages (3V to 12 V) to be applied to the peristaltic pump. The flow rates in ROI ranged from $3.475 \cdot 10^{-7} \pm 0.698 \text{ m}^3\text{s}^{-1}$ and $19.727 \cdot 10^{-7} \pm 3.883 \text{ m}^3\text{s}^{-1}$. A flow rate of $12.353 \cdot 10^{-7} \pm 2.452 \text{ m}^3\text{s}^{-1}$ was obtained for 8V, which is similar to the flow rate value for average brachial artery flow rates $(12.286 \cdot 10^{-7} \text{ m}^3\text{s}^{-1})$ [2-3].

The pressures in ROI ranged from $42.167 \pm 3.225 \text{ Pa}$ to $201.031 \pm 5.595 \text{ Pa}$. Despite the pressure values are not compatible with those from brachial artery, the achievement of low pressure values was desirable to minimize the risk of TMM damage.

The use of the reservoirs (B1 and B2) dampens oscillations from the peristaltic pump flow, and minimizes variation of the water level in the column during the pump cycle, which makes the flow laminar and continuous. The continuous flow system was chosen because it facilitates obtaining a laminar flow that is more common in small arteries [6-7].

The regime of flow in the phantom is laminar and continuous, but the model can be adapted to mimic a different anatomic region with large size vessels and pulsatile flow, eliminating B1 or B2 reservoirs.

The Reynolds number (Re) was obtained by equation (1). Re is directly proportional to the flow rate (Q) and inversely proportional to the tube diameter. Moreover, in laminar flow Re ≤ 2000 and the fluid flows in lamina or parallel layers. In turbulent flow Re ≥ 3000 and the fluid flows in a nonlinear behavior. In other cases, for 2000 ≤ Re ≤ 3000 one of two types of flow (laminar or turbulent flow) can occur [6]. The higher Re was 547, obtained from the higher Q = $19.727 \cdot 10^{-7} \pm 1.409 \text{ m}^3\text{s}^{-1}$, which leads to Re ≤ 2000. Therefore, the flow was considered laminar within the ROI.

The theoretical and experimental resistance values are compatible with literature [7]. As the theoretical resistance values of $R_a$ are smaller when compared to $R_c$, it can be assumed the influence of the accessories on flow resistance is minimum, so the flow tends to be laminar in the phantom.

Theoretical values of resistance are smaller when compared to experimental resistance values. Thereby, it can be assumed that theoretical resistance values are underestimated for the phantom, especially for the values of $R_a$ as irregularities in accessories (connectors) inner can increase the flow resistance.

Flow phantoms are intended to many applications, such as calibrating ultrasound equipment, training medical personnel skills on blood vessel access, evaluation of vessels and parenchyma perfusion, and ultrasound imaging applications [8-9]. Diathermy or hyperthermia assays were not listed in the applications of ultrasound flow phantoms in literature. Besides that, future works aims to apply the flow phantom built to improve experimental models for studying the heating pattern in biological tissues.

4. Conclusion

A phantom with a laminar flow was confectioned. The dimension and flow rate values on phantom are compatible with brachial artery [2-3]. The pressure values on the phantom were compatible with similar models of literature [6-7]. This work aims to improve the experimental models for studying the heating pattern in biological tissues, especially therapeutic ultrasound safety tests. As future perspective, is to apply the flow phantom to therapeutic ultrasound essential performance testing. Furthermore, improvements are proposed in the phantom as the use pulsatile flow to better mimic larger artery flow.
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