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BIOMECHANICAL OPTIMIZATION OF CO_2 ANGIOGRAPHY

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Carbon dioxide (CO_2) angiography represents an important technique to overcome most clinical problems related to the use of iodine contrast medium. The recent technologic advancements in the fields of gas injection and image reconstructions made CO_2 angiography a very efficient method for clinical evaluation of peripheral cardiovascular system. Despite that, some challenges are still open and a better knowledge of the biomechanical behavior of CO_2 and its interactions with blood flowing into the vessels is necessary to optimize this technology and to expand its field of application. This paper presents a quick overview about biomechanical behavior of carbon dioxide during injection, suggesting possible optimization tricks to make CO_2 angiography procedures more effective to improve imaging and reduce the patients' radiological dose. Particular attention has been also paid to 3D imaging techniques, which can certainly be opened to the use of carbon dioxide.

Keywords: CO_2 angiography; arterial pressure; injection pressure; injection flow; dosimetry; cone beam computed tomography.

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1. Introduction

Carbon dioxide (CO_2) angiography is substantially different from traditional Iodine Angiography for three main reasons[1]:

(1) Iodinated contrast medium mixes with blood, besides CO_2 displaces it;
(2) CO_2 gas bubbles behave differently in different dimensions and flow vascular chambers;
(3) Injection lines filled with CO_2 show a very low hydraulic resistance and a careful control of injection pressure is important to have good imaging.

Clinical procedures for the manual injection of iodine ("inject as strong as you can")[2] are not valid for CO_2 and an accurate application of biomechanical knowledge makes the difference, giving good images and controlled radiological dose without patients' pain and procedural complexity.

In this paper, the approaches to be used in different conditions to optimize the diagnostic CO_2 angiography are shortly described, considering the dimension of the vascular cavity, the blood pressure and flow (values and timing) and the dimensions and motion if the injected gas bubbles. The diagnostic need will be first highlighted, the main difficulties will be outlined, the optimal procedural approach will be proposed, considering the biomechanical behavior in the specific context.

The vascular context can be divided in three particular subsets as follows:

(a) Very large cavities, where the injected gas bubbles float randomly;
(b) Medium size high blood flow arteries and veins, where the injected gas forms a train of bubbles floating on a below running blood stratus;
(c) Small diameter vessels ($< 6\,\text{mm}$), where the injected bubbles can fill the whole vascular section and the vessel shows a sequence of running gas and blood sectors.

In these three different biomechanical conditions, to have a good radiological image of the vessel, it is necessary to fill it as possible with gas, but blood is moving, the pressure is changing and the result is not always optimal.[3]

In the large vascular cavities, the element to be controlled and used is the gas floating and random bubbles movement. It is necessary to inject rapidly a big amount of gas, to take advantage of bubbles movement to outline the cavity shape: Large gas volume and high injection pressure. The same for Iodine? No! Because with CO_2, the hydraulic resistance of the injection line is very small ($\sim 5\,\text{mmHg/mL/s}$) and the whole gas volume (up to $100\,\text{mL}$) can be injected in a very short interval ($1\,\text{s}$), with a remarkable intravascular pressure increase and an imaging result highly dependent on the cardiac phase of the injection.

As an example of this, we can focus our attention on the interventional procedure of aortic prosthesis positioning for abdominal aneurism treatment (Fig. 1). In this case, the use of CO_2 is highly advised, to save a big amount of dangerous iodinated contrast medium. With the procedure the clinician has to obtain three goals: (1) To

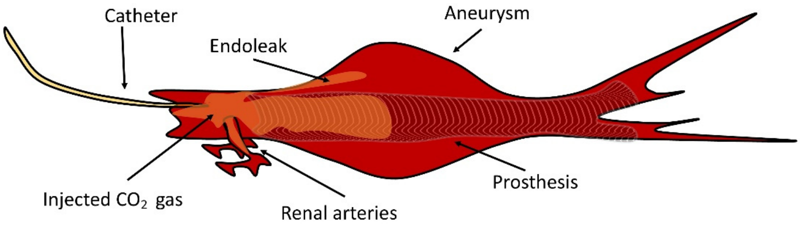

Fig. 1. Aortic prosthesis positioning for abdominal aneurism treatment. With respect iodine contrast media, CO_2 is more effective in endoleaks highlighting.

fill the prosthetic cavity with gas to optimize the positioning; (2) to visualize the renal arteries input, to avoid to cover them with the prosthesis; (3) to detect possible endoleaks between prothesis and arterial wall, to be sealed before procedure closing. These three aims are difficult to obtain all together and the procedure has to be managed with an acceptable compromise. In fact, the high gas injection flow, necessary for optimal prosthesis positioning, increases the "local" endovascular pressure and, through the wall dilatation, may facilitate the gas passage between prosthesis and vascular wall, highlighting an inexistent leakage. The same for renal arterial input visualization in case of pretty systolic or diastolic injection.[4–6]

The optimal compromise would be a prevalent diastolic injection with no excessive gas flow. Devices and catheter lines could be studied and tested for this purpose, and also the clinician way of thinking would be deeply changed. At the moment, the procedural aspects (injection pressures and flows) are based on general guidelines and clinical previous experience with no optimization for the single subject, limiting the possible advantages on imaging and increasing the procedural risks.

For arteries and veins with diameter larger than 6 mm, which lumen cannot be completely and stably filled with gas, the most important parameter for imaging optimization is the blood flow in the vessel.[7] This knowledge is necessary to have a good gas filling for optimal radiological image reconstruction, avoiding excessive gas reflows. Knowing the mean blood flow, the injection pressure to set is easily calculated, and precisely that, divided for hydraulic line resistance, which produces a gas flow equal to the mean blood flow. By increasing the gas flow, the refluxes are increased with a limited benefit on imaging.

But, actually, the most challenging situation is the optimal gas filling of vessels with diameter lower than 6 mm. In this case, the bubbles can completely fill the vessel lumen and if the gas input is insufficient (lower than mean blood flow), the radiological apparatus will show subsequent running sectors of gas and blood and the whole reconstruction by image subtraction and staking will be difficult and sometimes incorrect. On the other hand, if the gas input is excessive (higher than mean blood flow) a reflow will occur with reverse motion of blood towards large arteries. This produces an increased pressure in the injection site, with possible pain and movement, which deteriorates the optical reconstruction. The optimal solution is challenging, because the endovascular pressure and flow are pulsatile and the

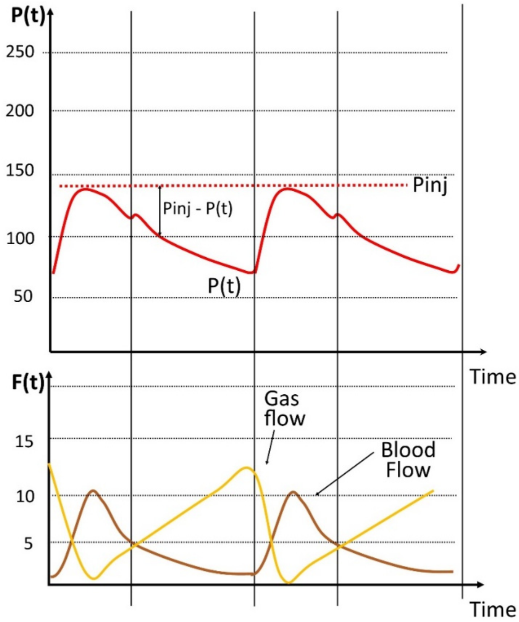

Fig. 2. In the top panel, aortic pressure waveforms (straight line) and injection pressure (dotted line) are represented. With an injection pressure equal to the systolic value, the gas flows onto the vessel mainly during the diastolic phase (bottom panel). When the CO_2 flow is higher than the blood one, a reflux is present.

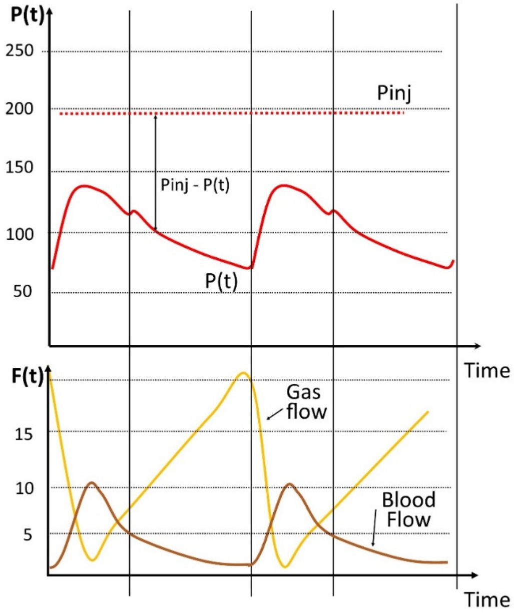

Fig. 3. In the top panel, aortic pressure waveforms (straight line) and injection pressure (dotted line) are represented. Here, the injection pressure is much higher than the systolic one, the gas flow increases and the reflux is greater (bottom panel).

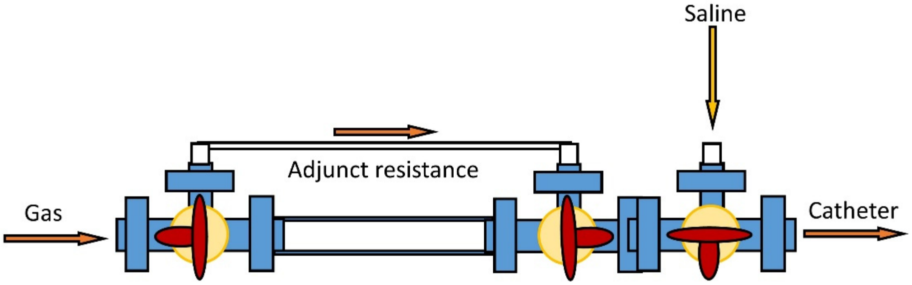

Fig. 4. A possible solution to modulate the injection gas flow. Carbon dioxide flows through an adjunct in parallel hydraulic resistance with a known and calibrated value.

hydraulic resistance of the catheter is very low. Also, using an injection pressure slightly higher or equal to the maximum pressure in the vessel will lead to permanent presence of gas reflux (Fig. 2).[7] The situation worsens if the injection pressure is increased (Fig. 3).

Our proposal is to insert an adjunctive hydraulic resistance in series with the catheter, to modulate the injection gas flow and to compensate the blood pulsatility (Fig. 4).

The value of the adjunct resistance can be selected on the basis of blood flow in the vessel, to use the right pressure to compensate the adjunct resistance pressure drop (see Fig. 5). Theoretically, the adjunct resistance does not have drawbacks; it standardizes the procedure and shortens the procedural phases, eliminating, in some cases, unrequired steps (i.e., line washout).

These procedural upgrading, based on biomechanical knowledge, also have an effect on radiological risk, which must be evaluated. This is apparently a complex problem because to evaluate the radiological risk of a new or modified procedure and to compare it with a standard one, is always a challenge. This is because the result is strongly conditioned by the operator's experience, and the new procedure tends to be penalized. Fortunately, this eventuality does not occur in this case, as the emission setup of the radiological apparatus (kV, mA, frame rate, frame time) is the same for CO_2 and iodine (the standard choice)[8]: We can compare and estimate the radiological risks simply by comparing the length of the records and we can reduce the dose by simply reducing the emission time of each record. Since CO_2 viscosity is very low when compared with iodinated contrast medium, the injection time can be easily shortened, particularly if adjunct resistances are used, and the limitation of a novelty may turn on advantage. Moreover, with CO_2, the injection can be performed with an automatic injector: The times, and then the doses, are independent from the operator and both evaluations and comparisons are facilitated. In any case, if the procedure is correctly executed, there is no reason to have an increased dose for the patient and, moreover for the operators, who can stay apart from the patient (the dose diffusor) during the injection (first rule of radiological protection).

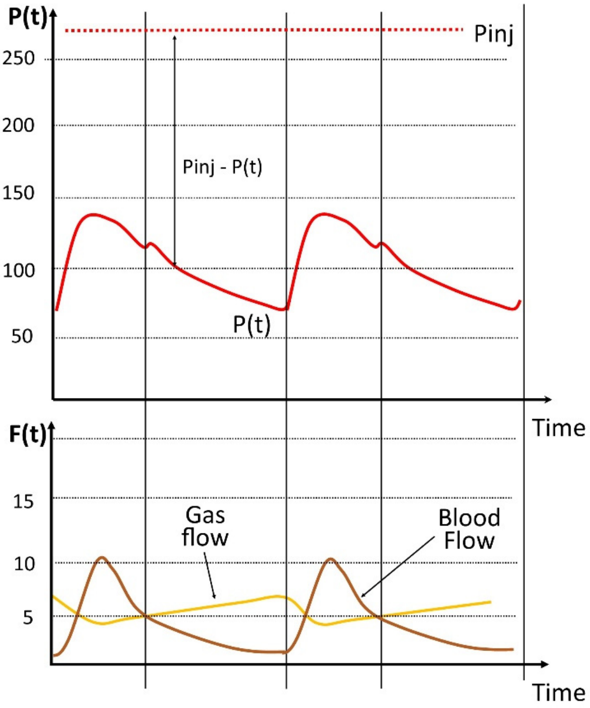

Fig. 5. With an appropriate adjunct hydraulic resistance, even if the injection pressure is much higher than the systolic value, the gas flows remain lower than the blood flow and no reflux is present.

During lower limb angiography, X-ray dose is most dependent on the amount of DSA images. Fluoroscopy time can be reduced by practice and education. If a lower dose for a single frame is applied with a lower frame rate, it would result in a reduction of the radiation dose. In this case, radiation dose often shows the stronger body-mass-index correlation.[9]

Furthermore, automatic CO_2 injection technology available on the market offers remote wireless controllers to decrease the dose for the operators, and even if a standardized protocols have been developed yet, preliminary experiences showed promising results, without a significant difference between dose-area product (DAP) considering different patient groups (with iodine or CO_2 as primary contrast).[4,6]

As there is a gap in the recent literature on clinical standardization and evaluation of standard protocol to improve the angiographic procedures during contrast perfusion, further studies are needed.

The last aspect to be evaluated for biomechanical optimization of CO_2 angiography is the use of 3D radiological reconstruction (CT, CBTC) to enhance the diagnostic information.[10] It is obvious that to have an optimal reconstruction, it is necessary to have the target vascular cavity stably filled with contrast medium at least for a complete circular scanning. With TC, this interval it is about 1 s, with longer CBTC, up to 10 s and more. Moreover, it is difficult to have scanners inside

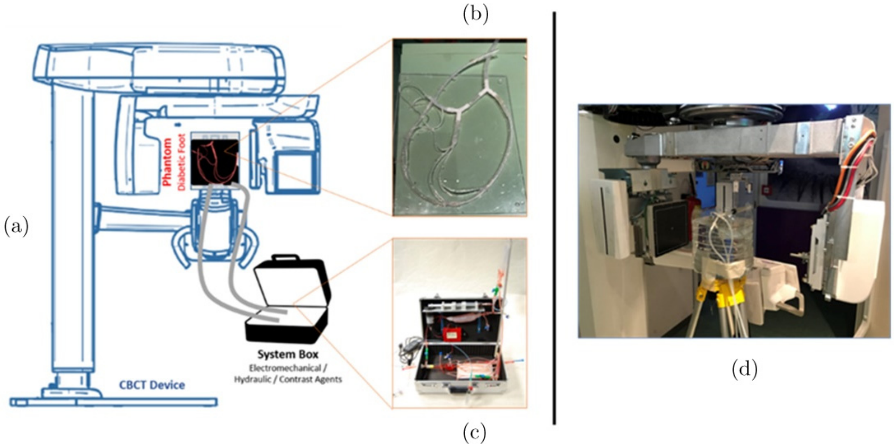

Fig. 6. Experimental set-up; (a) view of a CBCT system. The plastic container filled with water and silicon tubes (b) is positioned between the X-ray source and the detector. An electromechanical simulator (c) is used to create pressures and flows. A picture of the experimental setup is shown on the right (d).

the interventional room, but some proposals are coming. The job is more difficult for large vessels, where pulsatility rapidly modifies the status of contrast vascular filling and movement, but an easier approach in possible for more peripheral vessels, which can be stably filled with contrast medium for the scanning interval. This is quite simple for iodine, more difficult for CO_2 and an increased attention to optimize the injection is necessary. We focused our attention to a specific diagnostic field where high-optical resolution and three-dimensional visualization are highly desirable: The diabetic foot angiographic study. In this clinical context, the arteries to be visualized

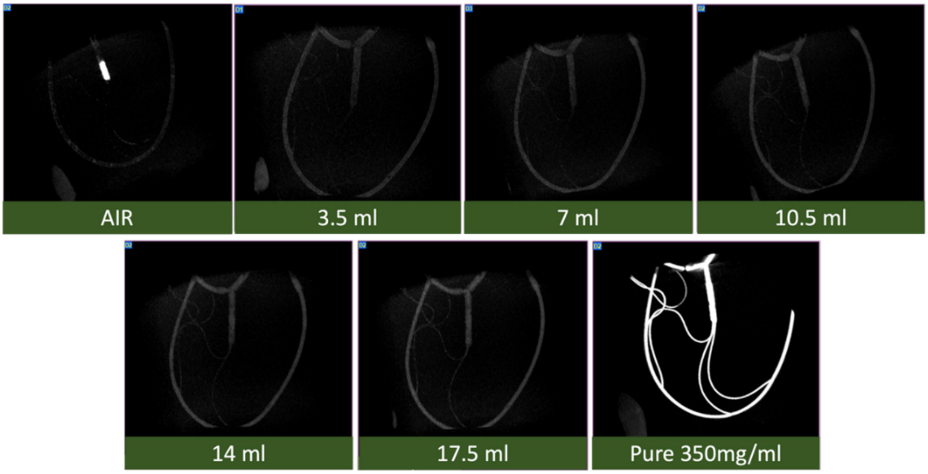

Fig. 7. CBCT images for different iodine concentrations.

are very thin and may be completely and stably filled with contrast for some seconds, to permit a CBTC scan.[11–13]

To test this possibility, we used a dentary dedicated CBTC system with an X-ray tube voltage of 90 KV scan time of 14.4 s, detector area of 13 × 10 cm. A thin (0.5 mm) silicone tubes phantom (20 × 10 × 0.5 cm) was placed within a plastic container filled with water (to simulate tissues) and it is located in the X-ray range on the CBCT system, connected to a pulsatile flow generator settled to physiological pressure and flow values[14] (Fig. 6).

For testing, we used diluted iodine at different concentrations, from air (start of injection) to 350 mg/ml, with a contrast similar to the one with CO_2 (Fig. 7). The test demonstrated the procedure to be feasible, and a "Dedicated" CBTC system for diabetic foot angiographic imaging is under project. Image quality increases with iodine concentration: A very small quantity of iodine is already sufficient to highlight the vessels. It is interesting to observe that the tube filled with air (Fig. 6) allows to evaluate the bigger vessels, despite no dedicated algorithms (masking and stacking) were applied to build the angiographic image.

2. Conclusion

CO_2 angiographic procedure can be highly upgraded both for imaging, discomfort and radioprotection by using biomechanical knowledge to optimize the gas injection. Also, the new diagnostic tendencies (CT, CBTC) need the biomechanical support to be correctly applied and optimized. Despite CBCT's limited soft tissue contrast resolution, the advantage is that a CBCT scan usually has a lower radiation dose than a CT scan while providing a higher resolution.[13] This characteristics combined with the use of contrast agents could lead to enhanced visualization of soft tissue contrasts and small vessels. As shown, it has been possible to visualize the opacification of vascular structures and the presence of stenosis.

This is a wide field of research for most scientists on a multidisciplinary context.

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