Proactive Air Management in CT Power Injections: A Comprehensive Approach to Reducing Air Embolization

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Abstract—*Objective:* Venous air embolism as a complication of contrast media administration from power injection systems in CT is found to occur in 7%–55% of patients, impacting patient safety, diagnostic image quality, workflow efficiency, and patient and radiographer satisfaction. This study reviews the challenges associated with reactive air management approaches employed on contemporary systems, proposes a novel air management approach using proactive methods, and compares the impact of reactive and proactive approaches on injected air volumes under simulated clinical use. *Methods:* Injected air volumes from three power injection systems were measured under simulated clinical use via custom air trap fixture. Two of the systems employed reactive air management approaches, while a new system implemented the proposed proactive air management approach. *Results:* The proactive system injected significantly less air (average of 0.005 mL $\pm$ 0.006 mL with a maximum of 0.017 mL) when compared to two systems with reactive approaches (averages of 0.130 mL $\pm$ 0.082 mL and 0.106 mL $\pm$ 0.094 mL with maximums of 0.259 mL and 0.311 mL, respectively) ($p < 0.05$). CT images were taken of static and dynamic 0.1 mL air bubbles inside of a vascular phantom, both of which were clearly visible. Additionally, the dynamic bubble was shown to introduce image artifacts similar to those observed clinically. *Conclusion:* Comparison of the injected air volumes show that a system with a proactive air management approach injected significantly less air compared to tested systems employing reactive approaches. *Significance:* The results indicate that the use of a proactive approach could significantly reduce the prevalence of observable, and potentially artifact-inducing, venous air embolism in contrast-enhanced CT procedures.

Index Terms—CT, power injectors, injection systems, piston-based, peristaltic pump, roller pump, air embolism, contrast injection, air injection, artifacts, air management, proactive, reactive, contrast injection.

I. INTRODUCTION

OVER 200 million computed tomography (CT) procedures are performed annually throughout the world. Approximately half of all CT procedures include the administration of intravenous contrast media for enhanced visualization of vasculature, specific organs, and/or varying tissue types [1], [2]. CT contrast media are typically delivered using a power injection system, unlike hand injections used in other imaging modalities, in order to achieve desired and repeatable injection profiles.

During injection of contrast media, an important safety concern is venous air embolism (VAE), defined as the entry of at least one air bubble into the venous circulation. VAE is most commonly identified in CT as air bubbles or air fluid levels in the intrathoracic veins, main pulmonary artery, or right ventricle [3], and has been found to occur in 7% to 55% of patients [4]–[9]. Air injected into the venous system is regularly trapped in the peripheral veins or in the lung capillaries, and is typically absorbed without leading to significant clinical symptoms [10]. While the prevalence of observable air is high, the injection of hazardous air volumes is exceedingly rare. Although an exact lethal dose of air is unknown, case reports suggest that 100 mL to 300 mL of air injected into the venous system of adults can be fatal [6], [11]–[17]. In rare cases, abnormalities such as atrial or ventricular septal defects or arteriovenous malformations may allow air that reaches the heart to transition into arterial circulation [4], [5]. In these cases air as small as 1 mL in volume may create blockages in vessels supplying the heart or brain, causing myocardial infarction or stroke [18], [19]. Examples of these malformations, such as a patent foramen ovale, are believed to be present in 25% to 35% of the population [20].

In addition to safety impacts, the presence of air in CT has the potential to introduce artifacts upon image reconstruction that may impact image quality and diagnosis (Fig. 1) [21]. For example, the motion of an air bubble flowing through the pulmonary artery of a vascular phantom, as shown in Fig. 1(b), creates semi-tubular artifacts upon image reconstruction that distort the surrounding anatomy. Air is particularly detrimental for diagnosis if identification of small structures is inhibited [21].

This paper reviews the current approaches to air management in CT power injectors, while proposing a new strategy which offers solutions to the drawbacks introduced by contemporary methods. The effectiveness of this new approach, relative to
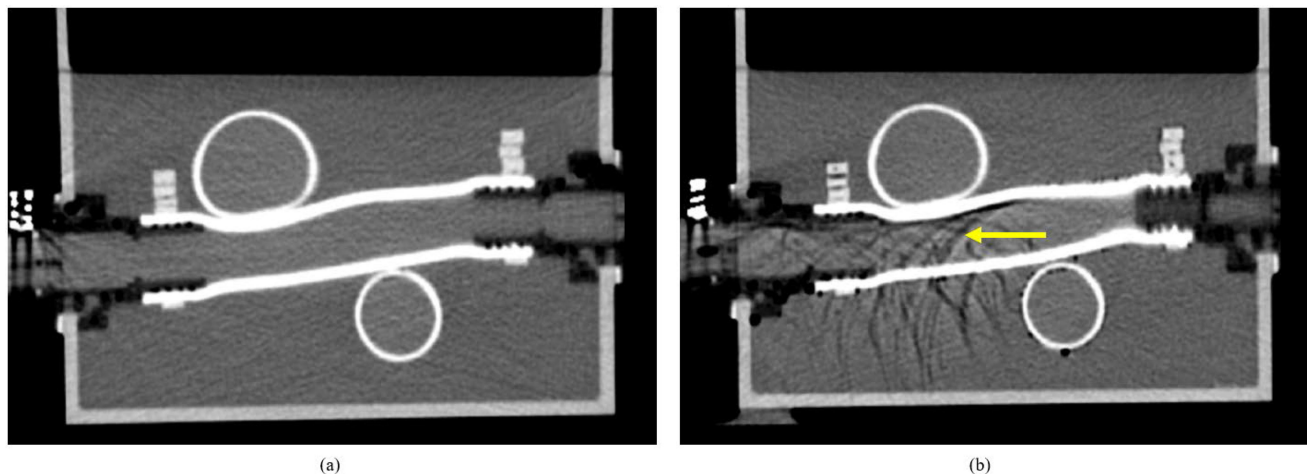
Fig. 1. Transient air bubbles in a vascular system can create artifacts that distort CT images. (a) represents a CT image of a pulmonary artery (horizontal tube structure), ascending and descending aorta (top and bottom circles) free of air, while (b) demonstrates the semi-tubular artifacts of a 0.1 mL air bubble traveling through the pulmonary artery. The artifacts are created as the moving bubble is unable to be reconstructed properly. Images were acquired in a circulation phantom, similar to those used to evaluate contrast media injections [22].

currently marketed injection systems, is then assessed by means of an experimental comparison of injected air volumes.

II. CURRENT APPROACHES

A. Contemporary Strategies for Air Management in CT

Commonly used CT power injection systems are electromechanical devices which typically use either pistons or peristaltic-pumps to deliver fluid from contrast media or saline containers into reservoirs or pump tubing sets, and subsequently into the patient via a patient tubing set. During the delivery of contrast media, air may be introduced at an intravenous access point. To prevent intravenous air injection, power injectors often employ a multi-stage approach which comprises: I) preventing air from entering the disposable components (i.e. reservoirs and/or tubing sets), II) purging internal air from the system, III) confirming air has been removed prior to patient connection, and IV) monitoring for air during injection. Some injection systems rely entirely on the operator for air management steps including filling, priming, bubble removal, and visual inspection prior to beginning the patient's injection. Manual methods, while proven to be safe and effective when performed correctly, are not optimal for workflow efficiency in high throughput departments.

Initial prevention of air from entering the disposable components is accomplished during the filling process. The operator attaches the fluid supply, ensuring that it contains sufficient volume to be used for the upcoming injection. However, during the filling and subsequent priming process, the air present in newly installed (empty) fluid paths may interact with the turbulent flow of the filling liquid. Additionally, air may be pulled out of suspension due to the negative pressures generated during filling. Each of these air sources form small bubbles which can be difficult to remove even with additional fluid flow, as surface adherence resulting from interfacial surface tension overcomes the buoyant force of the bubbles. Though the presence of these small air bubbles does not typically pose a safety risk in CT procedures,

they likely represent the majority of clinically injected air that are found in retrospective analysis of the CT images.

After priming, the system must be visually inspected by the operator to ensure hazardous volumes of air are not present, after which the injection can be initiated. Some power injectors include sensors to monitor the fluid path during the injection for the presence of air and to aid in prevention of intravenous air injection by aborting the injection if air above a specified threshold is sensed. Typically, these sensors are either optical or ultrasonic, relying on light refraction or sound attenuation differences between air and liquid to indicate the instantaneous state of the fluid path. However, calculation of air volume from these sensors requires continuous monitoring of the sensor output combined with three time-varying injector parameters: cross-sectional area of the fluid path, volumetric flow rate of the air, and pressure in the system at the location of the sensor.

To illustrate the importance of pressure measurement, Boyle's Law shows that with a pressure error of just 100 kPa (1 bar or 14.5 psi), a 100 mL volume of air can be inaccurately calculated as having a volume of 50 mL (Eq. 1). P_{atm} and P_{inj} are atmospheric and injector pressure, respectively, while V_{atm} and V_{inj} are the air volume at atmospheric and injector pressures, respectively.

$$P_{atm}V_{atm} = P_{inj}V_{inj}$$

$$V_{atm} = \frac{P_{inj}}{P_{atm}}V_{inj} \qquad (1)$$

As illustrated in Eq. 1, if the injector pressure measurement error doubles, the inaccuracy of the system to calculate air volume doubles. While this simplistic approach assumes air follows the ideal gas law and that the injector perfectly predicts cross-sectional area and flow rate of the air through the sensor, it demonstrates the importance of pressure on measurement of air volume. Notably, the advertised pressure accuracy of many of these injection systems includes a possible error significantly
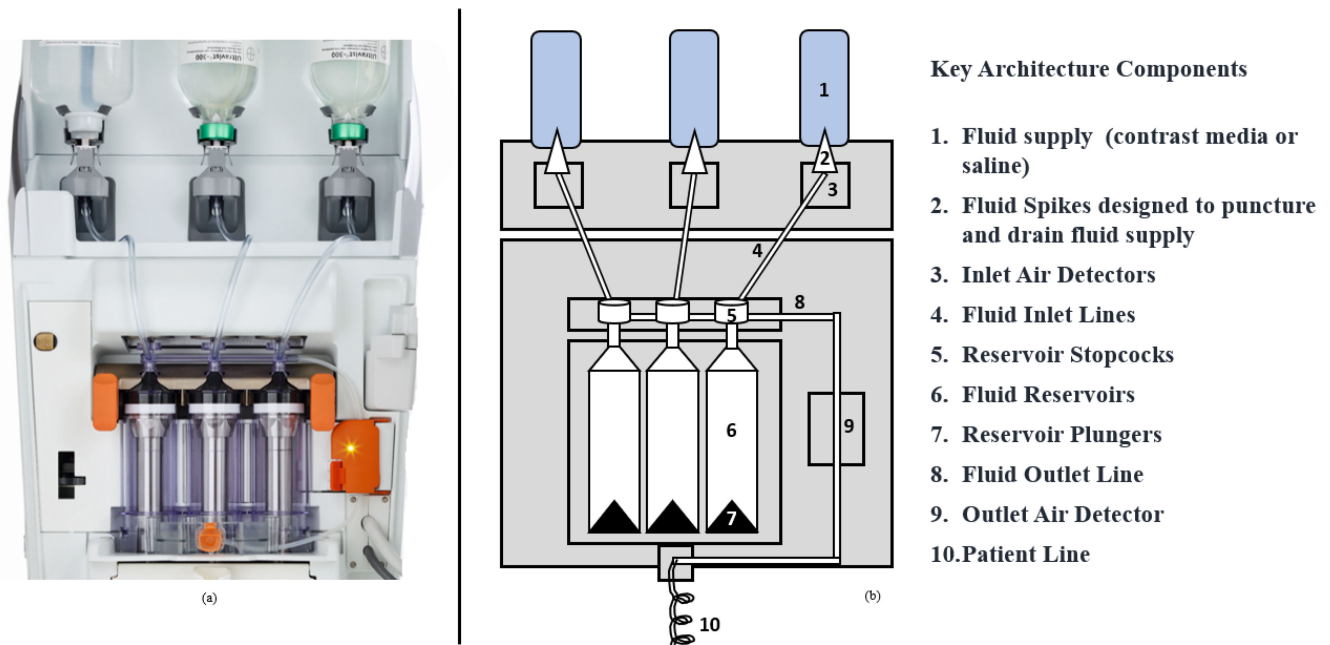
Fig. 2.   Overview of the architecture of the Centargo CT Injection System, including a photograph of the system (a) as well as a schematic with a legend of key architecture components that allow for a proactive air management approach (b).

greater than 100 kPa used in the example above [23]. Further, exact knowledge of tubing cross-sectional area and air flow rate is improbable given that injector tubing expands under pressure, dynamically changing the cross-sectional area and resulting in transient errors in flow rate estimation.

In order to compensate for the errors introduced by these dynamic injector parameters, while balancing the desire to reliably detect small air volumes (e.g. 1 mL), injection systems must take a conservative approach to aborting injections. Increased sensitivity, however, increases the risk of false detections and premature termination of injections. These aborted injections are a significant disruption, impacting workflow and user/patient satisfaction. Aborting an injection may also force the procedure to be repeated or rescheduled, leading to additional radiation dose for the patient. By primarily relying upon air sensors during injection, injectors apply what will hereafter be referred to as a reactive approach to air management. A reactive approach mainly uses a sensor to passively monitor for air during an injection, and upon detection of air, reacts per the manufacturer's design. Alone, a reactive approach is poorly positioned to balance air detection sensitivity with the risk of false detections that impact workflow.

B. Current Clinical Need

An optimal system design would reliably prevent both hazardous and artifact-inducing air injections while avoiding the negative impacts of aborted injections or impeding user workflow. This is not possible on systems that employ reactive air management approaches for the reasons previously outlined. However, a proactive air management approach, which aims to prevent air from entering the system and/or actively removing

air from the fluid path before the patient is connected for the procedure, may offer this potential.

III. PROPOSED SOLUTION

A. Proactive Air Management Architecture

To address this clinical need, the architecture of the MEDRAD Centargo CT Injection System (Hereafter referred to as 'Centargo' for simplicity) was designed to allow for implementation of a proactive air management strategy. The system utilizes two different disposable components. The first is referred to as a "day set" with three reservoirs gated by stopcocks and connected by a manifold, that can be used for 24 hours across multiple patients. The stopcocks are automatically controlled by the injector, and allow for filling of the contrast medium or saline into the reservoir as an intermediate step. Subsequent delivery to the patient occurs through the second disposable component, the "patient line". The patient line is a flexible tube that connects the fluid outlet line of the day set to the patient IV site, and includes check valves to prevent cross contamination between patients. This architecture provides the means through which proactive air detection is employed (Fig. 2).

Centargo completes three proactive air mitigation steps prior to allowing an operator to start an injection. First, inlet air detectors monitor the fluid inlet lines of the day set. Second, vacuum air removal occurs in the reservoirs during filling. This process removes small air bubbles that may go undetected by a reactive sensor and have the potential to induce artifacts. Finally, reservoir air detection, completed in the reservoirs prior to injection, measures the volume of air to determine if a hazardous air volume is present prior to connecting to the patient for injection. If a hazardous air volume is detected, reservoir air detection
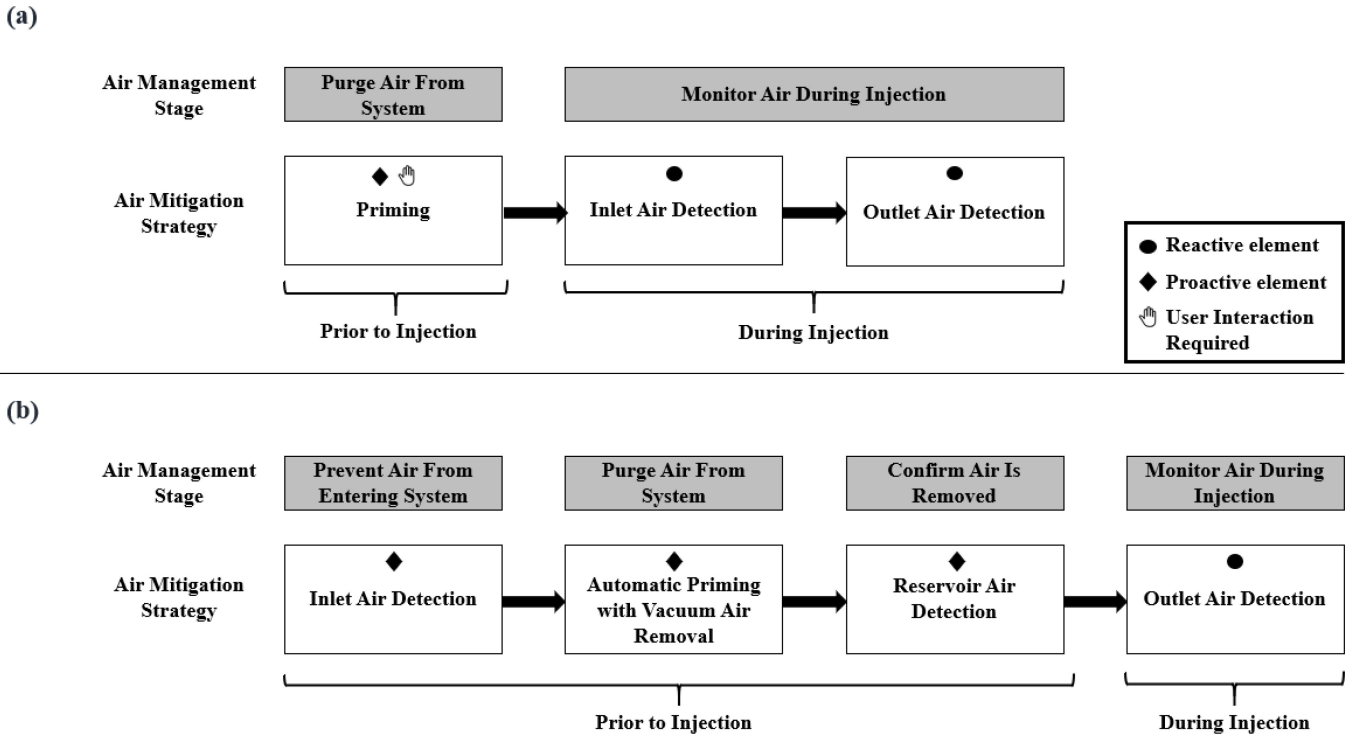
(a)

(b)

Fig. 3. A comparative overview of the reactive (a) and the proactive (b) air management approaches, including where user-initiated actions are required.

automatically removes the air from the system. Each of these strategies are conducted automatically by the system without user intervention, preserving workflow efficiency.

In addition to the proactive approach, Centargo provides a backup method to detect air should the aforementioned mechanisms simultaneously fail. Upon starting an injection with Centargo, an ultrasonic outlet air detector prevents air volumes of 1 mL or greater from being injected into the patient. Contrary to a reactive approach where monitoring for air during injection is the primary mechanism for preventing air injection, it is only used as a failsafe on Centargo which predominantly relies on the proactive steps previously introduced. Further, as monitoring for air during injection is only a backup measure in a proactive approach, and small air bubbles have been removed at this point in the workflow, the sensitivity of the detector can be tuned to focus on larger air volumes. This ensures that injections are not aborted due to false detections. The proactive approach used on Centargo is compared to a reactive approach in Fig. 3.

B. Inlet Air Detection

Air management on Centargo starts by preventing air from entering the system. The primary method by which air may enter the system is during the reservoir filling process, in which reverse movement of a piston draws fluid from a fluid supply into the reservoir. If the fluid supply runs empty or the fluid supply is not connected properly, there is the potential for air to be drawn into the reservoir.

To address this, each fluid inlet line must be installed into an inlet air detector (IAD) prior to filling. The IAD used by Centargo is an optical sensor that is tuned to differentiate between the
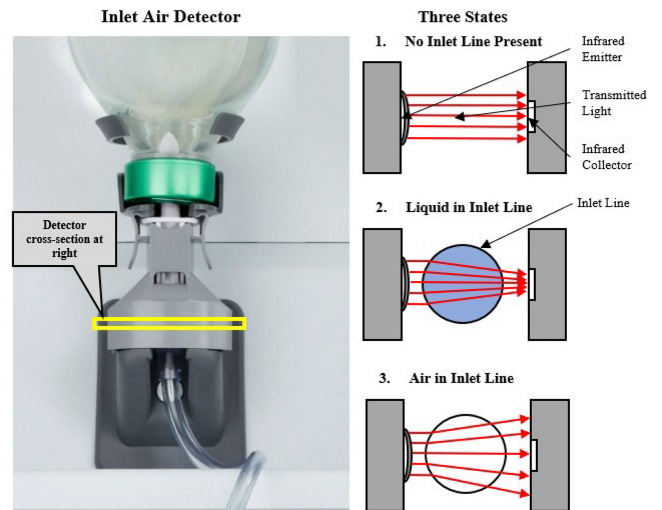

Fig. 4. An overview of the inlet air detector which is the first stage of the proactive approach. Left provides a photo of the detector in use, as the fluid path from the contrast media bottle passes through the detector before traveling into the system. Right provides a schematic of the three states of the detector which are determined by differences in refractive index of plastic, air, and liquid.

presence of air and fluid in the inlet line. In operation, infrared light is transmitted through the inlet line, with a collector monitoring the light received on the opposing side. As light travels across a boundary between two different materials (e.g. plastic, air, or liquid), the differences in index of refraction between the materials determine how the path of the light is altered at a given angle, noted by Snell's Law. In the context of the IAD, as shown in Fig. 4, light is scattered as it passes through a tube filled with

Vacuum Air Removal Process

1. Air bubbles in reservoir adhered to walls and plunger

2. Increasing negative pressure causes bubbles to increase in volume

3. Under absolute vacuum bubbles dislodge and de-gassing occurs

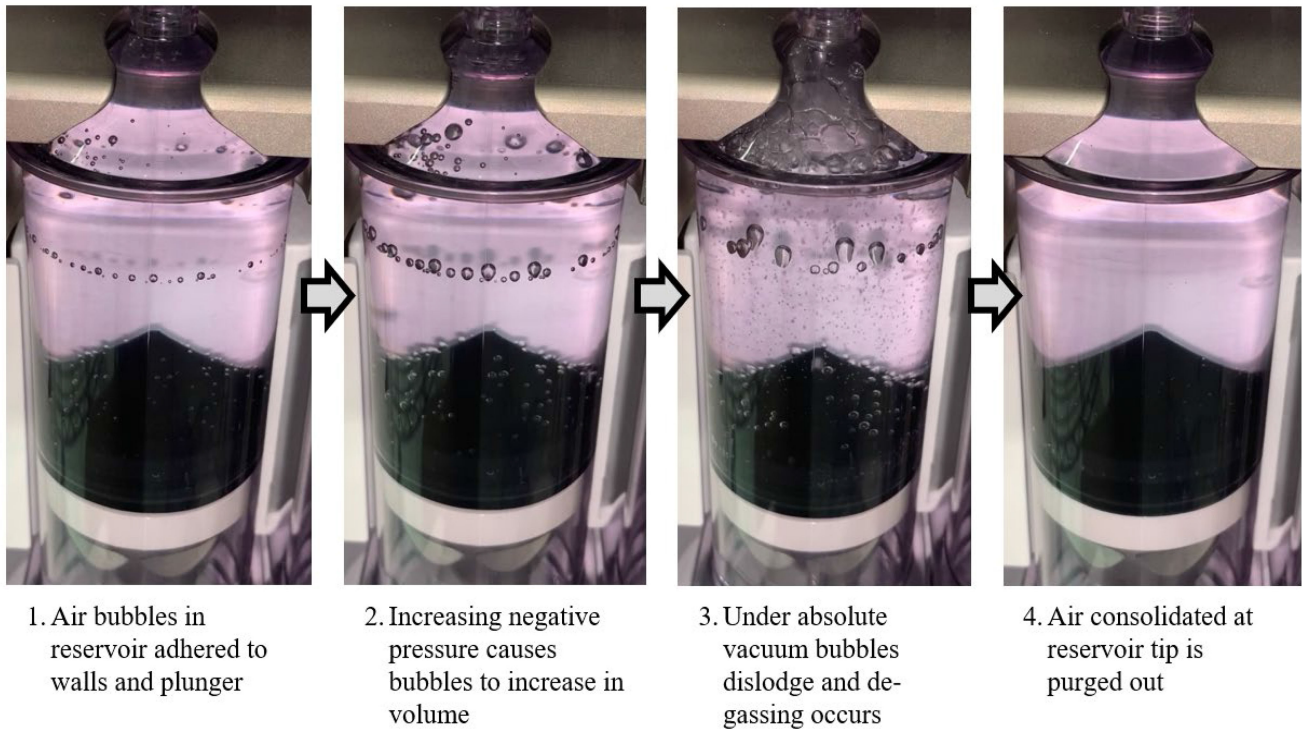4. Air consolidated at reservoir tip is purged out

Fig. 5. Sequential steps of the vacuum air removal process. Step 1 shows a reservoir which has numerous air bubbles adhered to the inner surfaces due to the turbulent filling process. Steps 2 & 3 show how the negative pressures increase the bubble sizes, causing them to float to the top, along with pulling dissolved gases out of liquid suspension. The result in Step 4 is a reservoir free of air bubbles that otherwise could have been injected.

air, while being focused when passing through a tube filled with liquid. This causes significant differences in the amount of light received at the collector, and the voltage change in the sensor can be calibrated to determine when air passes through the tube. This optical technique is commonly used for fluid assurance in a variety of industries, however the calibration techniques and specific use for CT injections are proprietary to the manufacturer.

The IAD allows the system to monitor the inlet line during a filling sequence, and if any air is detected while filling the reservoirs, the system will automatically stop and push the detected air volume back into the fluid supply. Such behavior prohibits filling the reservoir from an empty fluid supply or air introduced from improper spiking of the fluid supply. While some injection systems also include sensors to monitor for air being drawn in from the fluid supplies, this occurs during injection where detection would result in an aborted procedure.

C. Vacuum Air Removal

To eliminate the air bubbles that adhere to internal surfaces during the turbulent filling process, Centargo utilizes the stopcocks attached to the disposable reservoirs. The system automatically controls the stopcocks via servo motors without the need for user intervention. By closing these stopcocks during the filling sequence, the reservoirs become a closed system in which an absolute vacuum can be generated. With the system closed, the pistons are retracted to increase internal volume,

thus reducing pressure. This large decrease in pressure forces dissolved gasses out of liquid suspension and causes an increase in the size of the air bubbles adhered to the inner surfaces of the reservoir (refer to Eq. 1). The resulting pressure gradient and buoyancy increase allow the air bubbles to overcome forces of surface attraction and float to the top of the reservoirs where they can coalesce and, upon opening the stopcock, be purged from the fluid path. A visual example of this sequence, and the impact on the air bubbles is shown in Fig. 5.

Upon completion of this process, the reservoirs are generally free of air bubbles that would otherwise have had the potential to be delivered to the patient.

D. Reservoir Air Detection (RAD)

Although the vacuum air removal process is effective for removing small air bubbles, it does not account for larger air volumes present in the reservoirs due to possible defects in the plastic disposable components. To ensure that air has not entered the reservoir, RAD occurs immediately after filling and prior to the start of the injection. In addition to mitigating against disposable defects (e.g. crack in the plastic) that allow air to be drawn into the reservoirs during filling, RAD provides redundancy in the case of a failure of the inlet air sensors.

In order to detect the presence of air, RAD leverages the large differences in bulk modulus between liquid and air (2.2 GPa vs 101 kPa). Assuming liquid is incompressible relative to air,
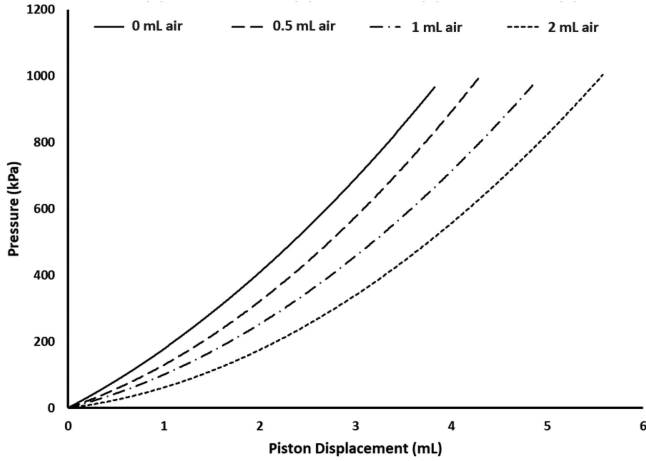
Fig. 6. Example demonstrating the differences in response to pressurization when a reservoir is filled completely with liquid, or contains varying volumes of air. The piston displacement represents the system compression which generates the pressure response. Increased air volumes require additional piston displacement (volumetric compression) to generate equivalent pressures.
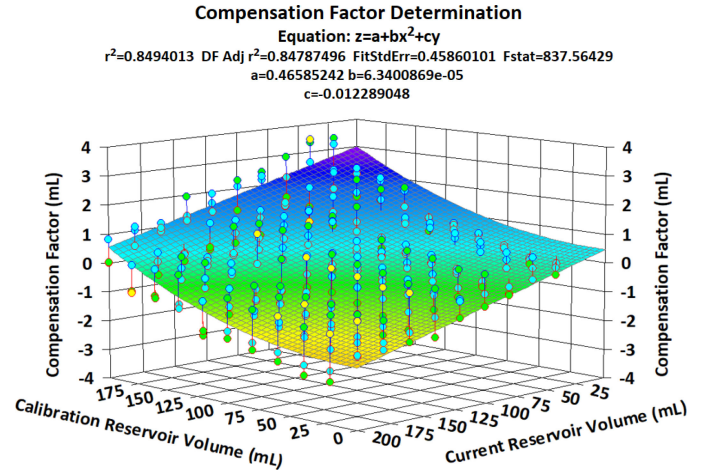

Fig. 7. Surface plot and resulting 3D equation generated to determine the compensation factor required during each RAD process. This compensation factor is based on the current volume of the reservoir being assessed, and varying calibration reservoir volumes were included to allow flexibility for re-calibration if needed.

Boyle's Law (Eq. 1) illustrates that when two reservoirs of the same size are pressurized equivalently, the reservoir containing air will require significantly greater volumetric compression to reach the target pressure relative to the reservoir containing liquid. This principle is the foundation of the RAD process on Centargo.

RAD is initiated immediately after filling a reservoir by closing the stopcock and advancing the plunger forward to a target pressure of 1000 kPa or greater. During the pressurization sequence, the plunger displacement and internal reservoir pressure are monitored by the system. These data are compared to a calibration data set which contains the plunger displacement and pressure values for a reservoir that is completely free of air (Fig. 6).

The differences in displacement values at each pressure are compared between the calibration set and the current reservoir condition. A resulting volume of air can be calculated from the following equation derived from the Ideal Gas Law (Eq. 2).

$$\text{Ideal Gas Law Equation}: PV = mRT$$

$$\text{Pre} - \text{Pressurization State}: P_{atm}V_{air} = M_{air}RT$$

$$\text{Pressurized State}: (P_{atm} + P_g)$$

$$+ (V_{air} + \Delta V) = M_{air}RT$$

$$P_{atm}V_{air} = (P_{atm} + P_g)(V_{air} - \Delta V)$$

$$P_{atm}V_{air} = P_{atm}V_{air} - P_{atm}\Delta V$$

$$+ P_gV_{air} - P_g\Delta V$$

$$P_gV_{air} = \Delta V(P_{atm} + P_g)$$

$$V_{air} = \frac{\Delta V(P_{atm} + P_g)}{P_g} \tag{2}$$

A confounding variable to this otherwise straightforward process is that the plastic disposables also expand under increasing pressure. This mechanical compliance is asymmetric depending on the internal volume of the reservoir and pressure generated. Under a pressure of 1000 kPa, a reservoir originally filled to maximum capacity (200 mL) has an internal volume increase of 6 mL due to expansion of the plastic disposables. Conversely, if the same reservoir is filled to only 10 mL, a pressure of 1000 kPa will increase the internal volume by less than 2 mL. Based on this information, the plunger displacement and reservoir pressure data for a reservoir containing 4 mL of air when originally filled to 10 mL will be indistinguishable from the same data collected from a reservoir originally filled to 200 mL with no air. To account for this source of error, a compensation algorithm was created which adjusts the calculated air volume depending on the position to which the reservoir is filled (Fig. 7).

E. Outlet Air Detection

After RAD has confirmed that no hazardous air is present in the reservoirs, Centargo initiates a priming routine designed to remove air from the patient line. During the prime sequence, an Outlet Air Detector (OAD) is used to monitor the outlet line and confirms that air is not traveling toward the patient line. As an ultrasonic sensor, the OAD determines the presence of air via differences in acoustic attenuation between fluid and air (Fig. 8). Due to the large density difference between injection fluids ($\sim$1000 kg/m^3 to 1400 kg/m^3) and air (1.225 kg/m^3), acoustic energy is more efficiently transmitted through liquid resulting in greater acoustic power from the OAD when liquid is present in the fluid path.

If air is detected during a prime sequence, the system informs the user that additional fluid is required to prime the patient line and does so automatically. Priming of the patient line delivers the air and fluid from the system into a built-in container for
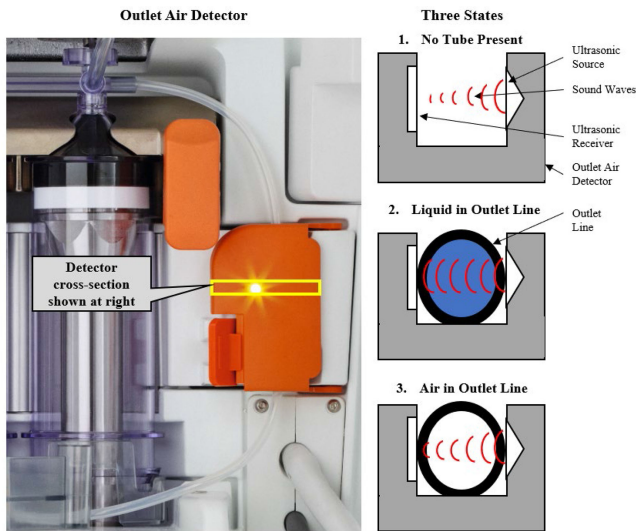
Fig. 8. Overview of the ultrasonic outlet air detector, showing the detector design and the difference in acoustic attenuation through an outline line filled with fluid or air. The relative size of the sound waves is exaggerated to represent acoustic power differences. Note, the entire tube is not required to be filled with air for the detector to sense attenuation differences. In addition, the LED shown (left image) is an indicator signaling that the air detector is properly closed and does not contribute to air measurement.

waste. While not unique to Centargo, this priming procedure is the final automated air mitigation step prior to connecting the fluid path to a patient.

After the operator completes a final visual check of the patient line and connects the fluid path to the patient's catheter, the system allows the user to initiate the injection. The OAD then monitors the fluid path during an injection. At this point in the CT procedure, the OAD is used as a reactive method for air detection, however interruption of an injection is only expected in the event that all previous proactive air detection methods fail simultaneously. When used as a back-up sensor, rather than the primary method of air detection as in contemporary systems, the sensitivity is able to be tuned in order to avoid interrupted procedures due to false detections.

IV. EXPERIMENTAL DESIGN

To provide a quantitative comparison of the performance of proactive vs. reactive air management in preventing venous air embolism, Centargo was tested against two contemporary injection systems employing reactive approaches. All systems underwent simulated clinical use, and the injected air volumes from each system were measured.

A. Materials

Three CT injection systems were used from three different manufacturers: the aforementioned Centargo injection system (Bayer AG, Berlin, Germany), ulrich CT motion$^{\text{TM}}$ Contrast Media Injector (Hereafter referred to as 'CT motion', ulrich

Medical, Ulm, Germany), and Bracco CT Exprès Contrast Injection System with Multi-Patient Set (Hereafter referred to as 'CT Exprès', Bracco Injeneering, Lausanne, Switzerland). The selection criterion for the injectors was an automated air management system, defined here as utilizing at least one air sensor. For the purposes of this study, injectors that rely solely on the operator for air management were excluded, as relying on the operator introduces inherent subjectivity. All tested systems were operated according to the manufacturers' instructions with standard disposable components from each manufacturer designed for multiple injections/patients. Catheters, contrast media, flow rates, and fluid volumes were chosen to be representative of standard clinical practice [23], though variation in these parameters is not expected to impact the volume of air delivered by each system. For consistency, the contrast media used in this study was at room temperature (21.5 °C), though warming of contrast media to body temperature is also not expected to impact the results of this study.

B. Methods

Injected air volumes under simulated clinical use were compared between Centargo with a proactive air management approach, and two injectors with reactive air management approaches, CT motion and CT Exprès. A total of 90 injections (30 per injector) were performed with the distal end of the patient lines connected to a custom air trap fixture (Fig. 9).

To mimic the clinical workflow, the patient line was replaced and primed for every injection according to each manufacturer's instructions. After the priming process was completed, and prior to attaching the patient line to the air trap fixture, the tube was inspected visually for the presence of any air bubbles. The presence or absence of bubbles in the patient line following priming was recorded for each trial.

The air trap is a test fixture specifically designed to collect all air delivered from the patient line during an injection and subsequently measure the air contained within the fixture. Similar to RAD, measurement of the air volume is based on the difference in the pressurization response of the fixture with and without air. Though unlike RAD the volume of the air trap does not change appreciably, as the fixture is constructed from rigid materials which limits volumetric expansion under pressure.

Prior to an injection, all air was purged from the air trap fixture. Then the air trap was closed and subsequently pressurized to 400 kPa using a precision micropump (neMESYS Syringe Pump, CETONI GmbH, Korbussen, Germany) and pressure transducer (-14.7 psi to 500 psi, STS Pressure Transmitter, PMC Engineering LLC, Connecticut, USA). Displacement and pressure data were sampled at 10 Hz and collected using a custom controller written in a C-based programming language. This initial pressurization is referred to as baseline data and accounts for any expansion of the fixture under pressure. After the initial pressurization, the air trap was opened to remove the internal pressure. Next, the injector patient line was primed and visualized for air bubbles, as previously noted, and the distal end of the patient line was connected to the fixture. Care was taken

Key Testing Components

1. Injection System
2. Data Acquisition
3. Displacement Pump
4. Pressure Transducer
5. Air Trap Fixture
6. Air Trap Inlet
7. Pump Outlet
8. Air Trap Purge Line
9. Stopcock Valve
10. Air Trap Structure
11. Air Trap Outlet
12. Linear Actuator
13. Precision Syringe
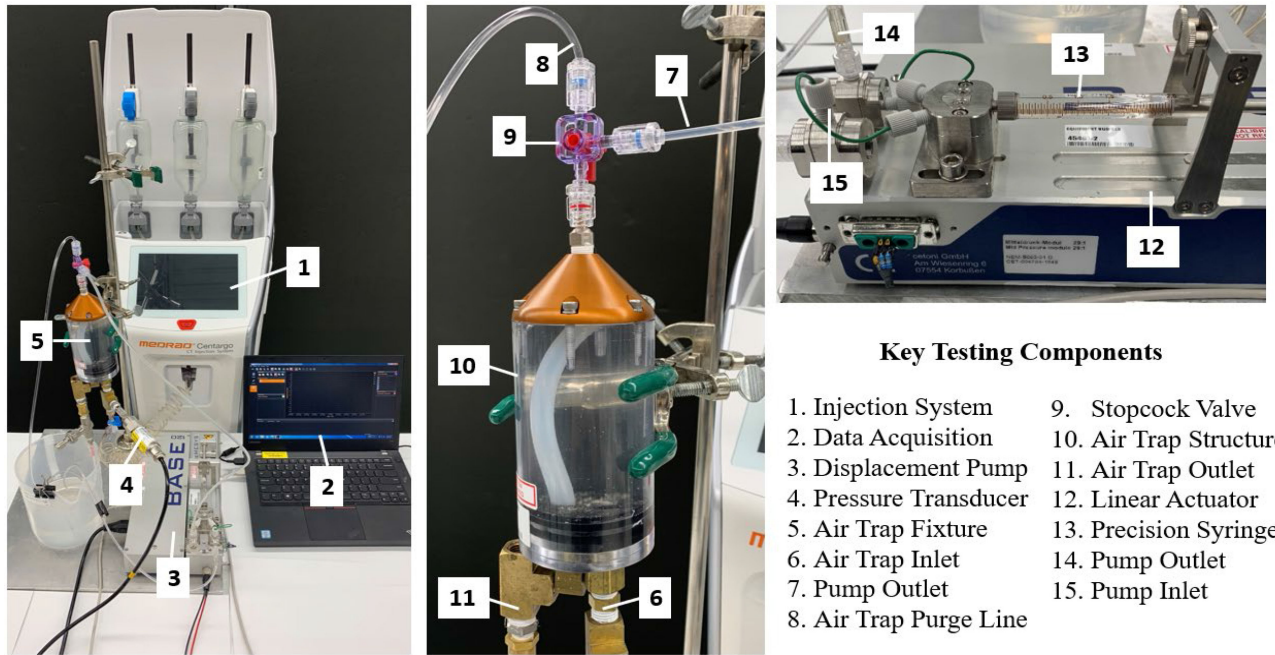14. Pump Outlet
15. Pump Inlet

Fig. 9. Overview of the experimental setup. The entire setup is displayed in the image on the left, with a close-up on the air trap fixture (middle) and the precision delivery system (right). Key testing components are identified in each image.

to ensure a wet to wet connection between the patient line and fixture inlet to avoid inadvertent introduction of air.

With the air trap outlet open, the injection is performed. A 20G catheter was placed on the air trap outlet to generate the desired injection pressure, consistent with clinical practice. During an injection the air trap design allows fluid to exit the air trap outlet, while air present in the injector fluid path is collected at the top of the fixture and retained for measurement (Fig. 9). After the injection was completed, the air trap was closed, and the fixture was again pressurized to 400 kPa. This second pressurization is referred to as the measurement data.

Using the ideal gas law in combination with the baseline and measurement pressure-displacement data, the volume of air present in the air trap fixture following an injection was calculated. This is similar to the calculation performed as part of the RAD process (Eq. 2), though no compensation factor was needed. To obtain a sufficient signal to noise ratio and avoid impacts of motor acceleration, baseline and measurement data were used to calculate air between 69 kPa and 345 kPa. Air volume calculations were averaged over this pressure range to provide a single measurement for the air volume contained in the air trap following an injection. An overview of the measurement calculations and resulting graphical representations are shown in Equation 3 and Fig. 10, where P_{atm} is atmospheric pressure, P_g is gauge pressure, V_p is the volume used to pressurize the reservoir, and V_c is the volume lost to expansion of the reservoir.

$$[P_{atm} + P_g][V_{air} - V_p + V_c \times P_g] = P_{atm} \times V_{air}$$

$$V_{air} = \frac{[P_{atm} + P_g][V_p + V_c \times P_g]}{P_g} \tag{3}$$

C. Statistical Analysis

A One-Way ANOVA with a Tukey Pairwise Comparison using $\alpha = 5\%$ as a significance level was conducted for individual comparison of injected air volumes between Centargo, CT motion, and CT Exprès. As an exploratory analysis, p-values ≤ 0.05 can be interpreted to be statistically significant. Minitab statistical software (Version 17, Minitab, LLC) was used for all analyses.

D. Measurement Method Validation

To ensure that the results from the study accurately represent injected air volumes, validation of the air trap fixture was conducted to establish an expected measurement uncertainty. Known air volumes of 0 mL, 0.05 mL, 0.1 mL, 0.2 mL, and 0.5 mL were introduced into the air trap using a precision automated delivery system (neMESYS Syringe Pump). The range of air volumes was chosen to encompass the expected air volume delivered by the injection systems under normal clinical use. Calculated air volumes from the air trap were measured and then compared to the known volumes to determine measurement uncertainty. In addition, three replicates were conducted at each air volume to assess repeatability.

The uncertainty of the measurement method was determined to linearly increase with increasing air volume, however the relative uncertainty was small. At 0.050 mL of air, the uncertainty was measured to be an average of +0.012 mL. From 0.1 mL to 0.2 mL of air, the average uncertainty was measured to be from +0.010 mL to +0.022 mL. Above 0.2 mL of air, the average uncertainty was measured to be +0.032 mL. For the purposes of

Fig. 11. Validation data for the air trap fixture showing the measured air volumes from the fixture compared to the known air volumes introduced with the precision pump. In parentheses, the average error at each data point is provided.
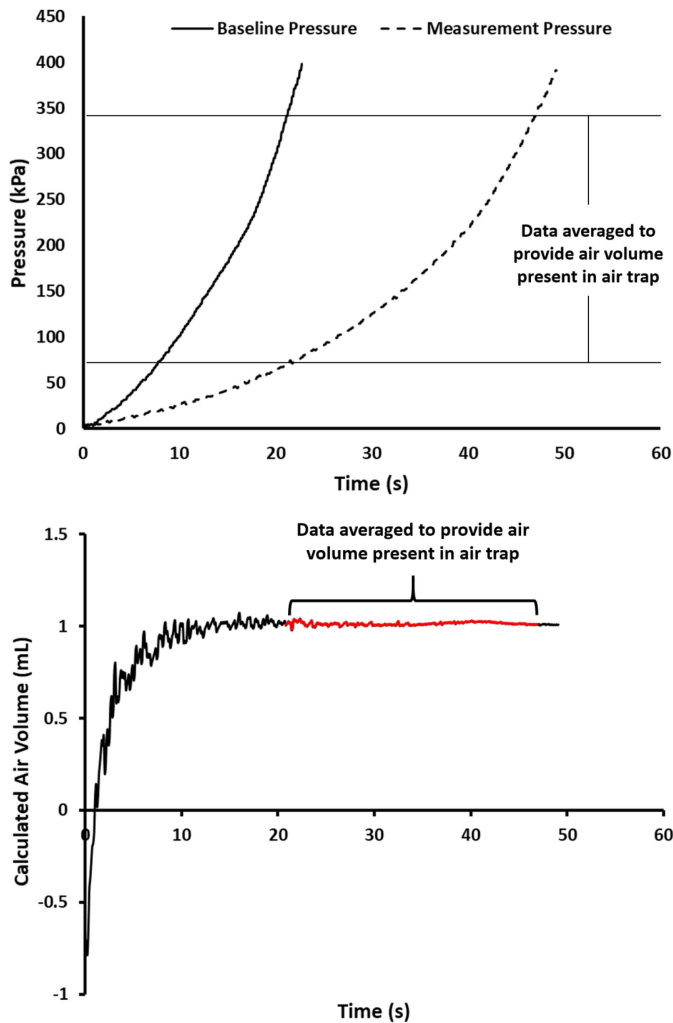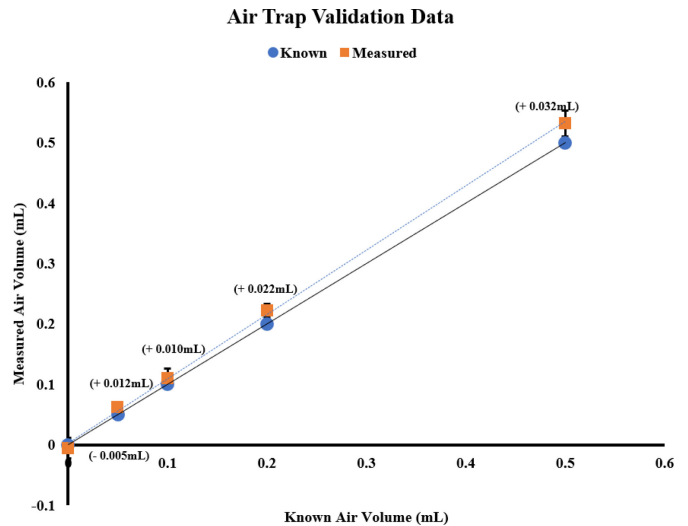

Fig. 10. Method of utilizing the custom air trap fixture to calculate the volume of air injected from the systems. (Top) represents sample data showing the difference in pressurization response between the baseline with 0 mL of air and the measurement with 1 mL of air (1 mL chosen as an example for simplicity). (Bottom) demonstrates the plot of the calculated air volume over time from Equation 3, highlighting the region over which the average measurement is taken (69 kPa to 345 kPa).
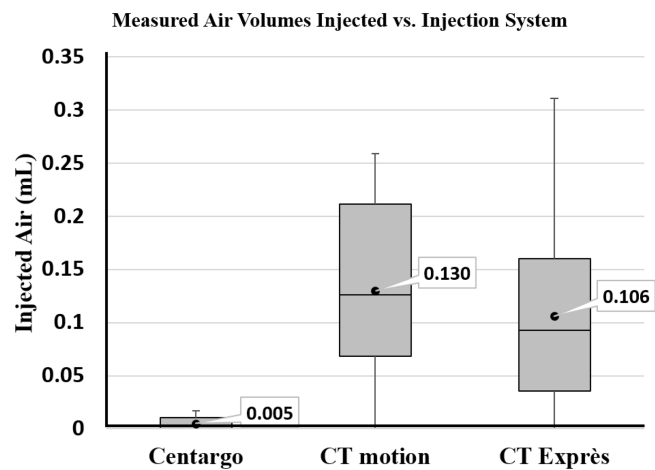

Fig. 12. Boxplot for injected air volumes among the three tested injection systems. The means are displayed for each system and represented by the black dot on the boxplot (30 injections per system). Centargo provided a statistically significant decrease in injected air volumes when compared to CT motion and CT Exprès ($p < 0.05$). Air volumes measured by the fixture to be negative were clipped at 0 mL.

this study, the overall uncertainty was deemed to be acceptable. Validation data are shown in Fig. 11.

V. RESULTS

A. Injected Air Volume Comparison

Injected air volume for all three injection systems, as measured by the air trap fixture, is provided in Fig. 12. Centargo injected significantly less air when compared to CT motion and CT Exprès under simulated clinical use ($p < 0.05$). Across 30 injections, there were zero observed cases of air bubbles in the Centargo patient line prior to injection, and the average injected air volume for Centargo was 0.005 mL $\pm$ 0.006 mL with a maximum of 0.017 mL. For 15 of the 30 injections performed on CT motion, at least one visible bubble was observed in the patient line prior to injection, while the average injected

air volume was 0.130 mL $\pm$ 0.082 mL with a maximum of 0.259 mL. For CT Exprès, 8 of the 30 injections saw at least one visible bubble in the patient line prior to injection, and the average injected air volume was 0.106 mL $\pm$ 0.094 mL with a maximum of 0.311 mL. Additionally, the observed distribution of measured air differs significantly, with Centargo having a standard deviation of 0.006 mL, while CT motion and CT Exprès had standard deviations of 0.082 mL and 0.094 mL, respectively. It was noted that no injections during this study were aborted by any system due to triggering of the sensors. Example images of air bubbles observed in the patient lines prior to injection are shown in Fig. 13.
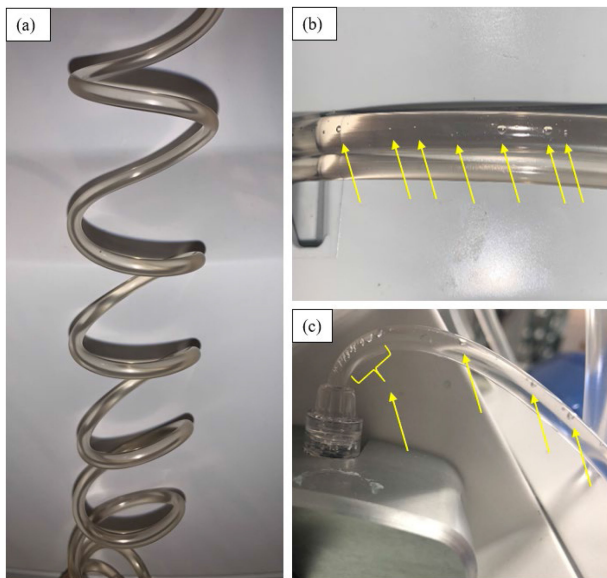
Fig. 13. Representative examples of the observed air bubbles, noted by the yellow arrows, that were visible prior to injection in the CT motion and CT Exprès disposables (b, c). As there were no observed instances of visible bubbles in the Centargo disposables, a sample image is provided of the tubing set showing it to be free of bubbles (a).

VI. DISCUSSION

A. Pros and Cons of Air Management Approaches

The implications of air injection in CT are well established and can impact patient safety, diagnostic image quality, workflow efficiency, as well as patient and radiographer satisfaction. Reducing the prevalence of air embolism in CT is desirable even for small air volumes that do not present a safety risk, as these air bubbles have the potential to cause imaging artifacts. While contemporary methods of air detection and management in CT power injectors are sufficient for preventing injection of potentially hazardous volumes of air, the methods are reactive and fail to prevent the injection of small yet visible bubbles. Additionally, transient, dynamic fluid flow presents challenges for sensors to accurately calculate air during an injection. The relatively wide potential error created by unknown flow conditions may lead to occasional false detection of air and aborted injections with non-hazardous air volumes present, as increased error reduces the ability to balance the sensitivity of the sensor against the desire to prevent false detections.

In order to address these shortcomings of traditional air detection methods, a proactive approach was proposed and implemented in an injection system. The architecture of this injection system, Centargo, provides three levels of automated, proactive air management. The inlet air detectors and reservoir air detection process ensure the system is free of potentially hazardous air volumes prior to beginning the injection, and the vacuum air removal sequence ensures removal of small, potentially artifact-inducing air bubbles.

To quantify the effectiveness of proactive air management, a novel air trap fixture was designed to measure air volumes delivered from several contemporary injection systems, including Centargo. The design of the air trap fixture leverages differences in compressibility between air and liquid to measure the volume

of air delivered by each system. Utilizing precision delivery and pressure monitoring equipment, along with a unique mechanical fixture, the air trap was found to be capable of determining the volume of air injected with a maximum calculated uncertainty of 0.032 mL. Analysis of the injected air volumes under simulated clinical use shows that Centargo, with a proactive air management strategy, injects significantly less air compared to the other tested systems. Additionally, the observed distribution of measured air from Centargo is narrow when compared to the other tested systems. Further, no air bubbles were observed in the tubing set of Centargo prior to injection, nor in the air trap upon the subsequent purge after injection. Given this evidence, in combination with the average measured air volume within the expected error distribution of the air trap fixture and the lack of observed air bubbles during simulated use, it can be reasonably interpreted that Centargo did not inject a detectable amount of air throughout the simulated clinical use. These findings suggest that the proactive air management strategy used for Centargo successfully eliminates the injection of air bubbles during simulated clinical use, while the reactive air management approaches used for the other tested systems allow detectable air volumes to be injected.

There are two significant implications to injecting even small air volumes, such as those observed in this study. First, given the complications of measuring air volumes during the transient flow of an injection, small air volumes injected have the potential to be misidentified as larger volumes and therefore prematurely abort the injection. As mentioned, this disrupts workflow, decreases operator and patient satisfaction, and can result in additional radiation exposure for the patient if the scan must be repeated. Measuring rates of aborted injections due to air detection in a clinical environment is an opportunity for future study. Second, air bubbles that are injected can create motion artifacts while flowing through the pulmonary vasculature as previously shown in Fig. 1B, or can become trapped in the right atrium or right ventricle of the heart and become clearly visible in images [25]. These artifacts and reconstructed bubbles have the potential to obscure small structures and possibly inhibit diagnosis. Even small air volumes of 0.1 mL, less than the average air injected by CT motion and CT Exprès in this study, are clearly visible in images, as shown in Fig. 14. An air bubble 0.1 mL in volume at a nominal blood pressure of 120/80 mmHg has a spherical diameter of between 5.5 mm to 5.6 mm, however common CT scanners have a spatial resolution down to 0.5 mm; meaning that an air bubble as small as $\sim$0.5 microliters is potentially visible [26].

The observation of air bubbles in the disposable sets for CT motion and CT Exprès are likely responsible for the higher volumes of injected air. As previously mentioned, significant flows (i.e. those seen during injection) are required to dislodge the bubbles, therefore it is expected that priming sequences are ineffective at bubble removal. The vacuum air removal process on Centargo addresses the presence of these bubbles, removing them prior to the start of both the priming sequence and the subsequent injection. While air bubbles in the patient lines of CT motion and CT Exprès can possibly be removed with additional manual priming, this process increases waste, disrupts workflow, and is only effective if the air bubbles are observed by an attentive operator.
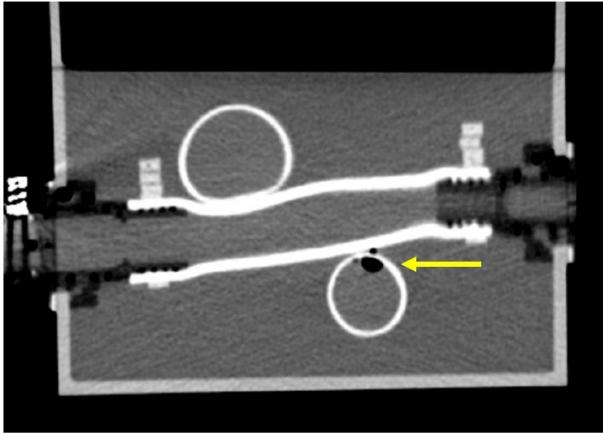
Fig. 14.   CT image demonstrating the presence of a static air bubble with a volume of 0.1 mL. The bubble, located by the yellow arrow, is clearly visible in the image.

B. Limitations

There are some limitations to this work that should be noted. First, the present study was not inclusive of all marketed CT power injectors; however, CT motion and CT Exprès represent two common injection systems with reactive air management against which a proactive approach could be compared. In addition, this study specifically excluded the use of injection systems that solely rely on the operator for air management due to the subjective nature of operator variability and the impact on workflow efficiency.

Additionally, the study performed injections into an air trap fixture, rather than a human patient. Due to ethical concerns regarding air injection into human patients, the present study is unable to directly relate measured air volumes from the injectors to artifacts in clinical images. Still the measured air volumes in this study are in line with air volumes previously shown to be present in CT images and contributing to degraded CT image quality (Fig. 1, Fig. 14) [21]. Future clinical studies may observe the occurrence of aborted injections due to air detection or the frequency of air artifacts while comparing the proactive and reactive methods.

VII. Conclusion

With proactive air management and automated air removal processes on Centargo, the injected air volumes were significantly lower as compared to CT motion and CT Exprès. While all tested systems are expected to prevent the injection of potentially hazardous air volumes, the results signal that the use of proactive air management with Centargo will significantly reduce the prevalence of observable venous air embolism in contrast-enhanced CT procedures. Proactive air management may not only reduce observable air found in CT images, but also reduce the workflow disruptions of aborted injections that can result in additional radiation exposure for patients.

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