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Dynamic tests of multi-detector radiometric system on central blood circulation phantom

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Abstract. Phantoms of organs and biological systems are widely used for verification of radioisotope protocols. The construction and operation of the heart and circulation phantom is described. The present model was designed for experimental testing of multi-detector radiometric system, prototype of which was designed in Ural Federal University as an extension and alternative to Anger camera and single-photon-emission tomography radionuclide diagnostics. The model represents vital dynamic properties of the single-chamber pulsing heart and circulation, featuring adjustable heart rate, blood volume, ejection fraction and flowrate. The trial experiments were performed with ^{99m}Tc-pertechnetate to obtain time-activity curves and the ejection fraction was thus measured basing on first-pass radio angiography technique.

1. Introduction

Assessing central blood circulation with nuclear medicine instruments requires a choice of variety of methods and equipment. The most popular device used in Russia for that is an Anger camera. Shortcomings of Anger cameras are the restricted field of view (typ. 50×50 cm^2) and the limited number of available projections. Multi-detector radiometric system (MRS) was designed as a special device, that can extend Anger camera capabilities or be used as an independent device for local radiometry. The MRS allows to bypass those flaws, although requiring some more conscious actions from the operating physician [1].

The MRS consists of tiny body-attachable scintillation detectors. The main advantage of the system is the capability to carry out scintigraphy assessments in several distant points of the body, while each detector could be positioned in an arbitrary point at arbitrary projection. One of the urgent applications of the MRS is the measuring of the radiopharmaceuticals kinetics, while others are similar to most common radioisotope protocols, e.g. renal, liver, heart functional assessments. Specifically, those protocols have been well developed for the past decades and are standardized for patients' regular monitoring in Europe and the US [2].

The current study is primarily focused on adjustment of the MRS for central circulation protocols, typically referred to as 'first-pass radioisotope angiography' and 'equilibrium radioisotope angiography' (FPRNA and ERNA).
Algorithms, applied for processing data from anger cameras and tomography assessments are hardly applicable for the concept of the MRS. The others, that were used for radiometers in the second half of the last century require verification and modification. The mechanical circulatory phantom with the contracting 'heart' and the 'vessels' system was designed to evaluate those protocols. The phantom provides several regimes with different heart rate, strike volume, ejection fraction, vessel diameter and flow, radiotracer injection options to simulate real assessment conditions.
The first processes simulated in a phantom were modelling of injection of radiopharmaceutical in various ways, circulation of the blood with a «heart rate» and dilution of radiopharmaceutical in blood pool.

2. Materials and methods

The phantom provided simulation of a contractible single-chamber heart and a single circulation circuit. A phantom previously developed by Pieter deBondt, MD et al. [3] was used as a prototype and modular system and compact size were featured from respective studies by Kirac [4] and Masood [5].
The key parts of the phantom included electrical drive, gear, piston pump with pneumatic transmission, 'heart-chamber' vessel, 'aorta' vessel, circulation circuit and flowmeter with their descriptions listed here (figures 1 and 2).

2.1. Electric drive

The RS-550 engine from a screwdriver was used, as it provided on-board reducing gear and relevant properties: torque of 4.5 N·m, 12 V supply and speed up to 500 rounds per minute (rpm). The supply circuit consisted of an ACDC 12 V 5 A converter, a pulse width based power governor 12 V 0–5 A, and a low-pass LC filter with cut off frequency 200 Hz. It provided a steady adjustment of revolution speed. Due to the fact that some regimes of the setup were incompatible with very low speeds, the general range of rpms from 40 to 160 was well-reproduced in the phantom. The engine with reducing gear was additionally fixed inside the bulk of a screwdriver which allowed for easy fixing of it on the operating plane.

2.2. Crank gear transmission

The crank mechanism was used to drive the piston pump. The crank was fixed in a jaw chuck, coaxial to the engine. The length of the crank provided an adjustment of the connecting rod stroke from 0 to 12 cm with a ruler attached to it. A magnet was attached to the end of the crank and the hall-sensor-based bike computer was used to instantly measure the average revolutionary speed of the engine. After computer calibration, its readings in kmph represented a third of the speed in rpm.

2.3. Piston pump

The Janet' syringe was used as a piston pump, as its pump was attached to the connecting rod of the crank mechanism and the syringe was fixed on an axis slightly below its lower wall. Its cross-section area was 12.8 cm^2, and the initial length of the piston chamber was 60 mm. The pump was connected to the 'heart' vessel via a silicon tube of 6 mm diameter with a faucet valve, being opened during connection rod pivot adjustment to allow for initial pressure to normalize. Due to high frequency of pump volume and pressure change, we did not use the water but air to reduce the inner losses in the tube and in the pump. All the connections were fitted tightly and seal-proofed with water-insoluble glue.

2.4. 'Heart-chamber'-vessel

A plastic jar of 200 mL was sealed and holed in several places for interconnections. A latex membrane was put inside that vessel and separated its main volume from the pneumatic path from the pump. Two

9 mm tubes with check valves provided main input and output of the fluid and the last tube with the faucet valve provided service access inside the vessel for setting the initial volume (end-diastolic volume) and dying it.

2.5. 'Aorta' vessel

The same jar was sealed and holed and represented the large arteries, having some air volume above the fluid volume. It provided a single input from the heart and an output to the main circulation as well as the service faucet for initial volume setting. The whole module provided the accumulation of the fluid during the systole and its release to the circulation during the diastole.

2.6. Circulation circuit

Silicone tubes of various diameters were used to construct the primitive circulation line, featuring several single-line sections of different cross-section and another section with 2 parallel paths. The diameters of 11, 14 and 25 mm were used, and connectors had inner diameters of 10 mm, so the total volume of the circuit was 670 mL. The tubes were catheterized in different sections with the 5 mm length and 0.49 mm outer diameter needles to allow for tracers administration. During the normal phantom operation, syringes were attached to those needles, sealing the circuit. For the injection, one of syringes was shortly replaced with the filled one as the injection was performed manually and rapidly. The compact metal clamp was used to imitate the tourniquet-aided injection.

2.7. Flowmeter

The YF-S402 hall-sensor water flow meter was used in the setup to initially calibrate it by means of the flow, rpm and stroke volume. The sensor was supplied via a USB-socket of the PC and the output pulses, their frequency proportional to the flow, were recorded via audio-input of the PC, and processed and counted with an audio-editing software and a MatLab script. Generally, the flow varied from 0.3 L/min to 1 L/min.

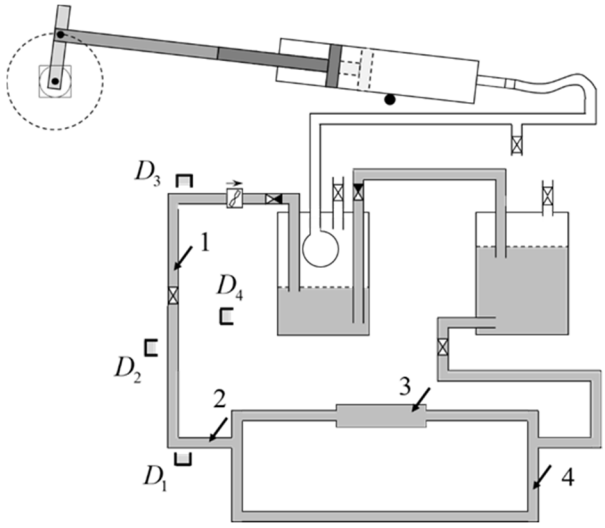
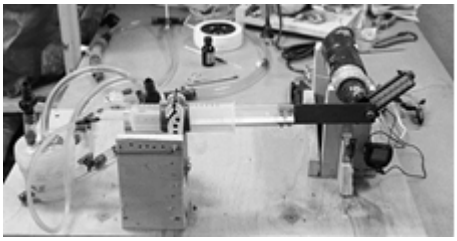


Figure 1. The scheme of the phantom setup, featuring the engine with crank gear, the piston pump, two vessels of the heart and aorta and the circulation. Arrows with numbers indicate needles injected and D-s indicate detectors positions. Detectors 1 through 3 are positioned at measured distances from injection point 2: 5 cm, 25 cm and 60 cm.



A

B

Figure 2. Setup overviews from the front (A) and from the rear (B).

The studies were performed at the radionuclide clinical laboratory of the Regional Clinical Hospital, Yekaterinburg Russia, equipped with the generator, producing solution of 50-700 MBq/mL. That radiopharmaceutical was used in the present study. Each injection contained 1 mL of the solution, dyed with the methylene-blue, with administered activity of 12 MBq, as measured with the on-site radiometer. The lead shielding was constructed around the circuit and heart and aorta parts of the phantom and time- and distance-protection of operators were implemented during studies.

Four CsI(Tl) scintillation detectors, covered with 3-mm lead shielding were used during acquisition. Injections were administered via the needle in position 2 (figure 1), three detectors were put proximal to the tube in positions, noted as D1, D2 and D3, so that tube solely was in their field of view. Their distances from the injection point were respectively (cm): 5, 25 and 60. The fourth detector was situated 3 cm away from the heart vessel at position D4, providing the whole volume of the vessel was inside the detector field of view and the aorta vessel was not.

The detectors output was recorded using a LabView script and analysed with Excel and Origin commercially available software. Basic array processing was used to determine the time gaps between characteristic points of plots, extremal points and the time-activity integral (count sums) of various curve regions.

3. Results and discussion

The phantom was set at the heart rate of 45 bpm, SV of 8 mL and the average flow of 0.34 L/min. The initial volume of the fluid in the heart chamber was set at 60 mL, thus the ejection fraction (EF) was 13.3%. Three consecutive injections of 1 mL of 12 MBq were administered in 15-minute period. The first one was performed without the clamp, in the second the tube was clamped before the injection point (respective to the flow), in the third it was clamped after the injection point. The readings of the detectors (figures 3 and 4) confirm expected time gaps between starting points of curve rises for consecutive detectors, each one wider and lower than the previous. The activity inside the relatively large 'heart' vessel is gradually ejected via pulses, so the 'heart' detector readings feature the slowest decrease. Finally, the recirculation section is observed for all detectors, as the activity is diluted and returned to all sections of the phantom. The heart detector additionally indicates oscillatory ejection that is scale-adjusted the best for the first injection (figure 4).

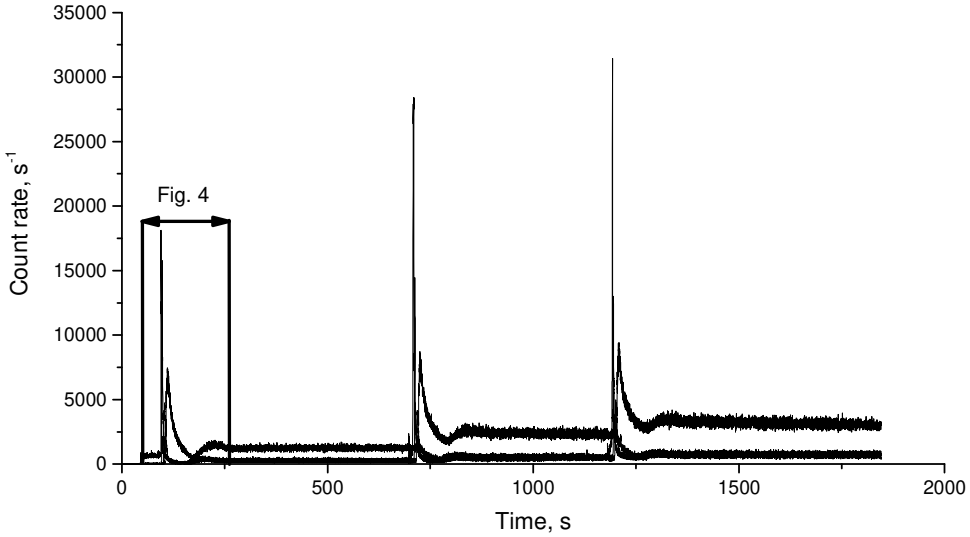


Figure 3. The readings of 4 detectors during first injection of radioactivity. Legend describes positions of each detector. Distance values denote the distance between the detector and the injection site.

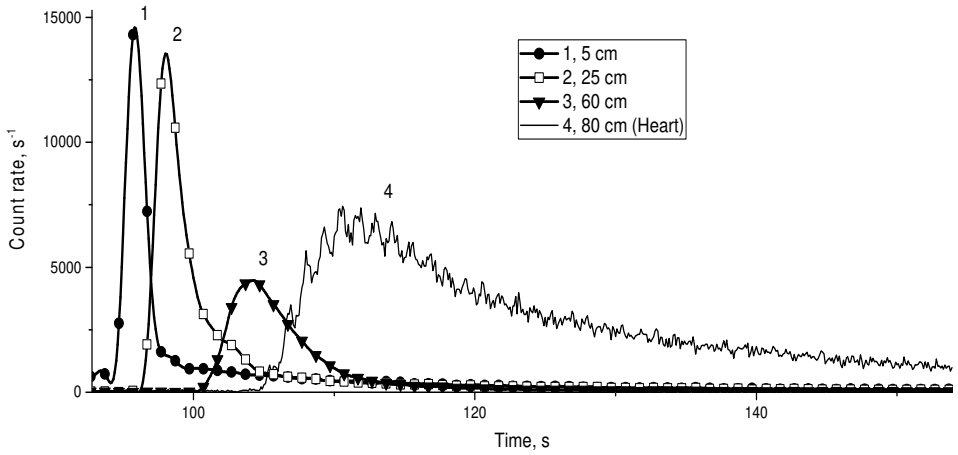


Figure 4. Readings of detectors after 3 consecutive injections, showing the general linear growth of equilibrium radioactivity at readings of all detectors.

Ejection fraction of the heart chamber was calculated, using a standard algorithm, during which, the min and max peaks on the ejection curve were identified, their integral counts were determined and their ratio taken as the EF [6]. Four consecutive pairs of min and max were accounted here, their average considered as the result. The ejection curve was fitted with an exponent, having points of 20% to 80% of max peak fitted and its rate determined from the fitting. Those results considering the heart are shown in the table 1.

Table 1. The calculated values of ejection fraction and ejection rate constant for 3 administered injections of radiopharmaceutical.

Type of injection	EF, %	s^{-1}
Without clamp	14.9	0.05
After clamp	15.1	0.049
Before clamp	17.2	0.049

The focus of the experiment was primarily to demonstrate the possibility of using the dynamic heart-and-circulation phantom for non-human research of the FPRNA and ERNA protocols with the MRS detecting system. The presented results for the FPRNA confirm that capability; the phantom imitates key hydrodynamic features of the heart and circulation, may be customized in different ways, is portable and compact and leaves a lot of capabilities for combining it with other phantom parts (e.g. organs and other circulation circuits).

The data obtained demonstrates the capability to analyze it by means of typical FPRNA algorithms, without the necessity to use SPECT or Anger camera equipment. The arbitrary choice of the region of interest (ROI) is alternated here with the one of detector placement, that is expected to require the same skills from a physician.

4. Conclusion

The reason for a EF difference is discussible. On the one hand, the FPRNA was numerously mentioned to assess the LVEF accurately with the similar method of peaks analysis, still the difference of 20% between actual EF and the measured leads to two possible reasons: it is either a methodical error of using a single detector for assessing the whole heart-vessel, or the actual EF was calculated

erroneously. A latter one requires more thorough analysis of physical processes, performed in such pulse pump, accounting for both membrane and air compression and expansion, combined with water flow regimes.

The next important task for future research work is to make more special and detailed phantom models of the human blood circulation system. Importance of such studies is determined by wide list of MRS applications and necessity of its preliminary testing.

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