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Exercise motion analysis demonstrating correction of paradoxical chest wall motion following 3D printed sternal implant for sternal chondrosarcoma resection

Aimee M Layton, David Swinarski, Jeffrey L Port, Alexander McCauley, Byron M Thomashow, William A Bulman

ABSTRACT

Introduction: Chondrosarcoma is a rare bone cancer. This type of cancer often presents in long bones and it is extremely rare to find it in the sternum. Resection and reconstruction of a sternal chondrosarcoma are difficult and may lead to abnormal chest wall mechanics. We report a case where the patient underwent a curative resection of the chondrosarcoma with sternotomy and chest wall reconstruction with Gore-Tex mesh. As a result of the surgery she had pectus excavatum and persistent pain with inspiration. She then received the first three-dimensional (3D) printed sternum implant in the United States. Cardiopulmonary exercise testing (CPET) and 3D motion analysis called optoelectronic plethysmography (OEP) were used to quantitatively assess her ventilatory mechanics and exercise ventilatory response pre- and post-3D printed implant. Case Report: Optoelectronic plethysmography measured the patient's ventilatory mechanics at rest and during exercise. Principal component analysis (PCA) analyzed the waveform of the marker movement. Results revealed preoperative complex, asynchronous chest wall motion by OEP 3D chest wall reconstruction, which included paradoxical movement of the sternal area. Postoperative testing revealed corrected chest wall movement. Specifically, the sternal body marker moved out of phase with the midline ventral chest (17% delay in movement) preoperatively; postoperatively the delay had decreased to 3%. Tidal volume of the rib cage improved postoperatively and compensatory abdominal movement decreased. Conclusion: Optoelectronic plethysmography in conjunction with PCA provided isolated areas of the chest wall to be analyzed and abnormal movement quantified. Optoelectronic plethysmography and PCA were valuable tools in the assessment of abnormal chest wall mechanics and may be helpful in future planning for reconstructive chest wall surgery. Further work may determine the usefulness of OEP and PCA in other reconstructive chest wall surgeries.

Keywords: 3D printed prosthesis, Exercise chest wall movement, Optoelectronic plethysmography, Sternal chondrosarcoma

Aimee M Layton[1], David Swinarski[2], Jeffrey L Port[3], Alexander McCauley[4], Byron M Thomashow[5], William A Bulman[6]

Affiliations: [1]Associate Research Scientist, Department of Medicine, Division of Pulmonary, Columbia University, New York, USA; [2]Associate Dean, Faculty of Arts of Sciences, Fordham University, New York, USA; [3]Professor of Clinical Cardiothoracic Surgery, Department of Surgery, Cornell University, New York, USA; [4]Senior Software Engineer, Waymo, San Francisco, California, USA; [5]Professor of Medicine, Department of Medicine, Division of Pulmonary, Columbia University, New York, USA; [6]Associate Professor, Department of Medicine, Division of Pulmonary, Columbia University, New York, USA.

Corresponding Author: Aimee M Layton, PhD, 622 W 168th St., VC3-365, New York 10032, USA; Email: aml2135@cumc.columbia.edu

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INTRODUCTION

Sternal chondrosarcoma is a rare primary malignancy of the chest wall that is often treated with en bloc removal of the tumor and surrounding tissue and a reconstruction of the chest wall [1, 2]. Resection can result in large chest wall defects that can be difficult to reconstruct, and the prosthetic materials commonly used can lead to bone fractures from excessive rigidity or paradoxical chest wall movement from excessive flexibility [3, 4].

Qualitative and quantitative measurement of chest wall instability and paradoxical ventilatory mechanics is possible by movement analysis via 3D reconstruction of the chest wall called optoelectronic plethysmography (OEP) [5], and it is unique in that it allows for respiratory mechanics to be assessed noninvasively during exercise [6]. Enhancement of the abnormal chest wall excursion for better visualization was made possible by the application of the principle component analysis.

We present the case of a woman with pain and exertional dyspnea thought to be due to paradoxical chest wall mechanics following a resection of a sternal chondrosarcoma with Gore-Tex reconstruction. She underwent reoperative reconstruction using a personalized 3D printed prosthesis, the first such case in the United States.

CASE REPORT

A 22-year-old woman with sternal chondrosarcoma underwent curative resection with sternotomy, partial sternal resection, rib resection, and chest wall reconstruction with a Gore-Tex mesh implant. As a result of the surgery she had pectus excavatum and later developed pain with inspiration and exercise intolerance. Three years later, she received a 3D printed sternum prosthesis (Figure 1) made of titanium and porous polyethylene (Anatomics, St. Kilda, VIC, Australia). This study was approved by the Columbia University Internal Review Board and informed consent was obtained by the patient.

Cardiopulmonary exercise testing with simultaneous ventilatory motion analysis using OEP (BTS Bioengineering, Milano, Italy) was performed two weeks before and 11 weeks after surgery. Pulmonary function testing (PFT) included standard spirometry and a maximum voluntary ventilation maneuver (MVV). The exercise testing was performed using a 15 W-ramping protocol on a stationary cycle ergometer with continuous gas exchange measurement (Carefusion Sentry Suite/ VMAX Encore v2.19, San Diego, CA). Optoelectronic plethysmography data was collected at rest and throughout exercise using 89 reflective markers on the chest, stomach, and back and eight infrared cameras.

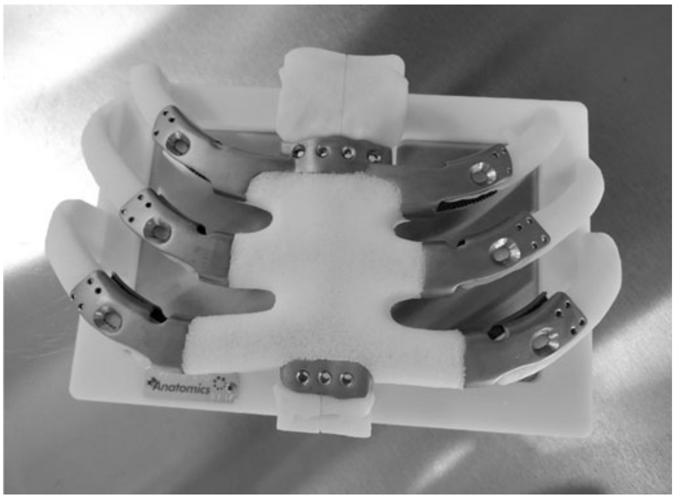


Figure 1: 3D printed sternum prosthesis.

Analysis

Optoelectronic plethysmography in conjunction with PCA was used to analyze chest wall mechanics. We also compared changes in spirometry, gas exchange, and exercise capacity measures pre- and postoperatively.

Results

Video of real time motion analysis capture has been included with simultaneous graphical representation of the chest wall markers over the sternal body where the prostheses were placed (Video 1). The preoperative processed OEP sternal imaging revealed complex, dyssynchronous chest wall motion at superior sternum. Paradoxical thoracoabdominal movement was seen by the sternal body marker moving out of phase with the remainder of the midline ventral chest (17% delay); these abnormalities were not evident postoperatively (3% delay) (Figures 2 and 3). Surgery reduced the number of principal components of exercise motion from 13 to 8, demonstrating a less complex chest wall motion overall. The improvement in chest wall mechanics allowed for an increase in tidal volumes from the pulmonary rib cage area (RCp) from 0.829 L/min to 1.248 L/min and decrease in compensatory movement of the abdominal area (AB) from 0.838 L/min to 0.819 L/min. The distribution of chest wall movement during exercise of pre-3D printed implant was: 45% from the RCp, 10% from the area of the diaphragm, and 45% from AB. Post-3D printed prosthesis implant, chest wall movement was corrected to a distribution of 53%:12%:35%, respectively.

The MVV improved from 84 L/min to 116 L/min and there was a marked improvement in exercise gas exchange

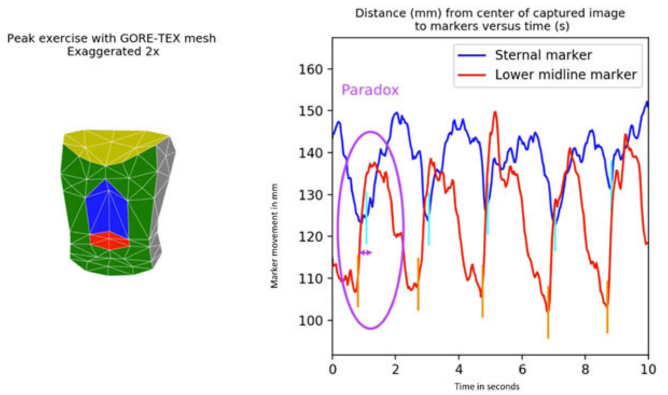


Figure 2: Paradoxical movement of the sternal body marker vs. total chest markers during exercise of tidal breathing with the Gore-Tex mesh implant. Such paradoxical movement may explain the pain the patient felt upon inspiration. The movement of the OEP marker reveals that the Gore-Tex mesh implant was moving into the chest wall on inspiration rather than outward, to allow for lung expansion.

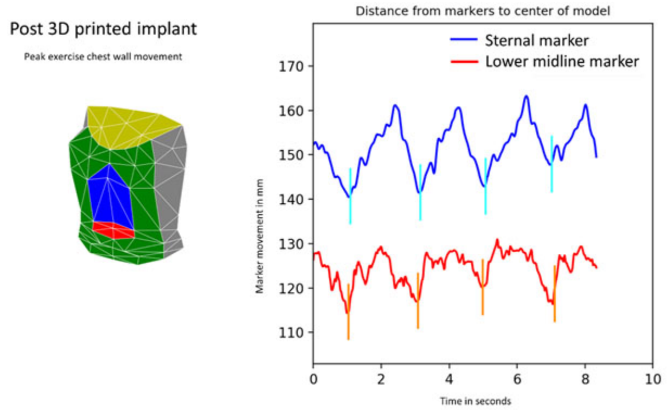
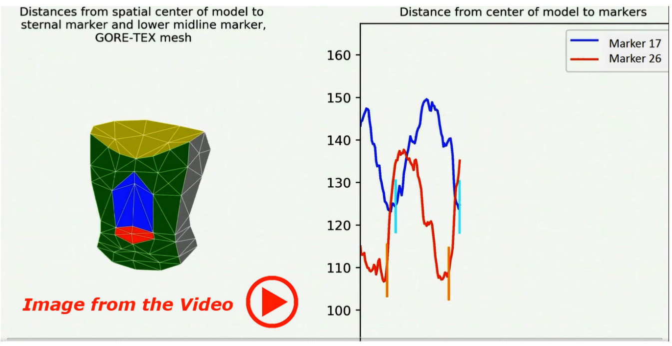


Figure 3: The OEP marker motion now reveals the chest wall moving in synchrony and the 3D printed prosthesis moving outward on inspiration, allowing greater tidal volumes to be generated.



Video 1: Video of the asynchronous movement the sternal body and post 3D implant now synchronous movement of the sternal body.

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Access Video on other devices

with a decrease in carbon dioxide retention with exercise seen by a decrease in end-tidal CO_2 ($ETCO_2$) at the anaerobic threshold (from 50.2 mmHg to 44.5 mmHg) and peak exercise (47.0 mmHg to 39.6 mmHg) and improvement in SpO_2 from 96% to 98% at peak exercise. Peak workload and respiratory rate also demonstrated mild improvements [peak workload improved from 175 W to 180 W and increase in respiratory rate (RR) from 31 fB to 34 fB].

At 11 weeks postoperatively, the patient had no pain and subjectively improved exercise tolerance.

DISCUSSION

This case study was the first 3D printed sternal implant in the country. This was also the first case to use PCA to isolate the respiratory motion captured by OEP to quantify the mechanical paradox due to a poorly suited sternal reconstruction. Restoration of more normal chest wall mechanics from the 3D printed prosthesis was demonstrated by postoperative OEP.

These findings suggest that the Gore-Tex implant may have been too flexible for the large reconstructed area, causing the prosthesis to be drawn into the thorax as thoracic pressure changes during inhalation, as has been described elsewhere [3, 7]. In this case, the patient appeared to be compensating for the smaller intrathoracic volume change during inspiration (45% vs. an expected value of 51%) with increased AB expansion (45% vs. an expected value of 32%). Replacement of the Gore-Tex with a more rigid 3D printed prosthesis restored a more normal RCp and AB distribution.

The reasons for the abnormal gas exchange response to exercise seen with the original prosthesis are unclear, although the higher $ETCO_2$ seen with paradoxical respiration may have reflected an extrinsic obstruction that was exaggerated by changes in intrathoracic pressures with the larger exercise tidal volumes. As the paradoxical movement of the chest wall was resolved, gas exchange also improved.

Optoelectronic plethysmography captures chest wall movement and provides waveforms that enable researchers to analyze the movement of different areas of the chest wall, such as the area of the RCp, diaphragm, and the ABs [6]. We combined the use of OEP technology with the statistical analysis called PCA [8] to isolate motion being records by OEP. By isolating the various motions, we are able to remove motion artifact from cycling to analyze just respiratory motion. Once we were able to isolate respiratory motion, we isolated and amplified the marker movement of sternal area during exercise to observe its inspiratory and expiratory motion for paradoxical motion. Prior OEP research has not isolated analyzed large areas of the chest wall, such as the movement from the entire upper thorax [6]. In this case, that would not have been helpful, as we needed to isolate the movement of just the prosthesis in order to determine why the patient was feeling pain on inspiration. Future application of this technique may be used in the design of chest wall prosthesis or in decision making for reconstructive chest wall surgery. For instance, future work may use this technique to determine a threshold of paradoxical movement that results in pain and thus reconstruction is warranted or lack of movement from a sternal prosthesis that results in rib fracture and using that information in improving the design of prostheses.

CONCLUSION

This use of PCA to analyze OEP movement signal is a novel concept and allowed for the area of the chest wall where abnormal ventilatory mechanics were suspected to be isolated and studied. This technique provided insight for both the patient and the surgeon as to why the original Gore-Tex material was ineffective as a prosthesis. These techniques may be useful in planning reconstructive surgery in future cases. Documentation of improved ventilatory mechanics and gas exchange with 3D printed implants may be important in acquiring FDA approval and reimbursement for these devices and supports the need for a personalized approach to chest wall prosthetics.

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Author Contributions

Aimee M Layton – Conception of the work, Design of the work, Acquisition of data, Analysis of data, Interpretation of data, Drafting the work, Revising the work critically for important intellectual content, Final approval of the version to be published, Agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved

David Swinarski – Conception of the work, Design of the work, Acquisition of data, Analysis of data, Interpretation of data, Drafting the work, Revising the work critically for important intellectual content, Final approval of the version to be published, Agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved

Jeffrey L Port – Conception of the work, Design of the work, Acquisition of data, Analysis of data, Interpretation of data, Drafting the work, Revising the work critically for important intellectual content, Final approval of the version to be published, Agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved

Alexander McCauley – Conception of the work, Design of the work, Acquisition of data, Analysis of data, Interpretation of data, Drafting the work, Revising the work critically for important intellectual content, Final approval of the version to be published, Agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved

Byron M Thomashow – Conception of the work, Design of the work, Acquisition of data, Analysis of data, Interpretation of data, Drafting the work, Revising the work critically for important intellectual content, Final approval of the version to be published, Agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved

William A Bulman – Conception of the work, Design of the work, Acquisition of data, Analysis of data, Interpretation of data, Drafting the work, Revising the work critically for important intellectual content, Final approval of the version to be published, Agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved

Guarantor of Submission

The corresponding author is the guarantor of submission.

Source of Support

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Consent Statement

Written informed consent was obtained from the patient for publication of this article.

Conflict of Interest

Authors declare no conflict of interest.

Data Availability

All relevant data are within the paper and its Supporting Information files.

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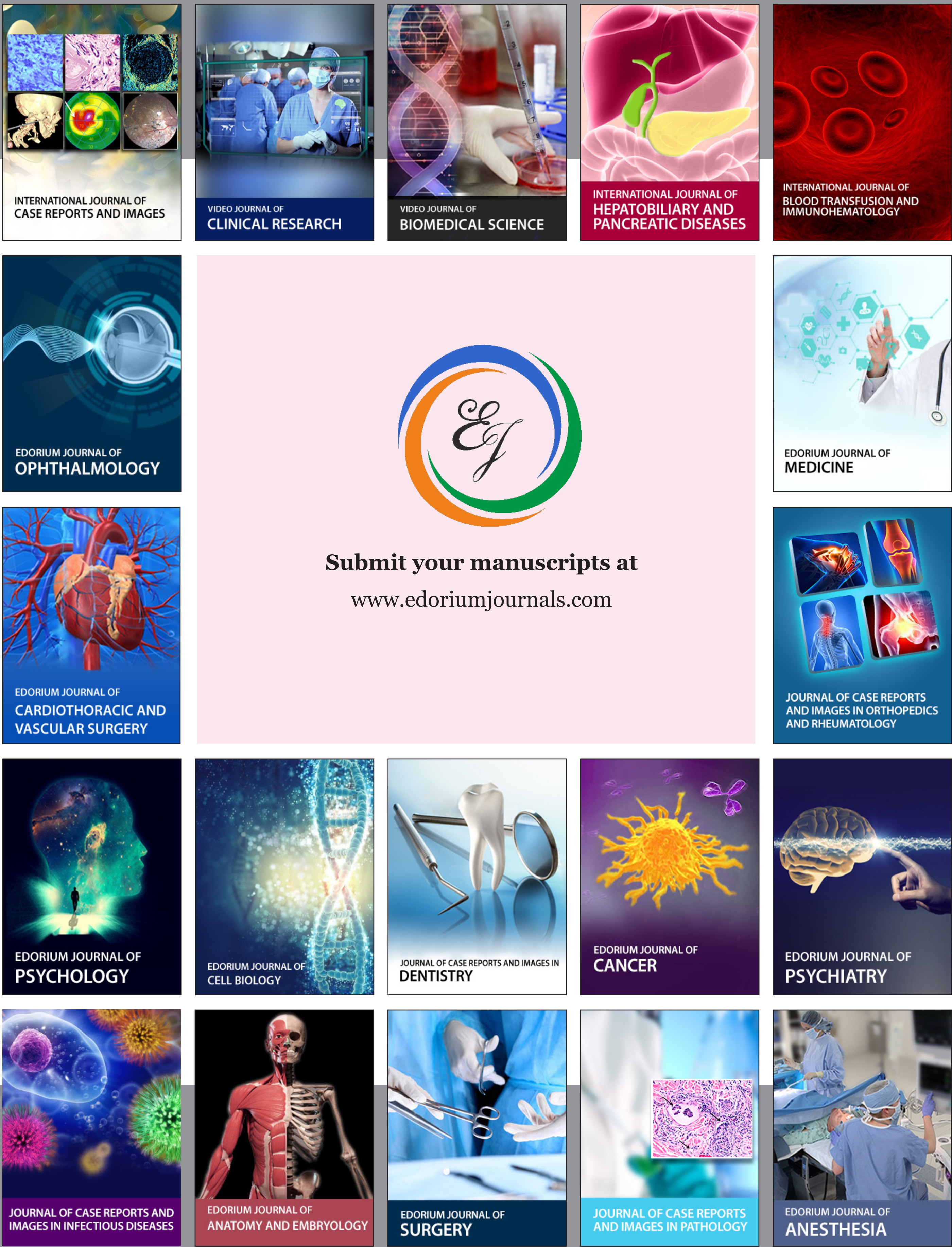
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