A New Era in Zero X-ray Ablation

Giuseppe Mascia[1] and Marzia Giaccardi[2]

1. Department of Internal Medicine, IRCCS Ospedale Policlinico San Martino, University of Genoa, Genoa, Italy;
2. Department of Internal Medicine, Azienda USL Toscana Centro, Florence, Italy

Abstract

In this article, the authors focus on the importance of the zero X-ray ablation approach in electrophysiology. Radiation exposure related to conventional transcatheter ablation carries small but non-negligible stochastic and deterministic effects on health. Non-fluoroscopic mapping systems can significantly reduce, or even completely avoid, radiological exposure. The zero X-ray approach determines potential clinical benefits in terms of reduction of ionising radiation exposure, as well as safe technical advantages. The use of this method can result in similar outcomes when compared to the conventional fluoroscopic technique. These results are achieved without altering the duration, or compromising the effectiveness and safety, of the procedure. The zero X-ray ablation approach is a feasible and safe alternative to fluoroscopy, which is often only used in selected cases for troubleshooting. The non-fluoroscopic approach is considered a milestone for cancer prevention in ablation procedures.

Keywords

Arrhythmia, cancer prevention, catheter ablation, radiation risk, zero-fluoroscopy, X-ray ablation approach

Disclosure: The authors have no conflicts of interest to declare.

Received: 19 January 2020 **Accepted:** 3 July 2020 **Citation:** *Arrhythmia & Electrophysiology Review* 2020;9(3):121–7. **DOI:** https://doi.org/10.15420/aer.2020.02

Correspondence: Giuseppe Mascia, Department of Internal Medicine, Clinic of Cardiovascular Diseases, IRCCS Ospedale Policlinico San Martino, University of Genoa, Largo Rosanna Benzi 10, 16132, Genoa, Italy. E: giuseppe_mascia@virgilio.it

X-rays used in interventional cardiology are proven (class I) carcinogens, and the electrophysiology community should make every effort to give "the right imaging exam, with the right dose, to the right patient".[1] This may be an effective strategy for the primary prevention of cancer for physicians, medical staff and patients (particularly children, young adults and women).[2] The impact of X-rays on male and female reproductive health is well known.[3] In men, radiation exposure could determine transient sperm count deterioration, resulting in long-lasting or permanent sterility, whereas in women, it can lead to alterations in the hypothalamic–pituitary axis function, affecting fertility and pregnancy outcomes.[4] X-rays could lead to potential brain malignancies or long-lasting cognitive impairment, and microRNA dysregulation has been found to be related to certain forms of brain cancer and Alzheimer's disease.[5,6] Moreover, during interventional cardiology procedures, the left side, in particular, is usually exposed to higher radiation doses.[7]

Radiation exposure related to conventional radiofrequency catheter ablation carries small but non-negligible stochastic and deterministic effects on health.[2] These effects are cumulative and potentially more harmful, and are worse in obese patients, who may need a far higher dose of radiation than people of normal weight, increasing their risk of cancer.[2,8] Lead aprons can place considerable pressure on the spinal column, and wearing them for hours while standing has potentially detrimental consequences. The long-term use of lead aprons is known to result in orthopaedic disability, and as consequence, early retirement among physicians, technologists and nurses.[9,10] Interventional cardiologists have reported neck and back pain, more time lost from work and a higher incidence of cervical disc herniations, as well as multiple-level disc disease.[11] Therefore, several tools have recently been developed to facilitate arrhythmia mapping and ablation, including 3D electroanatomic mapping systems, magnetic navigation and intracardiac echocardiography, which significantly reduce the need for the fluoroscopic visualisation of catheters.[12] Comparable long-term ablation outcomes, with clinical benefits for both patients and physicians, have been documented; the non-fluoroscopic approach is considered a feasible and safe alternative to fluoroscopy for arrhythmias ablation.[12–15] The zero X-ray ablation approach is a milestone for cancer prevention in electrophysiological procedures.

The History of Zero X-ray Procedures

Transcatheter ablation has undergone impetuous advances in the past 25 years. Ablation mechanisms have been largely investigated, with electrophysiologists focusing on the link between anatomical aspects and electrophysiological properties.[16–21] In the 2002 Pediatric Radiofrequency Ablation Registry, Kugler et al. compared 'early' and 'recent' eras, and found that the mean overall fluoroscopic time decreased by 21% in the paediatric population (from 50.9 ± 39.9 minutes in the early era to 40.1 ± 35.1 minutes in the recent era).[22] However, X-ray doses were still high, and further improvements were necessary. In a study in the same year, Drago et al. used a 3D navigation system to eliminate fluoroscopic exposure to 21 paediatric patients.[23] They demonstrated that ablation of right accessory pathways in children could

Table 1: Studies on the History of Zero X-ray Procedures

Author	Study Type	Arrhythmia Included	Patients (n)	Follow-up (Months)
Drago et al. 2002[23]	Re non-RT	Right AP	21	15 ± 7
Sporton et al. 2004[24]	Pro RT	AVNRT, right AFL, AP, AT, VT	102	NA
Raju et al. 2016[28]	Re non-RT	AF	21	NA
Casella et al. 2016[26]	Pro RT	AVNRT, right AP, Left AP, AFL, AT	262	12
Giaccardi et al. 2016[12]	Re non-RT	AVNRT, right AFL, AP, AT, VT, other	442	NA
Pani et al. 2018[15]	Pro non-RT	AVNRT, right AFL, right AP, left AP, AT	435	12
Giaccardi et al. 2019[13]	Re non-RT	PVC, AF, right AFL, left AFL, AV node ablation, AVNRT, AP, AT, VT	266	35 ± 19
Santoro et al. 2019[14]	Pro non-RT	AVNRT, AP, AFL, AT, PVC/VT	485	6

AFL = atrial flutter; AP = accessory pathway; AT = atrial tachycardia; AVNRT = atrioventricular nodal re-entrant tachycardia; NA = not available; pro non-RT = prospective non-randomised; pro RT = prospective randomised trial; PVC = premature ventricular extra beat; re non-RT = retrospective non-randomised; VT = ventricular tachycardia.

be performed without fluoroscopy, using a single catheter with minimal amounts of radiofrequency applications, with a high success rate.[23] There was a considerable reduction in the use of fluoroscopy after procedure 8, with a definitive and complete elimination of fluoroscopy from procedure 12 to procedure 21.[23] Their study represented the start of the zero X-ray era.[23] Two years later, in a study of 102 randomly selected patients referred for catheter ablation, Sporton et al. compared the routine use of electroanatomic imaging with that of a conventional fluoroscopically guided activation map, and documented a similar acute procedural success with both strategies.[24]

In 2005, the American College of Cardiology recommended that all catheterisation laboratories should adopt the ALARA (as low as reasonably achievable) principle for radiation doses, constituting a pivotal step towards minimising radiation use in invasive cardiology.[25] In a multicentre randomised trial, Casella et al. compared a minimally fluoroscopic ablation with conventional fluoroscopic-guided ablation for supraventricular tachycardias in terms of ionising radiation exposure for 262 patients.[26] They focused on the radiation exposure during electrophysiological procedures as non-negligible for both patients and medical staff, and found that a minimally fluoroscopic approach dramatically reduced the estimated risk of cancer incidence and mortality (96% reduction). They also found a reduction in estimated years of life lost and years of life affected, while retaining the safety and efficacy of procedures.[26] Based on these findings, the electrophysiology community appealed to the industry to reduce costs and educate physicians to facilitate the implementation of this new electrophysiology for left atrial procedures.[27] In their study, Raju et al. demonstrated that general anaesthesia, transoesophageal echocardiography and contact-force mapping catheters may all facilitate a minimised fluoroscopic approach among AF ablation patients.[28] In this population, complete zero-fluoroscopy was possible in cases with patent foramen ovale (PFO), which was documented in 36% of patients.[28]

In 2016, we published a study of 442 consecutive patients who were referred for radiofrequency catheter ablation during a 5-year period (2009–2013).[12] The patients were included in a retrospective observational study, where the first 145 patients (group 1) were treated only under fluoroscopic guidance; the other 297 patients (group 2) were treated with a non-conventional mapping system.[12] The acute success rate did not differ between two groups, and there were no differences in either the procedure or complication rate. Moreover, fluoroscopic exposure in group 2 was significantly reduced compared with group 1 (14 ± 6 seconds versus 1,159 ± 833 seconds, p<.0001).[12] We demonstrated how a near-zero radiation approach could lead to similar outcomes and significantly reduce or eliminate ionising radiation exposure. These reductions were achieved without altering the duration, or compromising the safety and effectiveness, of the procedure. In 2019, our group published the long-term outcomes of 266 patients who had undergone zero X-ray ablation, as no information was available on the long-term benefits.[13] Patients were followed up for an average of 2.9 ±1.6 years, and a 100% rate of acute success was observed, with a complication rate of 0.8%; chronic success was achieved in 90.8% of cases, confirming that the complete elimination of fluoroscopy is advantageous and does not compromise results or patient safety.[13]

In a multicentre prospective study, the Zero Fluoro Study Group evaluated the determinants of zero-fluoroscopic ablation of 430 supraventricular tachycardias in 20 centres.[15] The multivariable analysis identified the following predictors of zero-fluoroscopy: operator's will, experience with >30 procedures, patient's age and the type of arrhythmia (electrophysiological study and atrioventricular nodal re-entry tachycardia ablation having the highest probability of zero-fluoroscopy). The Zero Fluoro Study Group confirmed high safety and effectiveness profiles.[15] In a recent study, Santoro et al. showed that catheter ablation can be performed without X-ray after an adequate learning curve.[14] In 2011, they commenced an X-ray-minimisation programme using the CARTO System (Biosense Webster), with the intention to not aid X-ray unless strictly necessary. From 2011 to 2013, catheter ablations were performed without X-ray in 38.5% of cases, whereas from 2014 to 2017, there were no differences between the two groups in acute success, complications or duration for 525 procedures in 96.2% of cases (*Table 1*).[14]

Additional Advantages of Zero X-ray Ablation

In addition to the reduction in X-ray exposure, a non-conventional mapping system could offer several benefits. In the EnSite Precision cardiac mapping system (Abbott), catheter electrodes are detected and displayed based on the impedance measurements from three separate, orthogonal electrical fields, visualising any catheter within the system. The observable region, in particular, is wider, and these catheters can be visualised from the point of access (femoral vein or femoral artery) to the heart.[29] The system's drawbacks include a shift in geometry resulting from impedance changes, as lung volumes or total body fluid volumes change; shift could also occur due to patient perspiration, as well as changes in reference electrode contact.[29] However, the benefits outweigh its limitations, such as the addition of magnetic capabilities of newer ablation and mapping catheters.[30] The CARTO System functions by measuring magnetic fields, rather than electrical impedances, and is less prone to shift, but requires proprietary catheters (no catheter visualisation outside the magnetic field) and a longer time to draw a reasonable geometry.[29] The Rhythmia mapping system (Boston Scientific) was specifically developed to support high-density/high-resolution mapping, and is a hybrid localisation system.[31,32] In particular, magnetic tracking supports navigation-enabled catheters, providing maximum accuracy and efficiency (magnetic localisation ≤1 mm), whereas open architecture supports impedance-based tracking of non-navigation-enabled catheters for flexibility of choice (impedance localisation ≤2 mm).[31,32] However, each of these systems functions in a unique manner, and due to rapid improvements, deficiencies are quickly disappearing.

Currently, mapping systems are able to locate the correct position of any pole at any time, and allow an accurate reconstruction of the geometry of both heart chambers and vessels, simplifying navigation and speeding up subsequent phases of the procedure.[12] It is also helpful to understand the relationship between bipoles and cardiac anatomy, and between different structures and facilitating complex anatomy cases, continuously visualising two projections at the same time.[33] Mapping systems allow visualisation of the catheters from the beginning to the end of the procedure.

In our laboratory, the first catheter inserted is a quadripolar/octopolar steerable catheter through the femoral vein, positioned in the coronary sinus (CS), whereas other diagnostic catheters are inserted and advanced using the previously reconstructed geometry as a guiding path. While moving the catheters, new anatomical points are typically collected in order to better define the boundaries of the areas of interest (both inferior and superior vena cava ostium, CS ostium, right atrial appendage, His bundle region). Integration with the continuous monitoring of intracavitary electrograms is useful during completely different ablation procedures.[12] In cases of AP ablation, the location of the AP could be marked and still used to direct radiofrequency pulses in cases of 'bump', causing the AP to be no longer visible. In cases of atrioventricular nodal re-entrant tachycardia ablation, the procedure can also be simplified because of an optimal reconstruction of the Koch's triangle, the anterior area of the CS and the proximity of the His bundle.[12,13]

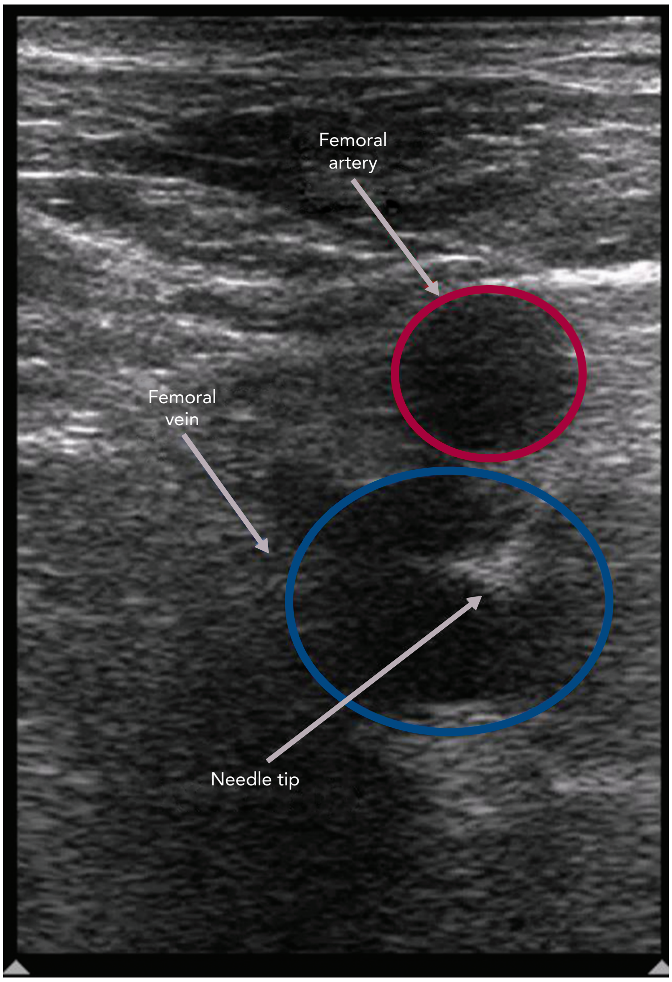
In typical atrial flutter (AFL) cases, an activation map during CS stimulation may easily locate any gap along the isthmus ablation line.[12,13] However, in atypical AFL, atrial tachycardia and ventricular tachycardia (VT) cases, mapping systems can be used to visualise arrhythmic circuits through activation maps, and to evaluate the electrical substrate through voltage maps.[12,13] The high-density multi-electrode approach has significantly improved mapping of both complex atrial and VTs, with quicker and more accurate map creation.[31,32] The additional advantages of a zero X-ray approach during pulmonary vein isolation should be considered. For example, it might be difficult to insert a standard spiral catheter in both lower pulmonary veins; in this case, it is possible to capture the spiral using a deflectable ablation catheter and to carry it in the lower vessels.

Our Daily Zero X-Ray Approach: Tips and Tricks

Ultrasound-guided Central Venous/ Arterial Cannulation

Ultrasound probes of 7–10 MHz are suitable for an ultrasound-guided central venous or arterial cannulation. Arteries are pulsatile and are identifiable, as they are difficult to compress. However, veins are non-pulsatile, are easily compressible and may distend when the patient performs Valsalva manoeuvre. A Doppler verification may also be used to confirm the anatomy. The superficial artery may overlie the femoral vein, and ultrasound imaging allows a differentiation of these structures, as well as an accurate puncture of the common femoral vein below the inguinal ligament during basic electrophysiology (*Figure 1*).

Figure 1: Ultrasound-guided Central Venous Cannulation



Ultrasound-guided central venous cannulation allows an accurate puncture of the common femoral vein (blue circle), below the inguinal ligament.

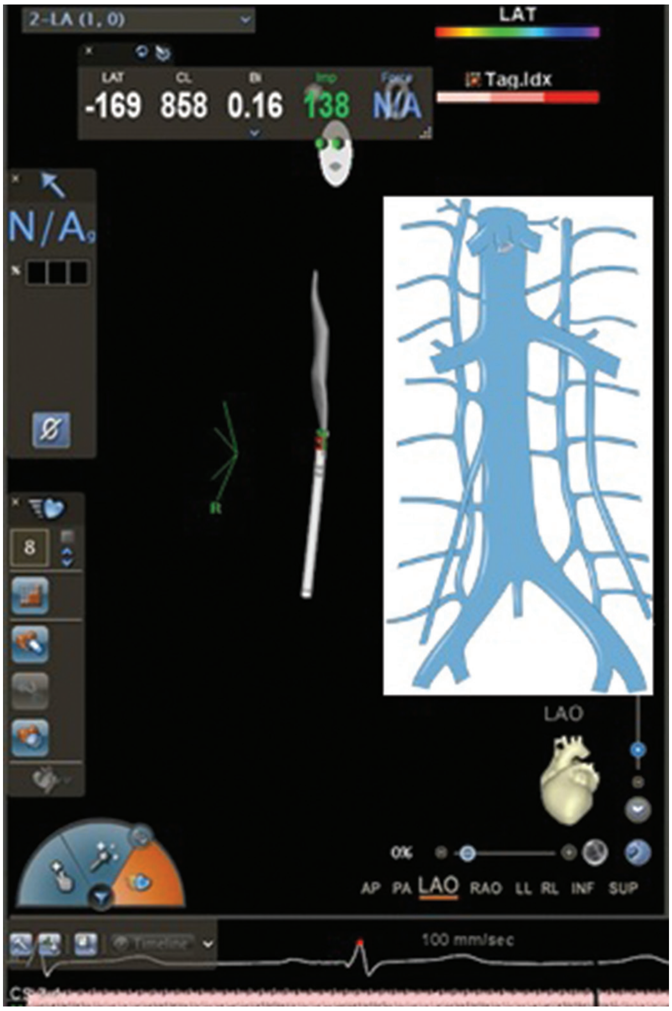
Zero X-ray Catheter Insertion: From the Groin Area to the Heart

After obtaining femoral vein access with short sheaths, the catheter is threaded through the patient's groin area to the heart. An anterior catheter direction is typically suggested to avoid collateral vessels. This direction may lead to the heart with no intermediate stops, as the anterior face of the inferior vena cava has no collateral vessels (*Figure 2*). The force that the catheter exerts on the blood vessel depends on the physician's experience. Utilisation of 'force-sensing' ablation catheters may provide a real-time measure of the contact force between the catheter and the vessels, without the use of X-rays. Monitoring electrograms for an atrial signal will inform the operator when the catheter is in the right atrium.

Patent Foramen Ovale and Fossa Ovalis Mapping

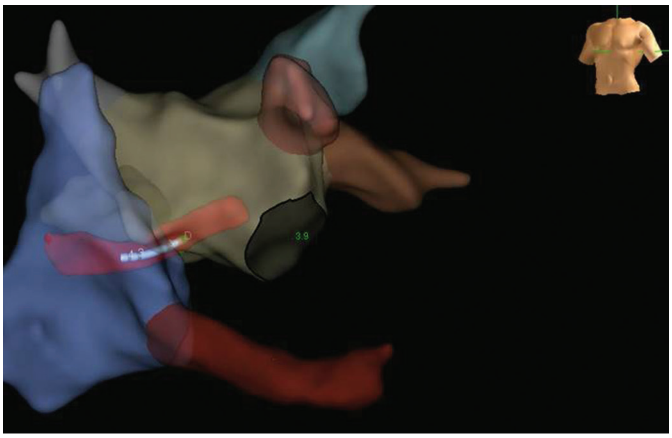
A PFO may be found after inserting the catheter into the right atrium and generating a 3D map with enough detail to identify both the septum and the fossa ovalis. Around 30% patients may have a PFO, allowing left-side procedures without the need for transseptal puncture (*Figure 3*).[34–36]

Figure 2: Anterior Catheter Direction May Lead from the Groin Area to the Heart with No Intermediate Stops



Anterior catheter direction may lead from the groin area to the heart with no intermediate stops, as the anterior face of the inferior vena cava has no collateral vessels.

Figure 3: Patent Foramen Ovale Allowing Left-side Procedures Without the Need for Transseptal Puncture



Transseptal Puncture: The Importance of an Adequate Learning Curve

Transseptal puncture could cause potential issues when performing left-side zero X-ray procedures.[37] In these cases, an in-depth understanding of cardiac anatomy, as well as high-level transoesophageal or intracardiac echocardiography (ICE) utilisation, is critical to reduce or minimise the use of X-rays. In the near-zero X-ray approach, the transseptal sheath may be visualised by inserting the ablation catheter via the long sheath and guiding it up to the superior vena cava (SVC) using the map as a guide. Once in the SVC, the sheath may be advanced slowly to cover the proximal ablation pole (which, for example, can be determined when the pole turns black on the CARTO System, or when a catheter deformation is documented on the Abbott system). The ablation catheter is then removed, and the physician may insert a dilator over a wire. The wire is then withdrawn and a transseptal needle is inserted 2 cm from the tip. At this point, the whole transseptal apparatus is withdrawn while looking at the transoesophageal or ICE images. The sheath could be observed to fall along the fossa ovalis, posteriorly directed towards the left-sided pulmonary veins. It is also possible to highlight the tip of the needle connecting the stylet to the system to confirm the descent of the needle tip until the fossa ovalis. Finally, when the needle reaches the fossa ovalis, it is possible to confirm its presence using transoesophageal or ICE images (*Figure 4*). Bidirectional guiding sheaths can be visualised on the mapping system and are important for eliminating sole dependence on fluoroscopy to determine their location.[38]

Contact-force Ablation Catheter Use During the Femoral Artery Approach

In the case of left chamber arrhythmic substrates, for which transseptal puncture is not required, the ablation catheter is inserted through the femoral artery from the start, as it is for the venous system. Modern ablation catheters enable monitoring of the contact force to avoid endothelial damage (*Figure 5*). Therefore, a contact-force catheter may not only be a therapeutic approach to arrhythmias but also a tool for achieving accurate characterisation of contact in the aortic vessel.

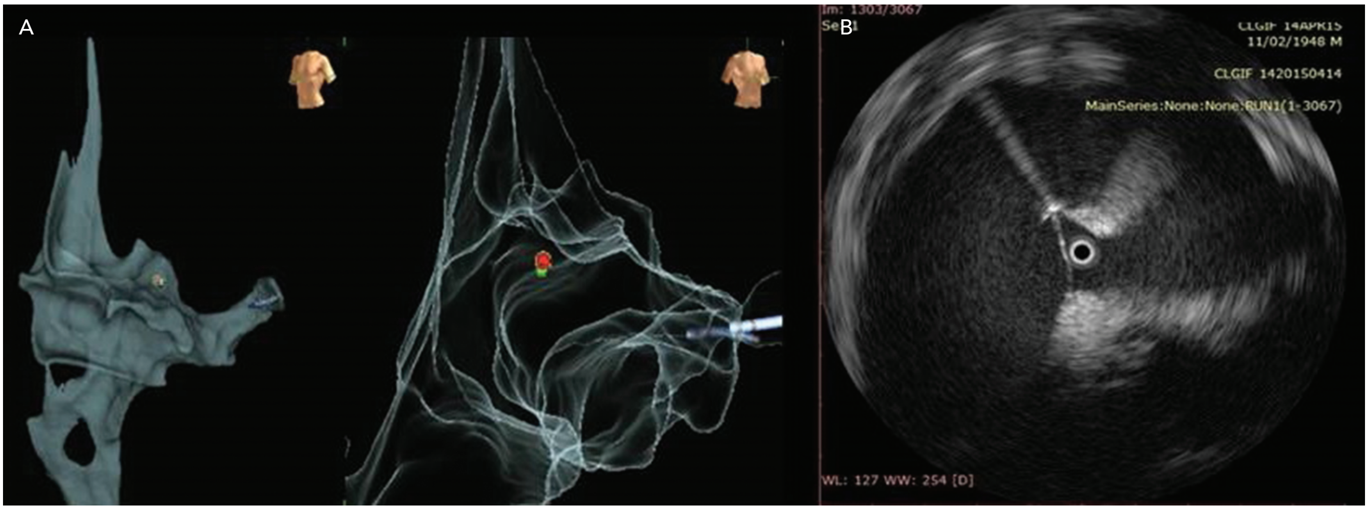
3D Imaging of the Oesophagus Before Pulmonary Vein Isolation Procedures

In our daily approach, the integration of an oesophageal tag into the electroanatomic left atrial map is usually performed during pulmonary vein isolations. The insertion of a quadripolar catheter into the oesophagus enables its 3D reconstruction and intraprocedural localisation. This approach can help physicians to correctly evaluate both the localisation of oesophagus and the distance between the posterior part of the left atrium and the anterior part of oesophagus (*Figure 6*). 3D imaging of the oesophagus may help to avoid an atrial-oesophageal fistula,[39,40] which is a rare but lethal complication of AF ablation. While imaging modalities have improved, it is important for clinicians to maintain heightened awareness of this complication in post-ablation patients.

Our Perspectives

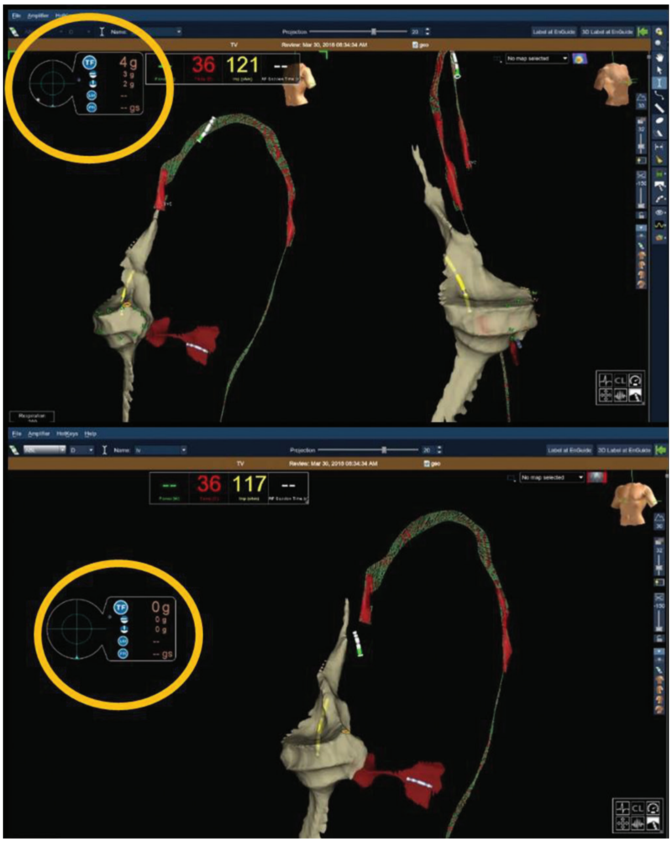
Innovative solutions have been found for reducing the dose per examination in all fields of medical imaging, including zero-fluoroscopy in electrophysiology, and the cancer- and non-cancer-related effects of medical radiation is currently the focus of the scientific community.[2] However, awareness of risks remains the best protection against radiation exposure. More information about the harmful effects of ionising radiation is required in the form of antismoking, anti-alcohol and anti-obesity campaigns, as risk awareness may lead to a risk reduction. Zero X-ray ablation uses expensive technology and equipment. In 2013, Winkle et al. estimated a high cost per case for the use of magnetic navigation ablation.[41]

Figure 4: Transseptal Puncture Highlighting the Tip of the Needle to Confirm its Descent



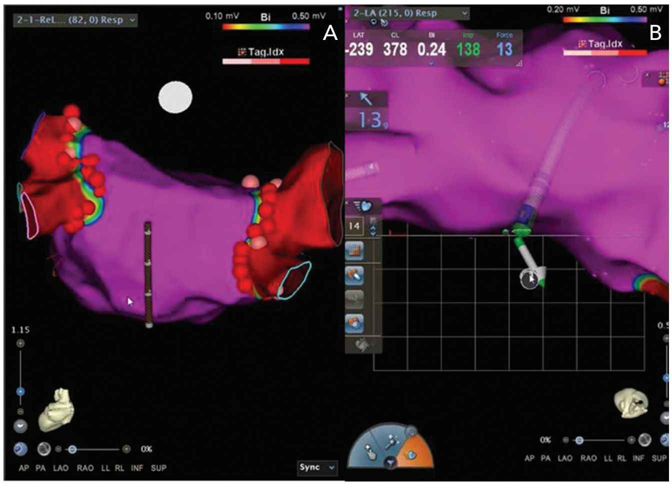
Transseptal puncture highlighting the tip of the needle to confirm its descent until the fossa ovalis (red dot; A) and intracardiac echocardiography utilisation to confirm the 'tenting' of fossa ovalis (B).

Figure 5: Contact-force Catheter Inserted Through the Femoral Artery



Contact-force catheter inserted through the femoral artery to monitor contact (yellow circle) to avoid endothelial damage.

Figure 6: 3D Imaging of the Oesophagus



3D imaging of the oesophagus helps the physician to correctly evaluate the localisation, as well as the distance, between the posterior part of the left atrium (A) and the anterior part of the oesophagus (B).

However, in the Near zerO fluoroscopic exPosure during catheter ablAtion of supRavenTricular arrhYthmias (NO-PARTY) multicentre randomised trial, Casella et al. found that a minimally fluoroscopic approach dramatically reduced the estimated risk of cancer incidence and mortality (96% reduction). They also found a reduction in estimated years of life lost and years of life affected, while retaining the safety and efficacy of procedures.[26] Considering the impact of cancer on quality of life and the cost-effectiveness of this approach, as discussed in other studies, the intervention would be affordable at net cost between €1,151 and €1,918, which is the approximate cost of the mapping system.[26,42]

Therefore, in our daily practice, the physicians performing electrophysiological procedures should first ensure that exposure is as low as reasonably achievable without affecting quality of care. The zero X-ray approach is considered a reliable and safe alternative to fluoroscopy for tachyarrhythmia ablation.[43] This method may yield potential clinical benefits in terms of reduction of ionising radiation exposure, as well as safe technical advantages. The benefits include no exposure of patients and staff to radiation, more precise definition or localisation of the mechanism of the arrhythmia, spatial display of catheters and arrhythmia activation, shorter procedure times (particularly in patients with complex arrhythmias) and easier access to ablation for certain populations (i.e. pregnant women and those undergoing radiation therapy). The long-term safety benefits of not using fluoroscopy have been documented, and the reduction in the use of X-rays has been achieved without compromising the duration, effectiveness and safety of the procedure.[12–14] A planned approach may be necessary to define the optimal learning curve.[14] The current role and next direction of cardiac magnetic resonance (CMR) in personalising arrhythmia management may be an important future point.[44] CMR can determine precise and reproducible assessment of scar and 'border zone' volumes, as well as predict the location of re-entrant circuits within the scar to guide ablation.[44] Detailed tissue characterisation may create personalised computer models to predict a patient's risk of arrhythmia. Computational modelling provides a framework for the integration of experimental and clinical findings, and has emerged as essential mechanistic research of arrhythmias.[45] Therefore, fluoroscopy may be used only in cases for troubleshooting, including transseptal puncture (considering the several tools we previously described to minimise the use of X-rays), potential peripheral vascular disease, previous lead implantation and epicardial ablation (especially for anterior/posterior pericardial access and for a potential coronarography prior to epicardial ablation). We have reached a new era in minimising X-ray radiation exposure, with new ideas and novel technologies still to be developed in the future.[46,47]

Conclusion

In ablation for arrhythmias, the zero X-ray approach is considered a feasible and safe alternative to fluoroscopy, which is only used in selected cases for troubleshooting. The non-fluoroscopic approach is a milestone for cancer prevention in ablation procedures. Awareness of radiation risk is a prerequisite to create a culture of respect for radiation hazard and a commitment to minimise exposure and to maximise protection. ■

Clinical Perspective

- The zero X-ray approach is a reliable and safe alternative to fluoroscopy for tachyarrhythmia ablation.
- The electrophysiologist should ensure that X-ray exposure is as low as reasonably achievable without sacrificing quality of care.
- A zero X-ray ablation may yield not only potential clinical benefits in terms of reduction of ionising radiation exposure, but also technical safe advantages.
- Fluoroscopy may be restricted to troubleshooting selected cases, since X-ray reductions are achieved without compromising the duration, effectiveness and safety of the procedure.
- The non-fluoroscopic approach represents a milestone for cancer prevention in ablation procedures.

1. US Food and Drug Administration. *Initiative to reduce unnecessary radiation exposure from medical imaging*. Washington, DC: FDA, 2010. http://www.fda.gov/Radiation-EmittingProducts/RadiationSafety/RadiationDoseReduction/ucm199994.htm (accessed 17 August 2020).
2. Picano E, Vañó E, Rehani MM, et al. The appropriate and justified use of medical radiation in cardiovascular imaging: a position document of the ESC Associations of Cardiovascular Imaging, Percutaneous Cardiovascular Interventions and Electrophysiology. *Eur Heart J* 2014;35:665–72. https://doi.org/10.1093/eurheartj/eht394; PMID: 24401558.
3. Latini G, Dipaola L, Mantovani A, et al. Reproductive effects of low-to-moderate medical radiation exposure. *Curr Med Chem* 2012;19:6171–7. https://doi.org/10.2174/092986712804485692; PMID: 23033948.
4. Sarkozy A, De Potter T, Heidbuchel H, et al. Occupational radiation exposure in the electrophysiology laboratory with a focus on personnel with reproductive potential and during pregnancy: A European Heart Rhythm Association (EHRA) consensus document endorsed by the Heart Rhythm Society (HRS). *Europace* 2017;19:1909–22. https://doi.org/10.1093/europace/eux252; PMID: 29126278.
5. Chambers CE. Health risks of ionizing radiation: Dr Roentgen Today. *Circulation* 2017;136:2417–9. https://doi.org/10.1161/CIRCULATIONAHA.117.031673; PMID: 29255122.
6. Borghini A, Vecoli C, Mercuri A, et al. Low-dose exposure to ionizing radiation deregulates the brain-specific microRNA-134 in interventional cardiologists. *Circulation* 2017;136:2516–8. https://doi.org/10.1161/CIRCULATIONAHA.117.031251; PMID: 29038169.
7. Roguin A. CardioPulse. Radiation in cardiology: can't live without it!: using appropriate shielding, keeping a distance as safely as possible and reducing radiation time are essential principles for radiation reduction. *Eur Heart J* 2014;35:599–600. https://doi.org/10.1093/eurheartj/ehu025; PMID: 24609722.
8. Ector J, Dragusin O, Adriaenssens B, et al. Obesity is a major determinant of radiation dose in patients undergoing pulmonary vein isolation for atrial fibrillation. *J Am Coll Cardiol* 2007;50:234–42. https://doi.org/10.1016/j.jacc.2007.03.040; PMID: 17631216.
9. Orme NM, Rihal CS, Gulati R, et al. Occupational health hazards of working in the interventional laboratory: a multisite case control study of physicians and allied staff. *J Am Coll Cardiol* 2015;65:820–6. https://doi.org/10.1016/j.jacc.2014.11.056; PMID: 25720626.
10. Pelz DM. Low back pain, lead aprons, and the angiographer. *AJNR Am J Neuroradiol* 2000;21:1364. PMID: 10954297.
11. Ross AM, Segal J, Borenstein D, et al. Prevalence of spinal disc disease among interventional cardiologists. *Am J Cardiol* 1997;79:68–70. https://doi.org/10.1016/S0002-9149(96)00678-9; PMID: 9024739.
12. Giaccardi M, Del Rosso A, Guarnaccia V, et al. Near-zero x-ray in arrhythmia ablation using a 3-dimensional electroanatomic mapping system: a multicenter experience. *Heart Rhythm* 2016;13:150–6. https://doi.org/10.1016/j.hrthm.2015.09.003; PMID: 26341606.
13. Giaccardi M, Mascia G, Paoletti Perini A, et al. Long-term outcomes after "zero X-ray" arrhythmia ablation. *J Interv Card Electrophysiol* 2019;54:43–8. https://doi.org/10.1007/s10840-018-0390-7; PMID: 29948584.
14. Santoro A, Di Clemente F, Baiocchi C, et al. From near-zero to zero fluoroscopy catheter ablation procedures. *J Cardiovasc Electrophysiol* 2019;30:2397–404. https://doi.org/10.1111/jce.14121; PMID: 31424119.
15. Pani A, Giuseppina B, Bonanno C, et al. Predictors of zero X-ray ablation for supraventricular tachycardias in a nationwide multicenter experience. *Circ Arrhythm Electrophysiol* 2018;11:e005592. https://doi.org/10.1161/CIRCEP.117.005592; PMID: 29874166.
16. Haïssaguerre M, Jais P, Shah DC, et al. Spontaneous initiation of atrial fibrillation by ectopic beats originating in the pulmonary veins. *N Engl J Med* 1998;339:659–66. https://doi.org/10.1056/NEJM199809033391003; PMID: 9725923.
17. Haïssaguerre M, Jaïs P, Shah DC, et al. Right and left atrial radiofrequency catheter therapy of paroxysmal atrial fibrillation. *J Cardiovasc Electrophysiol* 1996;7:1132–44. https://doi.org/10.1111/j.1540-8167.1996.tb00492.x; PMID: 8985802.
18. Swartz JF, Pellersels G, Silvers J. A catheter-based curative approach to atrial fibrillation in humans. *Circulation* 1993;88(Suppl I):I-335.
19. Gaita F, Riccardi R, Calò L, et al. Atrial mapping and radiofrequency catheter ablation in patients with idiopathic atrial fibrillation: electrophysiological findings and ablation results. *Circulation* 1998;97:2136–45. https://doi.org/10.1161/01.CIR.97.21.2136; PMID: 9626174.
20. Ernst S, Schlüter M, Ouyang F, et al. Modification of the substrate for maintenance of idiopathic human atrial fibrillation: efficacy of radiofrequency ablation using nonfluoroscopic catheter guidance. *Circulation* 1999;100:2085–92. https://doi.org/10.1161/01.CIR.100.20.2085; PMID: 10562265.
21. Pappone C, Oreto G, Lamberti F, et al. Catheter ablation of paroxysmal atrial fibrillation using a 3D mapping system. *Circulation* 1999;100:1203–8. https://doi.org/10.1161/01.CIR.100.11.1203; PMID: 10484541.
22. Kugler JD, Danford DA, Houston KA, et al. Pediatric radiofrequency catheter ablation registry success, fluoroscopy time, and complication rate for supraventricular tachycardia: comparison of early and recent eras. *J Cardiovasc Electrophysiol* 2002;13:336–41. https://doi.org/10.1046/j.1540-8167.2002.00336.x; PMID: 12033349.
23. Drago F, Silvetti MS, Di Pino A, et al. Exclusion of fluoroscopy during ablation treatment of right accessory pathway in children. *J Cardiovasc Electrophysiol* 2002;13:778–82. https://doi.org/10.1046/j.1540-8167.2002.00778.x; PMID: 12212697.
24. Sporton SC, Earley MJ, Nathan AW, et al. Electroanatomic versus fluoroscopic mapping for catheter ablation procedures: a prospective randomized study. *J Cardiovasc Electrophysiol* 2004;15:310–5. https://doi.org/10.1111/j.1540-8167.2004.03356.x; PMID: 15030422.
25. Hirshfeld JW Jr, Balter S, Brinker JA, et al. American College of Cardiology Foundation; American Heart Association/; HRS; SCAI; American College of Physicians Task Force on Clinical Competence and Training.ACCF/AHA/HRS/SCAI clinical competence statement on physician knowledge to optimize patient safety and image quality in fluoroscopically guided invasive cardiovascular procedures: a report of the American College of Cardiology Foundation/American Heart Association/American College of Physicians Task Force on Clinical Competence and Training. *Circulation* 2005;111:511–32. https://doi.org/10.1161/01.CIR.0000157946.29224.5D; PMID: 15687141.
26. Casella M, Dello Russo A, Pelargonio G, et al. Near zerO fluoroscopic exPosure during catheter ablAtion of supRavenTricular arrhYthmias: the NO-PARTY multicentre randomized trial. *Europace* 2016;18:1565–72. https://doi.org/10.1093/europace/euv344; PMID: 26559916.
27. Anselmino M, Sillano D, Casolati D, et al. A new electrophysiology era: zero fluoroscopy. *J Cardiovasc Med (Hagerstown)* 2013;14:221–7. https://doi.org/10.2459/JCM.0b013e3283536555; PMID: 22526222.
28. Raju H, Whitaker J, Taylor C, et al. Electroanatomic mapping and transoesophageal echocardiography for near zero fluoroscopy during complex left atrial ablation. *Heart Lung Circ* 2016;25:652–60. https://doi.org/10.1016/j.hlc.2016.01.018; PMID: 26979468.
29. Bigelow AM, Smith G, Clark JM. Catheter ablation without fluoroscopy: current techniques and future direction. *J Atr Fibrillation*. 2014;6:1066. https://doi.org10.4022/jafib.1066; PMID 27957068.
30. Ptaszek L, Moon B, Sacher F, et al. Novel automated point collection software facilitates rapid, high density electroanatomic mapping with multiple catheter types. *J Cardiovasc Electrophysiol* 2017;29:186–95. https://doi.org/10.1111/jce.13368; PMID: 29024200.
31. Frontera A, Takigawa M, Martin R, et al. Electrogram signature of specific activation patterns: analysis of atrial tachycardias at high density endocardial mapping. *Heart Rhythm* 2018;15:28–37. https://doi.org/10.1016/j.hrthm.2017.08.001; PMID: 28797676.
32. Lackermair K, Kellner S, Kellnar A, et al. Initial single centre experience with the novel Rhythmia© high density mapping system in an all comer collective of 400 electrophysiological patients. *Int J Cardiol* 2018;272:168–74. https://doi.org/10.1016/j.ijcard.2018.07.141; PMID: 30126655.
33. Giaccardi M, Mascia G, Paoletti Perini A, et al. Ablation of recurrent malignant idiopathic ventricular tachycardia: when proper diagnosis and success is a matter of contact. *Clin Case Rep* 2018;6:2193–7. https://doi.org/10.1002/ccr3.1777; PMID: 30455919.
34. Hagen PT, Scholz DG, Edwards WD. Incidence and size of patent foramen ovale during the first 10 decades of life: an autopsy study of 965 normal hearts. *Mayo Clin Proc* 1984;59:17–20. https://doi.org/10.1016/S0025-6196(12)60336-X; PMID: 6694427.
35. Fisher DC, Fisher EA, Budd JH, et al. The incidence of patent foramen ovale in 1,000 consecutive patients. A contrast transesophageal echocardiography study. *Chest* 1995;107:1504–9. https://doi.org/10.1378/chest.107.6.1504; PMID: 7781337.
36. Meissner I, Whisnant JP, Khandheria BK, et al. Prevalence of potential risk factors for stroke assessed by transesophageal echocardiography and carotid ultrasonography: the SPARC study. Stroke prevention: assessment of risk in a community. *Mayo Clin Proc* 1999;74:862–9. https://doi.org/10.4065/74.9.862; PMID: 10488786.
37. Guarguagli S, Cazzoli I, Kempny A, et al. A new technique for zero fluoroscopy atrial fibrillation ablation without the use of

intracardiac echocardiography. *JACC Clin Electrophysiol* 2018;4:1647–8. https://doi.org/10.1016/j.jacep.2018.08.021; PMID: 30573134.
38. Shenasa M, Al-Ahmad A. *Advances in Cardiac Mapping and Catheter Ablation: Part I, An Issue of Cardiac Electrophysiology Clinics, Volume 11-3*. Philadelphia, PA: Elsevier, 2019.
39. Kapur S, Barbhaiya C, Deneke T, et al. Esophageal injury and atrioesophageal fistula caused by ablation for atrial fibrillation. *Circulation* 2017;136:1247–55. https://doi.org/10.1161/CIRCULATIONAHA.117.025827; PMID: 28947480.
40. Susi F, Mascia G, Milli M, et al. Esophageal visualization changes atrial fibrillation ablation strategy: from encircling to segmental approach. *J Interv Card Electrophysiol* 2020. https://doi.org/10.1007/s10840-020-00774-2; PMID: 32494895; epub ahead of press.
41. Winkle RA, Mead RH, Engel G, et al. Physician-controlled costs: the choice of equipment used for atrial fibrillation ablation. *J Interv Card Electrophysiol* 2013;36:157–65. https://doi.org/10.1007/s10840-013-9782-x; PMID: 23483336.
42. Eichler HG, Kong SX, Gerth WC, et al. Use of cost-effectiveness analysis in health-care resource allocation decision-making: how are cost-effectiveness thresholds expected to emerge? *Value Health* 2004;7:518–28. https://doi.org/10.1111/j.1524-4733.2004.75003.x; PMID: 15367247.
43. Canpolat U, Faggioni M, Della Rocca DG, et al. State of fluoroless procedures in cardiac electrophysiology practice. *J Innov Card Rhythm Manag* 2020;11:4018–29. https://doi.org/10.19102/icrm.2020.110305; PMID: 32368376.
44. Nelson T, Garg P, Clayton RH, et al. The role of cardiac MRI in the management of ventricular arrhythmias in ischaemic and non-ischaemic dilated cardiomyopathy. *Arrhythm Electrophysiol Rev* 2019;8:191–201. https://doi.org/10.15420/aer.2019.5.1; PMID: 31463057.
45. Aronis KN, Ali RL, Liang JA, et al. Understanding AF mechanisms through computational modelling and simulations. *Arrhythm Electrophysiol Rev* 2019;8:210–9. https://doi.org/10.15420/aer.2019.28.2; PMID: 31463059.
46. Romanov A, Dichterman E, Schwartz Y, et al. High-resolution, real-time, and nonfluoroscopic 3-dimensional cardiac imaging and catheter navigation in humans using a novel dielectric-based system. *Heart Rhythm* 2019;16:1883–9. https://doi.org/10.1016/j.hrthm.2019.06.020; PMID: 31255845.
47. Nicholls M. KODEX-EPD mapping for AF ablation. *Eur Heart J* 2019;40:3003–5. https://doi.org/10.1093/eurheartj/ehz647; PMID: 31541550.