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ORIGINAL ARTICLE

Design and Function of a Circulation Phantom for the Bolus Tracking Technique Use on a Computer Tomograph

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Abstract

Background/Aim: Bolus tracking (BT) is a widely adopted technique for both the administration and monitoring of contrast media in computed tomography (CT) scans. The aim of this study was to create a circulation phantom for the BT technique for CT. The phantom has been tested for functionality and is intended to be used for teaching radiology technology students.

Methods: Contrast media acquisitions were performed in a circulation phantom. Test setup with five different flow rates (2 [mL/s], 3 [mL/s], 4 [mL/s], 5 [mL/s] and 6 [mL/s]) were used for each cannula size with different gauge (G) units (22 G, 20 G, 18 G and 17 G). Each cannula's trigger time (TT) was measured three times with each flow. A total of 60 measurements were performed to show the functionality.

Results: The measurements have shown that in each cannula with a flow of 2 [mL/s] and 3 [mL/s], BT was triggered at roughly 100 HU at the same time. If the flow was higher than 3 [mL/s], the blue cannula with 22 G deviates from the others by one second until BT is triggered.

Conclusion: The function of the phantom was verified. The CT started the scan automatically using the BT technique. The verification was performed for each cannula size and each flow.

Key words: Tomography, computed; Bolus tracking; Phantoms, imaging; Contrast media; Flow rate.

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Introduction

Computed tomography (CT) is an important tool in modern medical imaging. It is a well-established, non-invasive method used for the diagnosis and evaluation of lesions and tumours, the assessment of blood vessels, the monitoring of cancer treatment and the evaluation of trauma.[1] The ability of CT to produce detailed cross-sectional images makes it an indispensable tool for the diagnosis and monitoring of a wide range of pathologies. The practice of contrast media, which is iodine-based due to its high X-ray attenuation properties, is a crucial aspect of enhancing CT imaging quality.[2] The intravenous application of contrast medium enhances the visibility of structures, tissue, pathologies and vessels, making them more distinguishable by increasing the Hounsfield Units (HU) and thereby improving diagnostic accuracy.[3]

A number of techniques have been developed to detect and achieve the optimum concentration of contrast media in the targeted body region. These include timing bolus, in which a small test dose helps determine the ideal scan timing and multiphase scanning, which captures multiple phases of contrast distribution to visualise different vascular and tissue structures.[4] X-rays are attenuated or absorbed to different degrees by different tissues (bones, organs, blood, etc). The presence of iodine-containing contrast agents leads to enhanced X-ray absorption, resulting in increased Hounsfield units and the manifestation of structures as more hypertensive (brighter than the surrounding tissue) on imaging. Hounsfield units are a unit of measurement used in CT scans to quantify the density of different tissues in the body.

The enhanced detectability of pathological structures leads to an improvement in diagnostic accuracy.[3] A range of techniques exists to detect and achieve the optimum concentration of contrast media in the targeted body region.[4] Bolus tracking (BT) is a widely adopted technique for both the administration and monitoring of contrast media in CT scans. This automated method optimises contrast delivery timing, ensuring that the contrast media reaches the target area at the optimal concentration. This enhances image quality while minimising the amount of contrast used and reducing potential adverse reactions.[5]

In the case of BT, every CT scan starts with a topographic scan, called topogram. This provides an overview image of the desired anatomical area, helping to determine the position of a blood vessel where the contrast medium concentration will be measured. A pre-monitoring layer (slice) is selected at the desired height of the topogram. The resultant image is axial. The subsequent step involves the selection of a circular region of interest (ROI) within the desired blood vessel, based on this axial image. Typically, the descending part of the *aorta descendens* or the pulmonary trunk is selected for this procedure. The contrast medium is then injected into the patient's vein, after which its passage and concentration through the previously determined ROI in the blood vessel is monitored with a series of single CT scans. Upon reaching the ROI, the CT scanner detects the increased concentration of the contrast agent. The CT scanner then triggers an automatic scan when the desired HU threshold is reached. The determination of this threshold is a bespoke process, influenced by several factors, including the iodine concentration of the contrast agent, the nature of the examination, and the medical question being addressed. The CT measures the HU periodically, typically at intervals of a few seconds within the selected ROI. Once the desired threshold is reached, the CT initiates the examination. The automatic triggering of the CT ensures that the contrast medium remains in the vessel during the examination.

The BT optimises image quality for each individual patient, reducing the potential for adverse reactions or side effects.[6, 7] While the BT technique is widely used, there is a need for efficient and cost-effective training methods for radiological technologists and students. The primary objective of radiological technology studies is to equip students with the knowledge and skills necessary to competently apply contrast media and BT in CT, thereby preparing them for real-world clinical scenarios. However, due to the associated risks of ionising radiation and the invasiveness of procedures, training on human patients is often not feasible. Consequently, the development of phantoms models designed to simulate human tissue and physiology has become increasingly important for educational and training purposes in radiology.

Phantoms offer a controlled and risk-free environment for the practice of imaging techniques, thereby obviating the need for patient exposure to unnecessary risks. They serve as invaluable tools for simulating a range of clinical conditions, anatomical structures and physiological processes, thus enabling technologists and students to accrue hands-on experience and confidence prior to the implementation of these techniques in a clinical context. There are several types of phantoms available for different imaging modalities, including X-ray, CT, MRI, PET and ultrasound. However, not all phantoms are equally suited to training in bolus tracking, as they frequently fail to replicate the dynamic properties of contrast media flow in a realistic manner.[8–10]

The aim of this study was to develop a circulation phantom specifically designed and tested for the BT technique used in CT. The phantom is intended to serve two purposes: firstly, as a training aid to ensure the correct use of the BT technique for radiological technologists and students; and secondly, as a tool to facilitate the training of radiological technologists and students in the

BT technique. The phantom under development simulates the flow of contrast media through a single vessel, focusing on key aspects of BT functionality. The phantom is designed to determine the time to peak (maximum enhancement) for different flow rates and cannula sizes, while ensuring a constant contrast media quantity. The presence of diverse flow rates and cannula sizes is inherent in the practical endeavours of radiologic technologists. In contradistinction to other phantoms that might mimic complete anatomical systems, this simplified model is tailored to be both cost-effective and functionally relevant for educational purposes. It facilitates the demonstration and training of the BT technique, thereby addressing the need for practical, hands-on learning tools that are accessible to educational institutions with limited resources.

In the development of the phantom, a number of factors were given consideration, including the selection of cannulas of differing gauges and the manipulation of flow rates to simulate realistic clinical conditions. The construction of the phantom incorporated the utilisation of cost-effective materials, while its design was conceived to ensure adaptability across diverse training scenarios. This approach was undertaken to facilitate a comprehensive comprehension of the BT technique. The model offers students the opportunity to engage in practical exercises, including measuring HU values, adjusting protocols and interpreting results in real time. Such training is vital for improving radiologic technologists' students' proficiency and ensuring they are well-prepared for clinical practice. This study also contributes to the extant body of research by presenting a methodology for phantom construction that balances functionality and affordability. Previous studies have developed phantoms for CT imaging; however, many of these studies involve complex and expensive setups, such as multi-organ simulations or models that replicate entire anatomical structures. By focusing on a single vessel simulation, this study highlights an approach that is both specific to BT training and feasible for widespread use in educational settings. The findings presented will demonstrate the phantom's effectiveness in training and verify its ability to replicate the BT process accurately across different flow rates and cannula sizes.[8–10]

Methods

The study was conducted on "SOMATOM go.All" CT *Siemens*, Erlangen, Germany.[11] This CT is characterised by 32 slices and a rotation time of 0.33s which means that the CT can produce 32 slices per rotation and allows 3 rotations per second. The contrast media injector employed was the ulrichINJECT CT motion model by *Ulrich Medical*, Ulm Germany,[12] which ensured consistent flow rates ranging from 2 to 6 [mL/s].

The blood was simulated by water and a microprocessor-controlled pump drive MCP-Process IP65 by ISMATEC was utilised for the blood flow.[13] The chosen pump parameters are shown in Table 1.

Table 1: Settings of the pump drive

Tube ID	3.2 mm
Pump	240 rpm
Flow rate	239 mL/min

Tube ID – Tube inner diameter; Pump: revolutions per minute; Flow rate: the amount of fluid that passes through the tube in one minute;

Circulation phantom construction

The base of the circulation phantom consisted of a wooden panel (OSB, 15 mm). To ensure a connection between the pump drive and the phantom, a polyvinyl chloride (PVC, a widely used plastic made from the monomer vinyl chloride) extension line with the (*B.Braun Discofix C*) system featured three stopcock manifolds (*Discofix system*) designed for infusion therapy and monitoring were used to simulate blood flow. To establish a connection between the contrast media injector and the blood flow-simulating lines, a 250 cm-long extension line was employed. Varied venous cannulas (22 G, 20 G, 18 G and 17 G) were affixed to the dedicated lines. A venous cannula is a small, flexible tube that is inserted into a vein. Two PVC extension lines, each measuring 150 cm, were implemented to increase the distance to the measurement point, resulting in a combined length of 300 cm.

Precise locations were identified along the extension lines: an injection point was positioned 10 cm after the *Discofix system* and a measurement point was situated 30 cm before the end of the lines. The length between the injection and measurement points encompassed 260 cm.

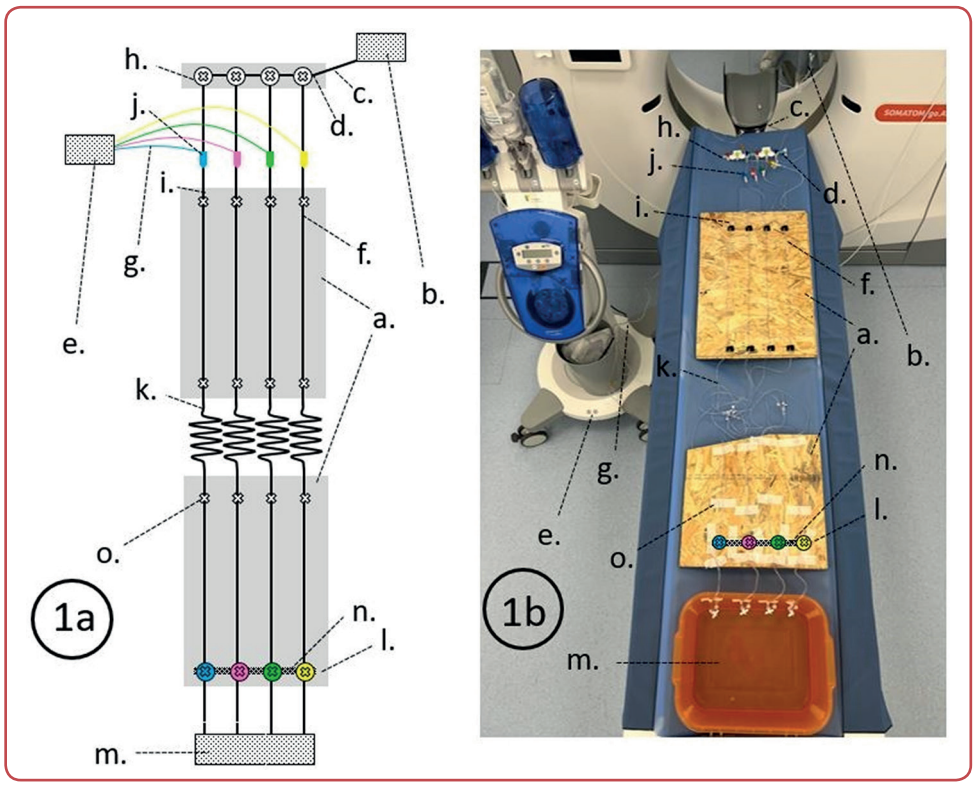

Figure 1: a. Wooden panel; b. Pump drive; c. PVC extension line with a 3-way stopcock; d. Multidirectional stopcocks; e. Contrast media injector; f. Blood flow simulating lines; g. 250 cm-long PVC segment; h. Three-way valves; i. B.Braun Discofix C; j. Venous cannulas / injection point; k. PVC extension lines; l. measurement point; m. Conclusion of the phantom; n. Hot glue stick; o. Clips and tapes;

At the measurement point, a hot glue stick was affixed to enhance visibility in the CT image. All materials were secured using clips and tapes (*Silkafix* 2.5 cm), as shown in Figure 1. Figure 1a depicts a schematic illustration of the circulation phantom. Figure1b shows the constructed circulation phantom for the experimental series.

Test setup

The scans were performed with 120 kV and automatic tube current modulation was used. Automatic tube current modulation in CT is a technique used to reduce the patient's radiation exposure during a CT examination without compromising image quality. For this purpose, the amount of radiation is individually adapted to the respective patient. The selected slice thickness was 0.7 mm and the rotation time was set to 0.33 s. The contrast media protocol consisted of 3 parts: previous bolus 30 mL saline, 10 mL contrast media (*Iomeron 300 Bracco S.p.A*. Milan, Italy)[14] and 50 mL saline as a post bolus.

Monitoring protocol

The contrast media injector and CT-scanner software protocols were synchronised, incorporating BT as the application technique. The 100 HU threshold was used at 120 kV X-ray tube voltage within the specified ROI in the dedicated phantom tube. A start delay of 10 s was introduced. Start delays are common, as it takes a few seconds after the

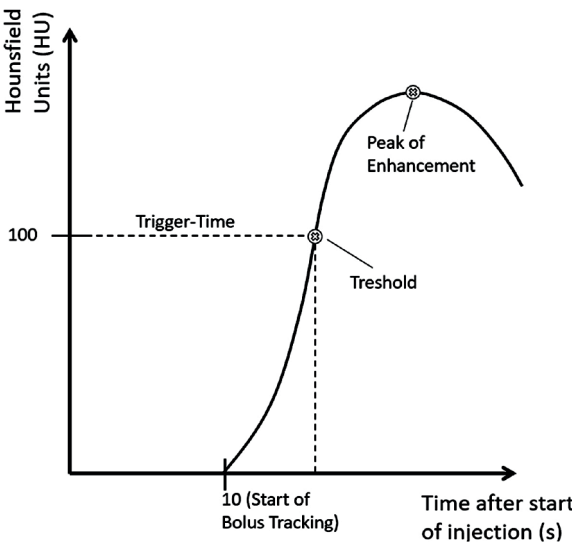

Figure 2: The trigger-time (the time from starting the bolus tracking (BT) technique until reaching the threshold of 100 HU)

Table 2: The characteristics of the selected cannulas

Blue cannula	Pink cannula	Green cannula	Yellow cannula
22 G	20 G	18 G	17 G
D: 0.9 mm	D: 1.1 mm	D: 1.3 mm	D: 1.4 mm
L: 25 mm	L: 32 mm	L: 45 mm	L: 51 mm

D: diameter; L: length;

start of the injection for the contrast medium to reach the desired location. The CT scanner configuration permits a measurement interval of 0.99 s. For every 0.99 s, the HU were measured within the predetermined ROI; the scan was started once the threshold was met.

Different contrast agent flow rates were measured (2, 3, 4, 5 and 6 [mL/s]) and used for each cannula size (22 G, 20 G, 18 G, 17 G). The characteristics of the selected cannulas is shown in Table 2. The TT (Figure 2)[7] of each cannula was measured three times, with each flow resulting in 60 measurements.

The abbreviation 'G' stands for Gauge, describing the outer diameter of cannulas. 'D' represents the diameter of the cannulas in mm and is synonymous with the Gauge unit. 'L' indicates the length of the employed cannulas.

Results

The phantom had shown a basic functionality that could be used for training. The time from the injection of the contrast media to the point of measurement was measured three times. The 22 G, 20 G, 18 G and 17 G venous flows measured in averaged at 2 [mL/s]: 10.40 s, 10.36 s, 10.24 s and 10.47 s respectively; 3 [mL/s]: 7.49 s, 7.43 s, 7.28 s, 7.24 s; 4 [mL/s]: 6.17 s, 5.75 s, 5.52 s, 5.55 s; 5 [mL/s]: 5.13 s, 4.61 s, 4.56 s, 4.59 s; 6 [mL/s]: 4.36 s, 4.20 s, 4.16 s, 4.16 s as shown in Table 3.

The average calculated time in correlation with the flow rate and the canula size is shown in Figure 3. The horizontal axis shows the flow in [mL/s]. The horizontal axis shows the different cannula sizes Yellow (17 G); Green (18 G); Pink (20 G); Blue (22 G). The vertical axis indicates the calculated trigger time in seconds [s]. The vertical axis shows the time until the threshold was reached. The TT is indicated in seconds [s]. Figure 4 illustrates all calculated data. Each line represents a correlation between the measured value the flow rates and the cannula size. shows the relationship between flow rate [mL/s] and trigger time [s] for various cannula sizes. The error bars indicate the standard deviation, showing the variability in measurements for each cannula size.

Table 3: Average value of the measurements

Cannula	Flow [mL/s]	Time [s]
Blue (22 G)	2	10.40
	3	7.49
	4	6.17
	5	5.13
	6	4.36
Pink (20 G)	2	10.36
	3	7.43
	4	5.75
	5	4.61
	6	4.20
Green (18 G)	2	10.24
	3	7.28
	4	5.52
	5	4.56
	6	4.16
White/Yellow (17 G)	2	10.47
	3	7.24
	4	5.55
	5	4.59
	6	4.16

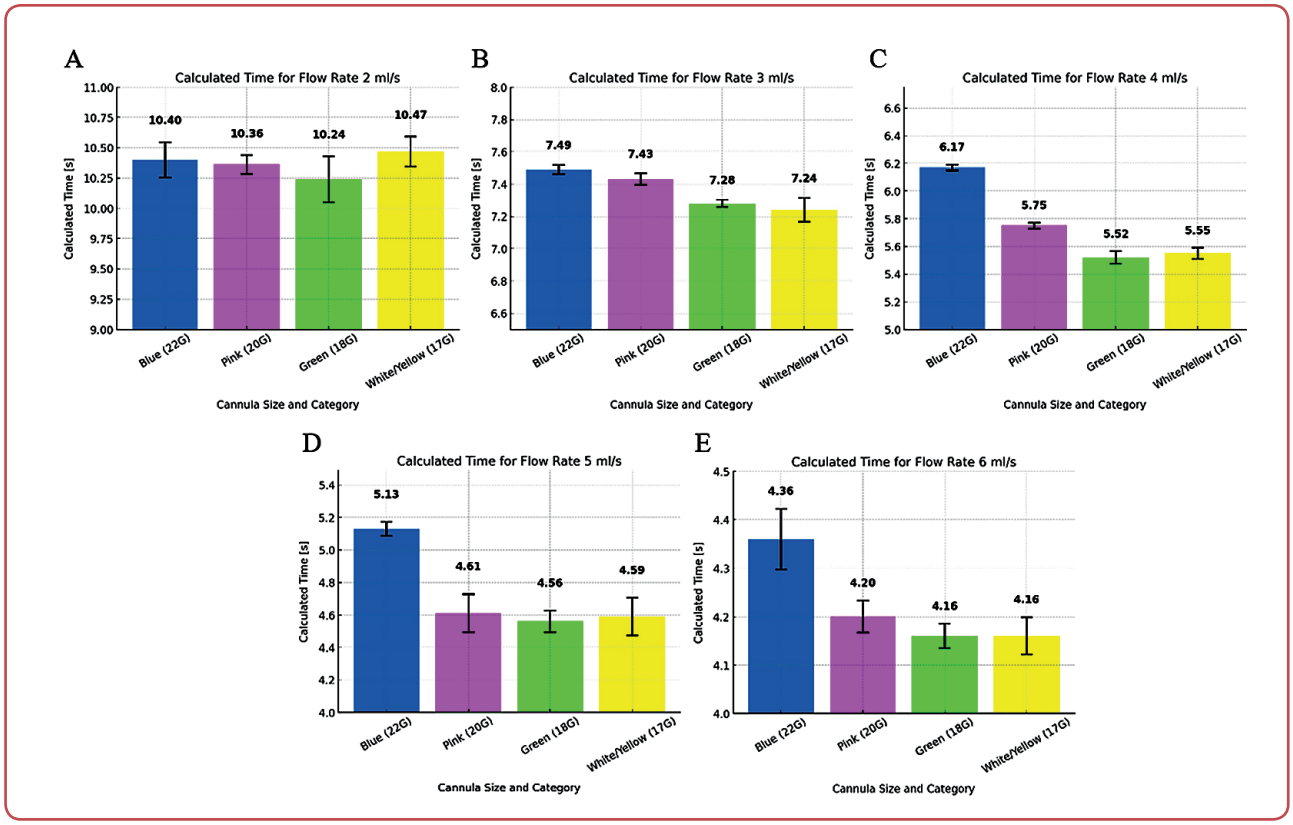

Figure 3: The trigger-time (the time from starting the bolus tracking (BT) technique until reaching the threshold of 100 HU)

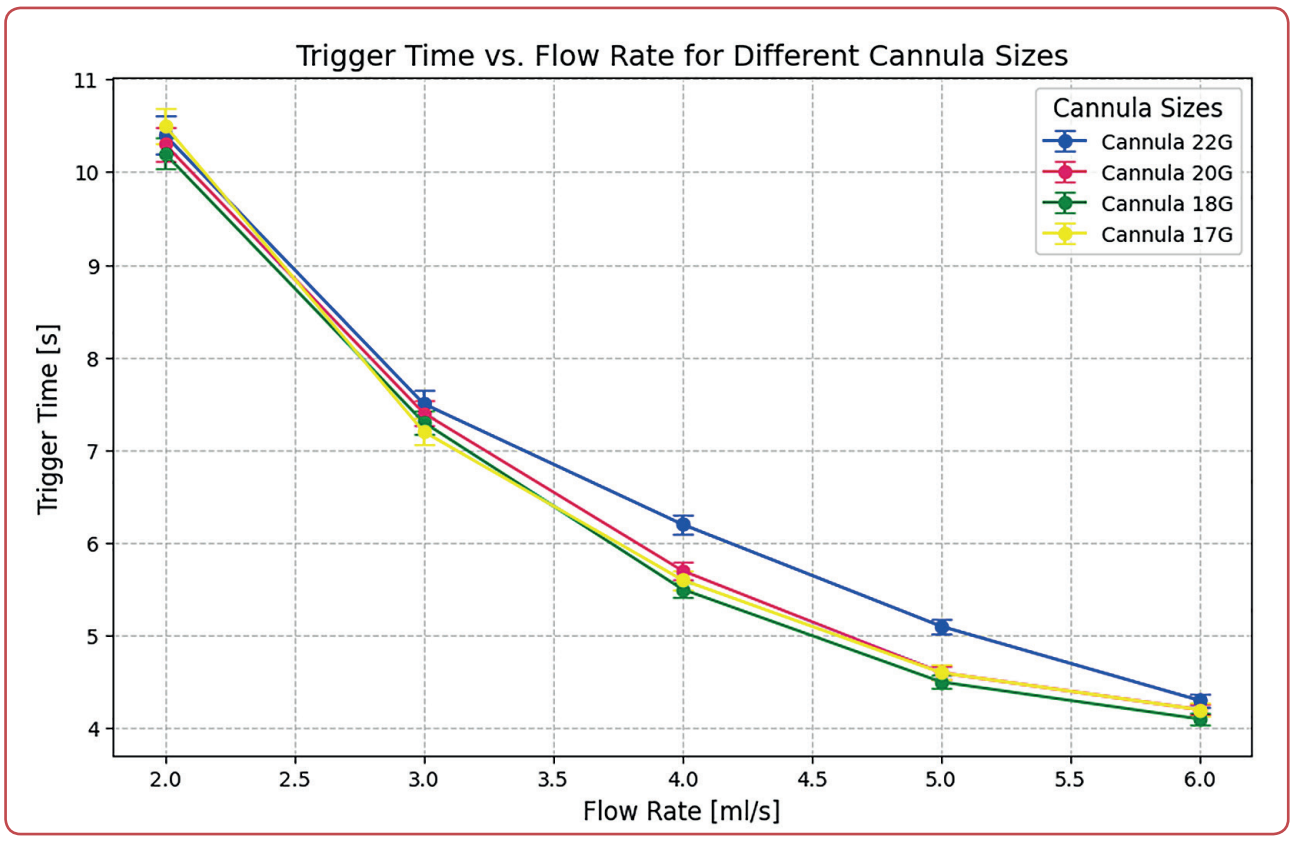

Figure 4: This graph shows the relationship between flow rate [mL/s] and trigger time [s] for various cannula sizes. The error bars indicate the standard deviation, showing the variability in measurements for each cannula size (22 G, 20 G, 18 G, 17 G). Colours are selected to distinguish cannula sizes as follows: blue for 22 G, pink for 20 G, green for 18 G and yellow for 17 G.

Discussion

The study demonstrated that the TT for the BT technique varies depending on the flow rate and cannula
size used in the circulation phantom. Notably, the 22 G cannula exhibited a deviation in TT at higher flow rates (above 3 [mL/s]), with the BT triggering later compared to the other cannula sizes. the biggest challenge was the measurements, which were limited by the temporal resolution of the CT scanner. The CT scanner "Somatom go All" can only measure the HU values every 0.99 s when using the BT technique. It is not possible to shorten the measurement intervals. This interval introduces a degree of uncertainty when measuring the exact moment, the contrast media reaches the desired HU threshold. For instance, slight fluctuations in contrast flow that occur within the 0.99 s window are not captured, potentially leading to small variations in trigger time that are not reflective of actual conditions. This limitation impacts the precision of the data collected, particularly when using higher flow rates or smaller cannulas (like the 22 G), where rapid changes in HU might occur within a shorter timeframe. However, it was still possible to show the function of the phantom, which was also the purpose of the study and to show the functionality of the phantom.

The time points from the BT sequence were recorded before triggering the CT protocol and initiating the scan. Due to the limited time resolution of the scanner (0.99 s), a curve-fitting model was employed using both linear and exponential functions between measured points because the exact function is unknown.

Each flow was measured three times to validate the acquired data. The values obtained from each measurement's linear and exponential functions were averaged.

This study aimed to create the circulation phantom to simulate the flow in the human body. Considering that our university is not allowed to do imaging on patients with CT, the main reason for building the phantom was to train new students in the BT technique.

As previously mentioned, different venous catheters were used in each test setup, while the pump drive simulated the blood flow using water. At the beginning of each measurement, a 30 mL saline bolus was injected to guarantee the 10 s delay. Afterwards, 10 mL of *Iomeron* 300 was injected. Subsequently, the time between the start of the contrast media application and reaching the threshold of 100 HU in the ROI was measured.

The measurements have shown that in each cannula with a flow of 2 [mL/s] and 3 [mL/s], BT was triggered at 100 HU after approximately the same time. If the flow is higher than 3 [mL/s], the blue cannula deviates from the others by one second until BT is triggered. This is due to the smaller diameter of the cannula. The other cannulas have shown no difference in the timing of the BT.

Based on the flow measurements, the function of the phantom could be verified. It is proven that BT sequence triggers the CT scan after applying contrast media and the threshold of 100 HU is met in the selected ROI. Verification was performed for each cannula size. The experiment has also shown that different flow rates impact the TT and reach the threshold to start a CT scan. Additionally, the educational value of the phantom is enhanced by its ability to simulate these clinically relevant deviations in TT. By observing how the 22 G cannula behaves differently at higher flow rates, students gain hands-on experience that goes beyond theoretical knowledge. They can practice troubleshooting and adjusting CT protocols in a controlled environment, which is vital for developing the decision-making skills needed in clinical practice. Such training ensures that radiological technologists can effectively manage various clinical situations, including those where smaller gauge cannulas are the only option due to patient conditions, such as paediatric cases or patients with fragile veins. The findings also emphasise the importance of equipment selection and protocol customisation in clinical settings. When a smaller gauge cannula must be used, it is crucial for radiological technologists to be aware of the possible impact on BT timing. Educational programs using the circulation phantom can simulate these scenarios, preparing students to handle real patient cases with greater confidence and accuracy. By understanding the specific limitations and adjustments needed when using smaller cannulas, students can optimise CT protocols to maintain high diagnostic quality even when ideal conditions are not achievable.

After reviewing analogous studies concerning the development of a circulation phantom, it was

determined that the construction of the circulation phantom would not entail replicating the vessels at their original scale. Instead, the primary emphasis was placed on the BT functionality.[15]

For the same reason, no electrocardiogram simulator or measure bar was used to construct the circulation phantom.[16–18] The installed BT software was utilised for the evaluation of the flooding curve. It was not necessary to use special evaluation software, as stated in the study of Mihl et al.[17] To verify the function of the phantom, it was not necessary to heat the water inside the phantom to body temperature (37 °C).[19]

Considering that phantom is not intended to mimic the whole human body but just a single blood vessel, the differences in measured HU and X-ray absorption can be observed compared to the human body. We have to bear in mind human anatomy, where the contrast agent is usually injected in the patient's arm vein; the contrast will flow to the heart, then to the lung and back to the heart again. After this, we would usually detect it in the arterial phase (usually in the abdominal aorta). The phantom setup that was developed resulted in faster triggering of CT scans since the desired threshold was met earlier than it would be in the human body.
The authors of this study tried to keep the cost of building the circulation phantom as low as possible and were forced to forego expensive imitations of the mimicking human body and it was decided to build a single-vessel phantom.

In a future study, authors will consider whether using a Harvard heart pump makes it possible to simulate further human vital parameters. A Harvard medical pump can simulate the heart rate, ejection volume and other vital parameters, which could further bring our setup of the phantom closer to realistic patient scenarios.[20]

On the other hand, the time resolution of the CT (BT measurement every 0.99 s) was observed as a limiting factor. Hence, flooding behaviour between measurement times was unknown. Therefore, the authors used two curve-fitting models (linear and exponential) to approximate the TT.

Conclusion

The function of the phantom was verified. The CT started the scan automatically using the BT technique. The verification was performed for each cannula size and each flow. If the flow was higher than 3 [mL/s], the blue cannula with 22 G deviates from the others by one second until BT is triggered.

Ethics

This study did not directly involve with human participants or experimental animals. Therefore, the ethics approval was not required in this paper.

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None.

Conflicts of interest

The authors declare that there is no conflict of interest.

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Data access

The data that support the findings of this study are available from the corresponding author upon reasonable individual request.

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