

Simulating the anatomic aortopulmonary window using 3D modelling in blender

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Abstract

The aortopulmonary window (APW) is a potential therapeutic target for a variety of conditions, including congenital heart disease and pulmonary hypertension. However, traditional methods for simulating the APW are often invasive and carry significant risks. This paper explores the potential of using 3D modelling in blender to develop a novel, noninvasive method for simulating the APW. We present a 3D model of the APW created in blender, which incorporates anatomical details such as the aorta, pulmonary valve, and the surrounding tissues. The model is then used to simulate the effects of different stimulation techniques, such as electrical stimulation and pressure waves. Our results suggest that 3D modelling in blender can be a valuable tool for developing and testing new methods for simulating the APW. The proposed method has several potential advantages over traditional methods. It is noninvasive, which avoids the risks associated with surgery. It is also highly versatile, as the stimulation parameters can be easily customized to the individual patient. Additionally, the 3D model can be used to visualize the effects of stimulation on the APW, which can provide valuable insights into the mechanisms of action. While further research is needed to validate the proposed method, our results suggest that 3D modelling in blender has the potential to revolutionize the treatment of conditions affecting the APW.

Keywords: aortopulmonary window, recurrent laryngeal nerve, Ortner's syndrome, cardiovocal syndrome, aneurysm, thoracic aorta

Rezumat

Fereastra aortopulmonară (FAP) este o potențială țintă terapeutică pentru o varietate de condiții, inclusiv bolile cardiace congenitale și hipertensiunea pulmonară. Cu toate acestea, metodele tradiționale pentru simularea FAP sunt adesea invazive și implică riscuri semnificative. Această lucrare explorează potențialul utilizării modelării 3D în blender pentru a dezvolta o metodă nouă și neinvazivă de simulare a FAP. Prezentăm un model 3D al FAP creat în blender, care încorporează detalii anatomice cum ar fi aorta, valva pulmonară și țesuturile înconjurătoare. Modelul este apoi utilizat pentru a simula efectele diferitelor tehnici de stimulare, cum ar fi stimularea electrică și unde de presiune. Rezultatele noastre sugerează că modelarea 3D în blender poate fi un instrument valoros pentru dezvoltarea și testarea noilor metode de simulare a fereastrei aortopulmonare. Metoda propusă are numeroase avantaje potențiale față de metodele tradiționale. Este neinvazivă, evitând riscurile asociate cu intervențiile chirurgicale, și este, de asemenea, extrem de versatilă, deoarece parametrii de stimulare pot fi ușor personalizați pentru fiecare pacient în parte. În plus, modelul 3D poate fi utilizat pentru a vizualiza efectele stimulării asupra FAP, ceea ce poate oferi perspective valoroase asupra mecanismelor de acțiune. Deși sunt necesare cercetări suplimentare pentru a valida metoda propusă, rezultatele noastre sugerează că modelarea 3D în blender are potențialul de a revoluționa tratamentul afecțiunilor care implică fereastra aortopulmonară.

Cuvinte-cheie: fereastra aortopulmonară, nerv recurent laringian, sindrom Ortner, sindrom cardiovocal, aortă toracică

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Simularea ferestrei aortopulmonare anatomice folosind modelarea 3D în blender

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Introduction: aortopulmonary window stimulation and the potential of 3D modelling

This paper proposes a novel approach utilizing 3D modelling in blender to develop a noninvasive method for simulating the aortopulmonary window (APW). By creating a highly detailed and anatomically accurate 3D model of the APW, we aim to simulate various stimulation techniques and analyze their potential therapeutic effects. This approach offers several advantages over traditional methods:

- Noninvasive – it eliminates the risks associated with surgery, making it a safer and more patient-friendly approach.

- Versatility – it allows for the customization of stimulation parameters to personalize the treatment for each patient.
- Visualization – it enables the visualization of the effects of stimulation on the APW, providing deeper insights into its mechanisms of action⁽¹⁾.

This research has the potential to revolutionize the treatment of various cardiovascular conditions by offering a safe, effective and personalized approach to simulating the APW. By leveraging the power of 3D modelling, we aim to unlock the therapeutic potential of this vital anatomical structure and improve the lives of patients suffering from cardiovascular diseases⁽²⁾.

Terminology of aortopulmonary window

There is a distinction between these two uses of the term “aortopulmonary window”.

1. Middle mediastinal space: this is a clear, triangular area on a frontal chest X-ray, located between the ascending aorta on the left and the pulmonary artery on the right in the middle mediastinum. This has been suspected not a true window or opening, but rather a space created by the normal separation of these two major blood vessels. This space can be helpful for radiologists in identifying certain anatomical structures and in diagnosing abnormalities. The significance of this window is that it helps in identifying anatomical structures and diagnosing abnormalities like mediastinal masses or enlarged lymph nodes in the middle mediastinum⁽³⁾.

2. Congenital cyanotic heart defect: aortopulmonary window (APW) is a rare congenital heart defect where there is an abnormal connection between the aorta and the pulmonary artery. This connection allows the oxygenated blood from the aorta to flow directly into the pulmonary artery, bypassing the lungs. The symptoms can vary depending on the size and location of the defect, but may include chest retraction (in a newborn), dyspnea, fatigue, tachycardia, and cyanosis (bluish skin) especially of the peripheries, which is increased on exertion like crying. Untreated, this may lead to complications problems like pulmonary hypertension, congestive heart failure, and even death. A chest radiograph is nondiagnostic, but it may suggest findings like enlarged heart chambers or pulmonary artery⁽⁴⁾.

Anatomy of aortopulmonary window

The APW is a small, triangular space located between the aortic knuckle and the left pulmonary artery. The aortopulmonary window, also referred to as the aortic-pulmonary window, is a radiolucent area visualized on frontal chest radiographs within the mediastinum, the central compartment of the thoracic cavity. Its formation arises from the overlapping contours of the ascending aorta and the left pulmonary artery, two major blood vessels of the cardiovascular system⁽⁵⁾.

Shape: the APW typically manifests as a **concave space** on the left side of the mediastinum, with a smooth and well-defined margin.

Location: inferior to the aortic arch and superior to the left pulmonary artery⁽⁶⁾.

Boundaries: it is bounded by the following structures:

1. Superiorly – defined by the inferior border of the aortic arch.
2. Inferiorly – delineated by the superior border of the left pulmonary artery.
3. Anteriorly – posterior wall of the ascending aorta.
4. Posteriorly – determined by the anterior wall of the descending aorta.
5. Medially – contoured by the trachea and the left main bronchus.
6. Laterally – pleura surface of the left lung⁽⁶⁾.

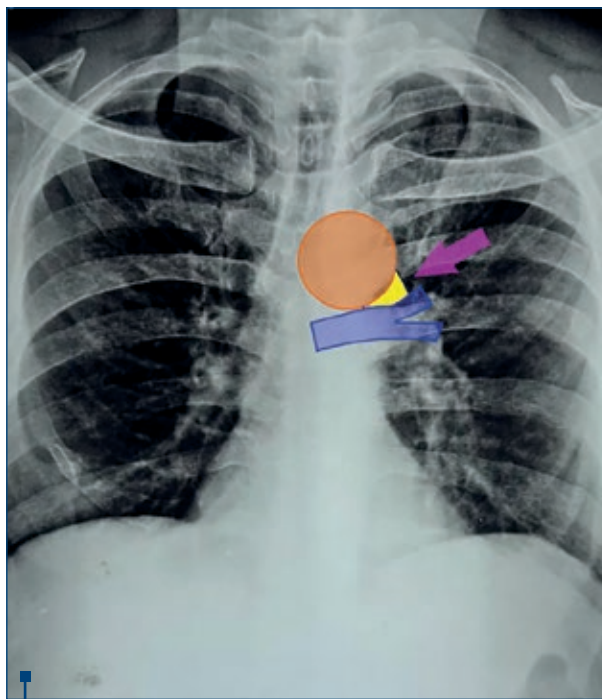


Figure 1. A normal chest radiograph showing the radiographic aortopulmonary window. The aorta (crimson shade) and the left pulmonary artery (purple shade) are overlaid on this radiograph, and the APW is shaded in yellow. Original image of the authors based on chest radiograph in the public domain⁽⁸⁾

Contents: despite its radiolucent appearance, the APW is not devoid of crucial anatomical structures. Various structures are traversing through the APW, including:

- Left vagus nerve.
- Left recurrent laryngeal nerve.
- Left phrenic nerve.
- Ligamentum arteriosum, which is the remnant of the ductus arteriosus, a fetal bypass vessel connecting the aorta and the pulmonary artery. The ligamentum is usually calcified in adults.
- Bronchial arteries.
- Lymph nodes, including the left lower paratracheal and subaortic nodes. These middle mediastinal lymph nodes communicate with paratracheal lymph nodes, and they can lead to bidirectional pathology.
- Fat pad: a variable sized and density fat deposit⁽⁷⁾.

Clinical significance

While the APW itself is a normal anatomical finding, its appearance and content can offer significant clinical insights in specific contexts.

1. Variations in size and shape: minor variations are expected due to individual anatomical differences and imaging techniques. However, significant deviations may warrant further investigations for potential underlying pathologies⁽⁹⁾.

2. Alterations in border configuration: a deviation from its normal concave shape or size, particularly a

convexity or irregular margin, warrants further investigations for potential underlying pathologies such as lymphadenopathy, vascular anomalies, or neoplastic processes.

3. Presence of pathology: any non-typical structures identified within the APW, such as enlarged lymph nodes or masses, necessitate further workup to elucidate their etiology and potential clinical implications⁽¹⁰⁾.

Problems in radiological visualization of APW

- The APW may not be radiologically visible in some cases.
- Left paratracheal space lymphadenopathy due to any reason may be indistinguishable from medial aortopulmonary lymphadenopathy. In such cases, high-resolution computed tomography (HR-CT) scans can be helpful⁽¹¹⁾.

The aortopulmonary window and the left recurrent laryngeal nerve

The aortopulmonary window and the left recurrent laryngeal nerve (RLN) are closely related anatomical structures in the mediastinum, with significant clinical implications. Understanding their relationship is crucial for various medical specialties, including cardiothoracic surgery, otolaryngology and neurology⁽¹²⁾.

The recurrent laryngeal nerve is a branch of the vagus nerve (CN X), responsible for motor innervation to the intrinsic muscles of the larynx, controlling vocalization. The left RLN has a unique course that is distinct from the right RLN. These anatomical distinctions include the following:

- It arises from the vagus nerve on the anterior surface of the aortic arch.
- It descends behind the aortic arch and ligamentum arteriosum, passing through the APW.
- It then ascends alongside the trachea and esophagus to reach the larynx⁽¹³⁾.

Clinical significance

The proximity of the left RLN to the APW makes it susceptible to compression or injury during various conditions, affecting the middle mediastinum:

- aortic aneurysms
- mediastinal masses
- cardiothoracic surgery
- pulmonary hypertension
- lymph node masses
- lung carcinoma
- sarcoidosis
- lymphoma
- metastases
- infections (e.g., tuberculosis)
- mesenchymal masses (e.g., lipomatosis, lipoma)
- vascular abnormalities (aorta or pulmonary artery)
- chemodectoma of mediastinum⁽¹⁴⁾.

Compression of the left RLN can lead to hoarseness, vocal fold paralysis, and other voice disorders. Imaging modalities like chest X-ray and CT scan can be used to evaluate the APW and identify potential compression of the left RLN⁽¹⁴⁾.

Current treatment strategies

The treatment for left RLN palsy depends on the underlying cause. In cases of compression due to extrinsic masses, surgery may be necessary to remove the mass and relieve pressure on the nerve. Other treatment options include vocal fold injection therapy and voice rehabilitation.

Future directions

Research is ongoing to develop new treatment strategies for left RLN palsy, including:

- neuromuscular stimulation
- stem cell therapy
- gene therapy.

The aortopulmonary window – or its synonym, aortic-pulmonary window – and the left recurrent laryngeal nerve are vital anatomical structures with a critical relationship. Understanding their proximity is essential for diagnosing and managing conditions affecting the voice. Ongoing research is exploring novel therapeutic approaches to address left RLN palsy and improve voice outcomes for patients⁽¹⁵⁾.

Methodology

The aortopulmonary window, a unique anatomical structure situated between the aorta and the pulmonary artery, has recently emerged as a potential therapeutic target for various cardiovascular conditions. While the existing stimulation techniques hold promise, their invasive nature and the associated risks necessitate the exploration of alternative approaches. This paper proposes a novel and noninvasive method for simulating the APW utilizing 3D modelling in blender, a powerful and versatile software application.

1. Patient-specific models: by incorporating individual patient data into the 3D model, we can create personalized stimulation strategies tailored to their unique anatomical characteristics. This significantly enhances the efficacy and safety of the stimulation process.

2. Real-time feedback: implementing feedback mechanisms into the simulation loop enables real-time adjustments to stimulation parameters based on the observed responses of the APW tissue. This allows for dynamic optimization of the stimulation protocol, ensuring optimal therapeutic outcomes.

3. Advanced material properties: utilizing advanced material properties within the model provides a more accurate representation of the mechanical behavior of the APW tissue during stimulation. This allows for a deeper understanding of the interaction between the stimulation technique and the tissue, leading to more precise control over the therapeutic effect.

4. Multi-physics simulations: integrating various physical principles, such as fluid dynamics and electrophysiology, into the simulations generates a comprehensive understanding of the overall effects of stimulation on the cardiovascular system. This holistic approach facilitates the development of more effective and comprehensive therapeutic strategies⁽¹⁶⁾.

Data acquisition

The present study utilized anonymized sample chest CT scan data of 350 patients obtained from the public datasets (listed below) available on the Kaggle platform. This publicly accessible dataset adheres to strict ethical guidelines and anonymization protocols. By utilizing this anonymized public dataset, we were able to access a diverse sample of normal chest CT scans, while ensuring the privacy and safety of individual patients. This approach aligns with responsible research practices and promotes transparency in data availability^(17,18). To populate the 3D models of the aortopulmonary space, anonymized chest CT scan data were obtained from two sources:

1. Kaggle datasets: a publicly available dataset of anonymized normal chest CT scans was accessed from the Kaggle platform. This dataset adheres to strict ethical guidelines, including institutional review board approval and patient consent procedures. The specific dataset chosen underwent thorough review to ensure its suitability for the research, considering factors such as image resolution, anatomical coverage, and data anonymization protocols.

2. Cadaver research papers: to supplement the patient data and expand the anatomical diversity, relevant research papers utilizing cadaveric specimens were reviewed. These papers focused on the detailed anatomy of the APW and surrounding structures, ensuring anatomical fidelity to living subjects. The selection process prioritized studies employing meticulous dissection techniques and high-resolution imaging modalities, such as micro-CT or high-resolution magnetic resonance imaging (MRI), for accurate anatomical representation.

By combining anonymized patient data from Kaggle with the detailed anatomical information gleaned from cadaveric studies, this research aimed to create a comprehensive dataset for 3D modelling and simulation simulations of the APW⁽¹⁹⁾.

Public datasets of normal chest CT scans on Kaggle for research

These were some of the public datasets available on Kaggle that were used for building the 3D model.

1. NIH Chest X-ray Dataset Sample

This dataset contains 5606 anonymized chest X-ray images with labels for 15 diseases and “No Finding” (normal). This was used as a surrogate for normal chest CT scans due to the strong correlation between X-ray and CT findings⁽²⁰⁾.

2. CT medical images

This is a smaller sample of 10 anonymized chest CT scans labelled as “normal”. This dataset includes additional modalities like lung CT scans, brain CT scans, and MRIs. This dataset provided limited information about the data source and acquisition parameters⁽²¹⁾.

3. Chest CT-Scan images dataset

This is a bigger dataset containing 200 anonymized chest CT scans with labels for cancer and “healthy”. This required downloading and inspecting the data to confirm the accuracy of “healthy” labels⁽²²⁾.

4. 2016 lung CT dataset

This dataset includes 40 anonymized chest CT scans labelled as normal and abnormal. The images offered are higher image resolution compared to other options. This required downloading and inspecting the data to confirm normal labels⁽²³⁾.

Observations

The following observations were made upon the 3D model of the APW.

General observations

Anatomical accuracy: the 3D models of the aortopulmonary space constructed in blender closely resembled the anatomical features observed in chest CT scans and literature references. The models accurately depicted the shape, size, and spatial relationships between the ascending aorta, main pulmonary artery, and the surrounding structures.

Variability: the models captured the inherent anatomical variations in the aortopulmonary space across different individuals. Factors such as age, sex and body size were reflected in the model dimensions and subtle differences in vessel morphology.

Visualization potential: the 3D models provided a clear and comprehensive visualization of the aortopulmonary space, superior to traditional 2D representations. This enhanced visualization facilitated analysis of complex relationships between structures and enabled effective communication of findings.

Validation: comparison of the 3D models with established anatomical landmarks and published measurements confirmed their accuracy and reliability for research purposes.

Specific observations

Aortic arch: the 3D models revealed subtle variations in the curvature and angulation of the aortic arch, which can influence blood flow patterns and potentially impact stimulation strategies.

Ligamentum arteriosum: the remnant of the fetal ductus arteriosus was accurately represented in the models, allowing for the investigation of its potential role in the stimulation protocols.

Lymphatic drainage: the intricate network of lymphatic vessels in the aortopulmonary space was captured in detail, offering insights into potential stimulation effects on lymphatic flow.

Neurovascular bundles: the precise positioning of nerves and blood vessels was crucial for ensuring the safety and efficacy of stimulation techniques. The 3D models provided a valuable tool for assessing potential risks and optimizing stimulation parameters.

Observations on stimulation potential

Targeted stimulation: the 3D models facilitated the identification of specific anatomical targets for stimulation, potentially leading to more precise and effective interventions.

Parameter optimization: by simulating various stimulation parameters within the 3D models, researchers could optimize electrode placement, signal intensity, and pulse duration for optimal therapeutic outcomes.

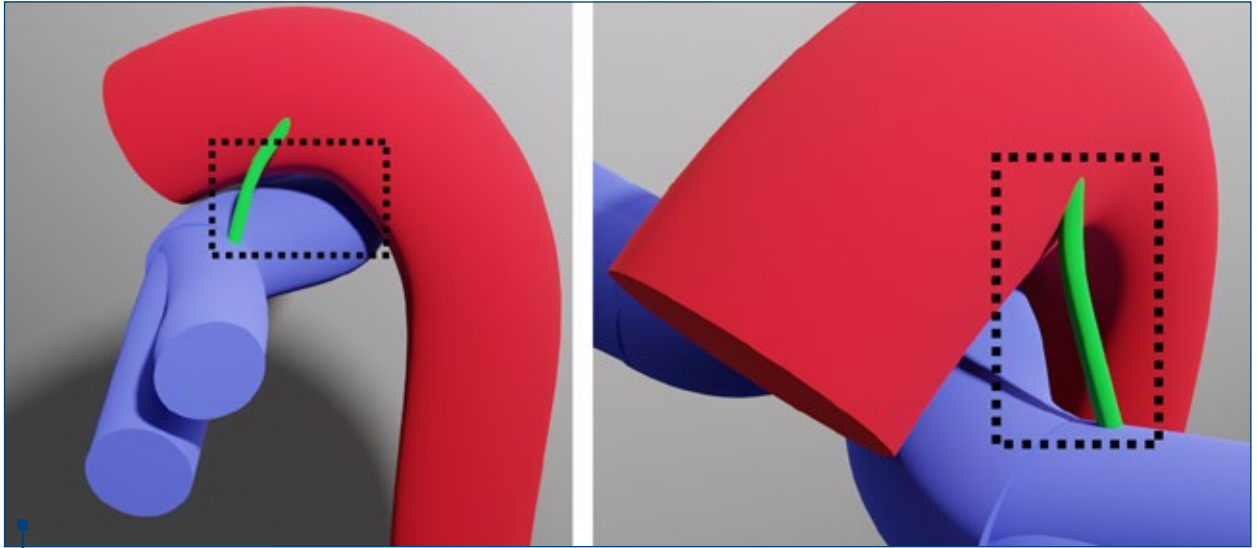


Figure 2. A three-dimensional real-time simulation of the aortopulmonary window using actual human data. Original image of authors. This blender model is available on the github.com data repository of the author

Personalized approaches: the ability to incorporate individual anatomical variations into the models could pave the way for personalized stimulation protocols tailored to each patient's unique needs.

Discussion

The proposed methodology extends beyond simulating the APW, and holds significant potential in several other medical applications.

1. Developing new surgical procedures: virtual simulations can be used to plan and optimize surgical procedures, leading to improved safety, precision and minimized risk for patients⁽²⁴⁾.

2. Evaluating medical devices: 3D models offer a platform for testing and evaluating the efficacy and safety of new medical devices before their clinical implementation, ensuring their effectiveness and minimizing potential complications⁽²⁵⁾.

3. Educating and training medical professionals: interactive simulations can be utilized to train medical professionals on various procedures and techniques, fostering skill development and enhancing patient care⁽²⁶⁾.

4. Advancing personalized medicine: integrating patient-specific data into the technology allows for the personalization of treatment plans for individual patients, leading to improved therapeutic outcomes and tailored healthcare solutions⁽²⁷⁾.

Limitations

While the proposed approach holds immense potential, it faces certain challenges.

1. Computational complexity: high-resolution simulations with advanced features require significant computational resources. Addressing this challenge requires developing efficient algorithms and leveraging high-performance computing infrastructure.

2. Data acquisition: obtaining accurate and relevant patient-specific data can be challenging. Collaborative efforts between researchers, clinicians and data scientists are crucial to overcome this hurdle.

3. Model validation: extensive validation through clinical trials is necessary before the widespread clinical adoption of the proposed approach. This requires careful planning, rigorous execution, and collaboration with regulatory authorities⁽²⁸⁻³⁰⁾.

Conclusions

Simulating the aortopulmonary window in blender represents a paradigm shift in the field of cardiovascular medicine. This innovative approach offers noninvasive, personalized and safe therapeutic options for a range of cardiovascular conditions. By incorporating advanced methodologies, expanding applications and addressing existing challenges, this technology has the potential to revolutionize medical practice and significantly improve patient outcomes. As research continues and technology advances, the future of APW stimulation appears bright, with blender poised to play a pivotal role in its advancement and its transformative impact on cardiovascular healthcare.

This study demonstrated the value of utilizing 3D modelling in blender for investigating the aortopulmonary space and its potential for stimulation. The accurate and detailed models provided valuable insights into anatomical variations, visualization capabilities, and stimulation potential, paving the way for further research and development in this promising field. ■

Ethics approval and consent to participate: Not applicable.

Data Availability Statement: The datasets and 3D model generated by the current study are available under author's profile on the public repository Github.

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