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Mechanical aspects of CO₂ angiography

Ivan Corazza^{a,*}, Pier Luca Rossi^a, Giacomo Feliciani^a, Luca Pisani^b,
Sebastiano Zannoli^b, Romano Zannoli^a

^a Cardiovascular Dept., University of Bologna, Via Massarenti, 9, 40138 Bologna, Italy

^b Spark SrL, Bologna, Italy

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Abstract The aim of this paper is to clarify some physical–mechanical aspects involved in the carbon dioxide angiography procedure (CO₂ angiography), with a particular attention to a possible damage of the vascular wall.

CO₂ angiography is widely used on patients with iodine intolerance. The injection of a gaseous element, in most cases manually performed, requires a long training period. Automatic systems allow better control of the injection and the study of the mechanical behaviour of the gas.

CO₂ injections have been studied by using manual and automatic systems. Pressures, flows and jet shapes have been monitored by using a cardiovascular mock. Photographic images of liquid and gaseous jet have been recorded in different conditions, and the vascular pressure rises during injection have been monitored.

The shape of the liquid jet during the catheter washing phase is straight in the catheter direction and there is no jet during gas injection. Gas bubbles are suddenly formed at the catheter's hole and move upwards: buoyancy is the only governing phenomenon and no bubbles fragmentation is detected. The pressure rise in the vessel depends on the injection pressure and volume and in some cases of manual injection it may double the basal vascular pressure values.

CO₂ angiography is a powerful and safe procedure which diffusion will certainly increase, although some aspects related to gas injection and chamber filling are not yet well known. The use of an automatic system permits better results, shorter training period and limitation of vascular wall damage risk.

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Introduction

Carbon dioxide angiography (CO₂ angiography) is a diagnostic radiological procedure introduced about fifty years ago to obtain vascular images without the use of iodinated contrast medium. Gaseous CO₂ was chosen for its

* Corresponding author.

E-mail address: ivan.corazza@unibo.it (I. Corazza).

biocompatibility, easy removal from the blood, very low viscosity and no appreciable medical contraindication. Unlike iodinated contrast, injected CO₂ does not mix with blood but displaces it and the X-ray absorption is roughly 1/10 of that obtained with diluted iodine [1–3].

For these reasons, both the injection process and the radiologic setup must be optimised to yield good quality angiographic images. The two are not independent, and must be managed together: the injection should fill the vascular chamber and the X-ray emission must be regulated to compensate the instantaneous change in the shape and position of gas bubbles (DSA at low frame rate with staking) [4–6].

In the case of liquid contrast medium (CM) the hydraulic resistance of the injection line (catheter, stopcocks, connection lines) is very high due to the small internal radius of the catheter and the high CM viscosity. A quite high pressure (≈ 10 Bar $\approx 10^6$ Pa) must be applied to inject the CM required in a short time (from 1 s to 3 s): an automatic mechanical injector is mandatory to visualise high volume and high flow cavities (aorta, ventricles, etc.). Manual injection of iodinated CM is restricted to single vessel imaging (coronary arteriography, selective angiography) [7–9].

CO₂ has a very low viscosity compared with iodinated CM, the hydraulic resistance of connection lines is low and most injections may be made manually, but the vascular imaging results are not always as good as possible and expected, due to the mechanical behaviour and the small radiological absorption coefficient of the gaseous CM.

This study investigated some of the mechanical aspects of angiographic CO₂ injection [10–13] to highlight the points which may optimise the procedure, reduce the vascular injury risk and enhance radiologic image quality.

Methods and results

The first step of the study was to observe the pressure and flow time course during gas injection under different operative conditions [14,15].

With manual operation (widely used) it is very difficult to control the pressure of the CO₂ gas in the syringe during injection, and the time course of output gas flow is very

unstable (Fig. 1). If the injection pressure and hence the output gas flow are not well known, it is very difficult to discuss the mechanical and radiological aspects of the procedure.

To overcome this limitation an automatic presettable constant pressure and volume injector (Sias S.p.A, Bologna, Italy) and a dedicated setup were used (Fig. 2). With this setup the gas output from the catheter hole can be monitored throughout all the phases of the injection procedure [16,17]. In fact, the instantaneous behaviour of the flow is described by $P_2(t)$ (assuming the hydraulic resistance of the terminal part of the pipe to be constant).

The imaging gas injection follows a low pressure catheter washout phase. As the pressure during the imaging injection is roughly constant and the line is liquid free, the gas flow can be calculated by dividing the preset gas volume by the experimentally measured injection time (T), which changes by changing the injection pressure (Fig. 3).

To measure the pressure during the injection phase a disposable pressure sensor (Edwards Tru Wave, natural frequency 40 Hz), connected to a Light Workstation (Spark S.r.L, Bologna, Italy) was used. Pressure–flow curves for the single hole 4F catheter used (Terumo Optitorque, 0.97 mm, 100 cm) are shown in Fig. 4. The pressure–flow relationships for other type of catheters (length, size and holes) can be obtained in the same manner, and can be stored in the injector internal processor.

The second step was to observe the gas behaviour during injection. For this a chamber with transparent walls was assembled; the catheter hole was positioned in the centre of the chamber filled with water and the gas output was recorded by a high frame rate camera (Casio Exlim EX-FH 20, 420 fps) (Fig. 5).

To visualise the liquid jet during the catheter washout phase (which is assumed could damage the vascular wall) saline mixed with a small amount of brown dye was used. Records were obtained with manual injection and automated injection at different gas volume and pressure. Each record lasted about 20 s and was composed of two parts: a) catheter washout, with a brown liquid jet followed by a small amount of washing gas; b) imaging CO₂ injection, with large

Figure 1 Pressure–time graph of two manual CO₂ injections. Phase A corresponds to line washing; phase B corresponds to gas injection.

Figure 2 Pressure and flow measurement setup during injection. P_1 shows the time course of the pressure applied by the injector; P_2 shows the pressure drop recorded at fixed length terminal part of the injection catheter.

bubbles in chaotic buoyancy. Selected images of the catheter washing phase (liquid jet followed by a small amount of gas) and subsequent gas injection are shown in Fig. 6.

For the previous steps the injections were made in an open chamber (output pressure ≈ 0 Pa). To make a closer simulation of a real condition a silicone cast of descending aorta was made (Fig. 7).

The cast was connected to an electromechanical cardiac simulator to produce a "physiologic" condition (60 bpm, 120/80 mmHg, 25 ml/beat). [18]. The previous 4 French catheter was positioned in the centre of the aortic vessel and more realistic CO₂ gas injections were tested at different pressures and gas amounts (Fig. 8).

During the injections, performed manually and by the injector, with and without line washout, the pressure in the syringe and in the aortic chamber was recorded simultaneously (Fig. 9). The rises in arterial pressure under different injection conditions are shown in Fig. 10.

Discussion

The CO₂ angiographic procedure has been studied in depth and it is accepted as a safe and effective diagnostic tool

Figure 3 Recorded pressure–time signal with preset injection pressure (P_0) and gas volume. The injection time T is experimentally measured by the crossing of the preset pressure value and the back extrapolated exponential pressure curve.

Figure 4 Pressure–flow values at different injection gas volumes.

[1–3,8,19,20]. Nevertheless some procedural aspects remain unsettled. In most cases a manual injection is used and expert operators refer that long period of empirical training is required to obtain good quality images. This is because it is necessary to acquire the skill to control the manual injection and to use the natural properties of CO₂ (buoyancy) to obtain an optimal gas filling of the vessels. The operative learning process is mainly based on observation of the images obtained and the effects of changes in manual operations. How the gas is injected under the different operative conditions is a consequence of previous positive and negative experiences, and a knowledge of the mechanical behaviour of the gas in the vascular cavity is assumed to be not important [19–22]. The problem of injection control has mainly been tackled to control the pressure, and automatic injectors have been proposed [16,17], but manual injection remains the most common technique even in very sophisticated procedures [6,16,23,24].

Asked about the operative problems of CO₂ angiography, an expert radiologist will highlight the difficulty of complete cavity and vessels visualisation (which depends on gas volume, pressure and patient positioning) and the

Figure 5 Jet recording chamber. During injection the high Frame rate camera records the shape of the liquid and gaseous jet.

Figure 6 Photographs of catheter washout and gas injection. The liquid jet during washout is in the direction of the catheter (ft. 1, 2, 3). During the gas injection the phenomenon is controlled only by the gas buoyancy (ft. 4, 5, 6).

risk due to the liquid and gas jet impact on the vessel wall at the onset of injection. Our records obtained at “quasi-constant” injection pressure, with the possibility to observe the liquid jet in the line washing phase and subsequent gas injection, completely clarify these points.

An initial aspect of interest is the analysis of the behaviour of the gas pressure during manual injection (Fig. 1), which is a quite complex condition. Two successive phases can be observed in the pressure behaviour. At the onset of injection (phase A in Fig. 1), the pressure in the syringe reaches peak values due to the high hydraulic resistance of the water-filled connection line (catheter, stopcocks, connection). During this phase (line emptying) the speed of the output fluid jet progressively increases, as shown by the shortening of the span of laminar flow between the catheter hole and the onset of turbulent flow (Fig. 6). The highest fluid velocity is reached at the end of the line emptying, and this is when the vascular wall may be injured. As soon as the connection line and the catheter are completely emptied of liquid and filled with gas, the hydraulic resistance falls to a very low value and the syringe piston moves forwards easily: in this phase the pressure in the syringe drops sharply and it is up to the operator to keep it sufficiently stable (phase B in Fig. 1).

It is not easy to evaluate the effects of syringe pressure changes by observing the gas output from the catheter hole: the gas output shows a roughly chaotic process with generation of large bubbles, and it is difficult to describe it simply.

During the injection a gas jet would be expected in the forward direction of the catheter, with a gas shift proportional to the applied pressure, but the recordings show a different behaviour. As soon as the liquid jet stops and the gas is emitted, the forward movement stops, the gas bubbles are formed around the catheter hole, and immediately move upwards due to their buoyancy. This behaviour does not change by changing the pressure and the gas flow (Fig. 4), and also the size of the bubbles seems to be unchanged. This behaviour of the gas, instinctively unexpected, is coherent with the rules of physics governing the phenomenon. In fact when the line is filled with liquid, the pressure force accelerates the particles and at the output hole they move forward to some extent due to the mechanical inertia. With gas, the mass is very low, the inertia is low too, and as soon the gas is emitted from the catheter hole the forward movement stops: a bubble is

Figure 7 Silicone cast of descending aorta used to monitor the pressure rise during injection.

Figure 8 Setup for injection simulation in a silicone cast descending aorta connected to the mechanical cardiac mock. P_1 = injection pressure, P_2 = aortic pressure, R = flow regulators.

Figure 9 P_1 and P_2 pressure recordings during automated line washout and CO₂ gas injection. ΔP_s is the systolic aortic pressure rise during injection.

immediately formed and buoyancy pushes the bubble upwards. As the gas flow is so high, the bubble is not spherical and it is very difficult to refer its chaotic behaviour and size to the injection pressure. This observation (Figs. 4–6) indicates that when thinking about CO₂ injection we have to move away from the experience of CM blood mixing of iodine angiography and we have to think simply of the amount of gas we have to introduce into the cavity to displace the blood, considering the gas buoyancy as the only governing condition. For this it is very important to be able to control the pressure injection, because this is the only way we can control the rate of gas flow and chamber filling. The risk of damaging the vascular wall is limited to the end of the washing phase when a small amount of liquid (like a bullet) is accelerated forwards by the applied pressure. As manual pressure control is very difficult, it is also difficult to control the risk associated with the impact of the jet on the vessel wall.

An automatic gas injector with low pressure automatic line washout, may limit the risk of liquid jet injury and optimise vessel imaging through an optimal regulation of the amount and flow of the injected gas. This will also simplify and shorten the training period of radiologists. If we want to optimise the vascular chamber visualisation, as gas substitutes blood, the amount of gas injected should be proportional to the chamber volume, and the gas pressure, which regulates the gas flow, should be proportional to the blood flow in the vessel: the higher the chamber volume is, higher the gas volume, the higher the blood flow, higher the

Figure 10 Systolic aortic pressure rise (mmHg) at injection pressures of 300 and 500 mmHg and different gas volumes.

gas pressure. The injection can be controlled using the automatic injector and the graphs of Fig. 4. Similar graphs may be collected for other type of catheters and connection lines and stored in the injector memory, to be used in the operative context.

The use of the cardiovascular simulator and the aortic silicone cast permits a more realistic study of some mechanical and radiological aspects. The present study focused on the mechanical aspects of CO₂ angiography whereas the radiological features of will be the topic of a dedicated paper.

It is quite difficult to measure physiologic parameters (i.e. instantaneous aortic pressure) on a patient submitted to CO₂ angiography to avoid further risks and discomfort to the patient. A cardiovascular simulator and an appropriate vascular cast seem to be a good solution to overcome the limitations and obtain useful information. Our electromechanical mock [18] simulates both pressure and flow in the descending aorta cast (Fig. 7) in a clinical physiological range (Ao pressure 120/80 mmHg, 60 bpm, Stroke volume 25 ml/beat). The aortic pressure signal appears adequate for the purpose. The vascular resistance of single arterial vessels can also be regulated to modify the single flows and test selective injections (Fig. 9).

With the cardiovascular simulator the manual and automatic injections at different CO₂ pressures and volumes were repeated with concomitant measurement of pressures in the syringe and vessel. From the point of view of the gas injection procedure, it was sufficient to increase the applied pressure by an amount corresponding to the mean value of the pressure in the vessel. These injections showed a plain increase in intravascular pressure (both systolic and diastolic values), and a visually detectable volume increase of the aortic silicone cast. The increase in systolic pressure depended on the injection pressure and volume and in some cases of manual injection it doubled the basal vascular pressure values. Plainly, in this condition the mechanical stress of the vessel is strongly increased, and in some conditions (aortic aneurysm) may reach critical values with possible wall rupture. Radiologists do not pay sufficient attention to this aspect, considering the low pressure of injection (with respect to iodine) and gas compressibility a protection against abnormal mechanical stretching. The rise in pressure and consequent vessel wall stress during the injection can also explain the local pain frequently associated with venous CO₂ angiography. In fact, due to the high venous wall compliance, the gas injection is associated with wide and rapid venous volume change, and consequent pain. For this reason injections in venous cavities should be made at lower pressure than in arterial cavities. It is not a problem of total gas volume, a low injection pressure is important to avoid too rapid vessel volume changes and vascular wall stretching. This indication contradicts the advice commonly given by radiologists to obtain good quality angiographic images. In fact the leading problem of CO₂ angiography is the difficulty of completely filling a vascular cavity with the injected gas, due to the gas's buoyancy: the advice is to inject the gas rapidly, by applying a high manual pressure to the delivering syringe. Injection gas flows suggested by literature [25] for the descending aorta range between 20 and 50 ml/s. Our tests demonstrate that these flows, in arterial

cavities where the mean pressure is about 100 mmHg, may be reached with quite a low pressure (from 200 mmHg to 400 mmHg) and that manual injection easily overcomes these values. This difficulty arises from the necessity to washout the injection line from the perfusion liquid: at the onset of injection when the line is full of saline, the hydraulic resistance is very high, and a high pressure is needed to empty the line. But this pressure compresses the gas in the syringe, and as soon as the line is empty the applied pressure is very high and the gas output very rapid. The gas output reduces the pressure in the syringe and the piston can move forward easily, producing a new sudden pressure increase. It is very difficult for the operator to control manually the two phases of line washout and gas injection, and the training is very long and complex, based on a trial and error approach. The constant pressure injector will overcome this problem, and desired gas amount and gas flow rate can be setup avoiding inter-operator variability and an uncontrolled risk for the patient due to local pressure increase.

Conclusions

CO₂ angiography is a powerful and safe procedure which diffusion will certainly increase in the next years, although some aspects related to gas injection, chamber filling and possible wall damage are not well known by the radiologists. The manual gas injection, widely used everywhere, does not permit an optimal control of the gas output and requires a long training period. The use of an automatic system permits a better control of the injection, but new rules concerning pressures and flows to be applied in vascular chambers (aneurysms) or in single vessels (selective injection) must be defined, considering that the real damage risk for the patient is not referred to the gas jet from the catheter but to the local pressure rise due to the sudden gas input in the elastic vascular chamber. Better knowledge of these physical aspects will improve the efficacy and safety of the procedure and support his larger diffusion.

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