Programmable flow simulator with simultaneous physiology and MR event acquisition

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Introduction

The development of MR angiographic techniques frequently requires the use of human volunteers for trial sequence and technique developments. The use of a flow simulator or “phantom” reduces the need for volunteers provided it can predictably and reliably simulate the required flow behaviour. MR flow phantoms have ranged from simple constant head gravity fed arrangements to sophisticated pulsatile flow simulators. Few of these systems have addressed the requirement for simultaneous data capture that allows monitoring of simulated physiological parameters, e.g. ECG, along with the MR gradient and RF timings. Pulsatile flow simulation is often difficult to achieve reliably in MR because of the requirement for the pump to be outside the MR scanner room, resulting in long tubing lengths that corrupt the waveform [1]. This work aims to: (1) build a programmable pump that is cost-effective, easy to assemble, offers simple configuration of waveform profiles; (2) simulate pump related physiological phenomena such as ECG; and (3) capture and display the flow waveform, triggers and MR scanner activity simultaneously.

Method

Programmable Flow Simulator Based on the approach described by Macgowan [2], a gear pump (G4-KCT-KKA, ECO Gearchem) with a good peak flow rate, bidirectionality and self-priming capability was used. This was linked to the motor shaft of an AC servo-driven motor (MAC800, JVL), chosen for its high acceleration, reasonable torque and integrated controller unit. This combined unit was mounted on an L-shaped metal alloy frame to provide stability. The pump was connected to tubes made from polyvinylchloride (PVC) or polybutylene (PBT) with inner diameters of 9.5mm and 12.0mm respectively using snap-on valved couplings (HFC-12 Series, CPC). The distance from the pump to the scan bore via the waveguides was 6m, and from the scan bore back to the reservoir was 14m. De-ionised water was used for all the experimental testing performed below. A software development kit (SDK) was supplied with full RS-232 communication support between the motor controller and PC, which we interfaced using custom developed software based on the LabView (8.0, National Instruments) SDK. This allowed constant flow and both sinusoidal and user-defined waveforms to be used to drive the pump at selectable frequencies.

To test the response of the phantom to flow driven by the motor-pump, sinusoidal waveforms of various frequencies were programmed into the controller. Flow was measured using a fast 2D cine phase contrast pulse sequence on a clinical 1.5T MRI scanner (Signa HD, GE Healthcare, Waukesha, WI) [3]. Graphs of physiological flow waveforms [4] were digitised (Engauge Digitizer 2.14, GPL) and used with LabView to drive the pump at 1Hz. Accuracy of simulated flow was calculated from the deviations of the measured flow to the programmed input waveform. Reproducibility was calculated similarly but using a mean of the measured waveforms as the reference. The standard deviation of a measured waveform *x* with *n* data points to a reference waveform *R* is given in Equation 1.

$$\sigma_{sample} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{x_i - R_i}{R_i}\right)^2}$$

Equation 1 *Flow simulator evaluated using deviation of measured waveform from a reference waveform.*

Data Acquisition System An analogue-to-digital converter (ADC) board (PCI-1002L, Omega) was installed in the same PC used for the LabView pump control software and connected to the scanner analogue ports to record RF and gradient waveforms. Event start triggers (simulating the ECG “R” wave) in synchronisation with the flow simulator were fed into the standard scanner ECG monitoring system. The board’s sampling rate of 110Ksamples/sec allowed capture of basic event timings when 4 channels are employed simultaneously for RF and gradients. These were displayed along with ECG (and potentially plethysmograph) data extracted (multiplexed digital data) via an RS-232 port on the system.

Results

Figure 1 shows results from frequency response tests of phantoms composed of either PVC or PBT to a sinusoidal input waveform. We observed significant waveform attenuation in the compliant PVC phantom. As expected, the frequency response of the curve improved for the stiff PBT phantom. Simulations of arterial waveforms are shown in Figure 2. Pulsatile flow can be achieved easily at desired frequencies and flow rates/velocities. Waveform accuracy and reproducibility are reasonable at 7.3% and 6.7% (standard error). Performance of the data acquisition system was found to be variable, largely depending on the computer load. As the multi-channel capability was built on a multiplex method and no timing information was provided, it was difficult to verify the precision of the event timing.

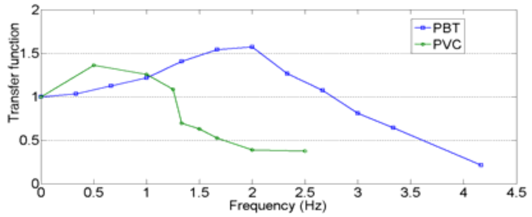

Figure 1 *Frequency response curves of phantoms made from PVC and PBT.*

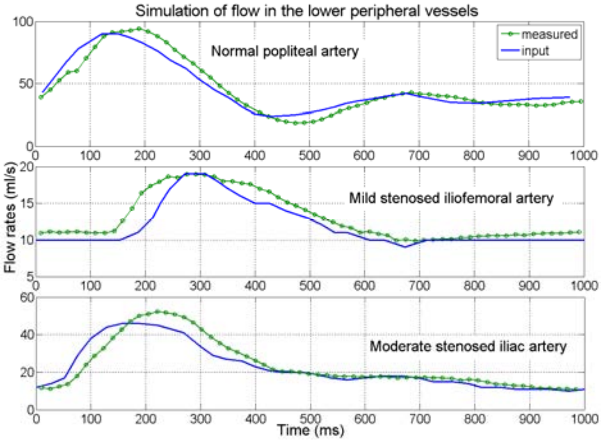

Figure 2 *Simulations of physiological flow using rigid plastic phantom. Blue lines represent unmodified digitised waveforms green lines represent PC flow measurements.*

Conclusion

A flow simulator was successfully constructed and reproducible pulsatile physiological flow generated.

This work also demonstrates the use of integrated data capture which allowed simultaneous monitoring of both physiological and MR pulse sequence events, which can also be used with human volunteers.

Improvements in the flow waveforms obtained in the scanner bore could be achieved by either using compensation methods that take into account the frequency response of the phantom or iterative strategies and further work will investigate this. In addition more precise data monitoring using a higher performance ADC with time-stamping capability is also planned for future work along with modification of the fluid to take account of blood relaxation times and viscosity.

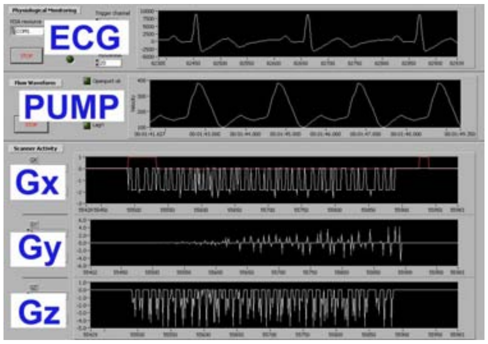

Figure 3 *Simultaneous execution of flow simulation and acquisition of physiological data and MR scanner activity. (Timescales differ in each chart.)*

References

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