Synthesis Lectures on Visualization

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BioMedical Visualization

Past Work, Current Trends, and Open Challenges

Springer

Synthesis Lectures on Visualization

This series publishes on topics pertaining to scientific visualization, information visualization, and visual analytics. Potential topics include, but are not limited to scientific, information, and medical visualization; visual analytics, applications of visualization and analysis; mathematical foundations of visualization and analytics; interaction, cognition, and perception related to visualization and analytics; data integration, analysis, and visualization; new applications of visualization and analysis; knowledge discovery management and representation; systems, and evaluation; distributed and collaborative visualization and analysis.

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Preface

Medicine and biology are important research fields with a significant impact on humans and their health. In the last few decades, many visualization strategies have been proposed for solving problems within these disciplines. From the early molecular models and medical volume representations to modern-day visual analytics for genomics or extended reality applications for surgery training and guidance, the area of biomedical visualization has progressed and expanded considerably.

The goal of this book is to provide an overview of biomedical visualization by highlighting the overall trends of research through the years and the evolution of topics over time. To uncover these trends, we have manually curated a total of 3856 research publications related to biomedical visualization, which we categorized according to their application field. A searchable repository of these publications accompanies this book at https://biomedvis-book.fi.muni.cz/.

The topics we cover in this book include visualization research in omics, interaction networks and pathways, biological structures, tumor diagnosis and treatment, vasculature, brain, surgery, educational contexts, therapy and rehabilitation, electronic health records, and public health. A separate chapter is dedicated to general visualization techniques commonly used for biomedical data, such as surface and volume rendering, as well as abstract and illustrative approaches. For each of these areas, the past and contemporary research trends are discussed, highlighting the most influential works. Furthermore, the book explains how research is affected by developments in technology, data availability, and domain practice.

Moreover, we discuss visualization challenges that can be considered solved, as well as research directions anticipated to thrive in the upcoming years. We further include the outcomes of interviews conducted with 16 researchers in the field of biomedical visualization to solicit their opinions regarding the evolution and trends in the domain as well as the future of this research field.

We discuss the individual topics in a concise manner to help readers orient themselves in the already mature and diverse field of biomedical visualization without overwhelming them with technical details. We also provide useful pointers for future reading. As such, we hope that the book can help young researchers to become familiar with past challenges and identify future ones. For more senior researchers, we believe our book can serve as an insightful overview of the research field and the direction it is heading.

We invite you to join us on our journey through the research history of BioMedical Visualization and hope you will enjoy reading this book.

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Introduction

1

Biological and medical visualization has been a growing research area for several decades. Through the years, many visualization strategies have been designed and the focus of the field has been changing and adapting to new challenges that arose over time. This book is intended to provide a comprehensive and structured overview of *BioVis*, e.g., molecular visualization and metabolic pathway visualization, and *MedVis*, e.g., 3D visualizations for diagnosis, treatment, and education. While some topics clearly belong to either BioVis or MedVis, there are also overlaps among the two domains. For example, the analysis of microscopic images at a cellular level integrates BioVis techniques, such as image analysis of sub-cellular components, with MedVis aspects, such as developing systems for supporting clinical workflows. In the context of this book, we refer to these techniques—*BioVis*, *MedVis*, or "in-between"—as *BioMedical Visualization*.

BioMedical Visualization has been an enabler for medical diagnosis and treatment and an influential component of today's life science research. Many BioMedical domains can now be studied at various scales and dimensions, employing different acquisition modalities and simulations, and supporting various purposes—from genomic to public health data, and from biomolecules to large-scale volumes.

This book is motivated by the maturity of BioVis and MedVis after several decades of intense research worldwide. Due to the growth of the field, it has meanwhile become very challenging for Ph.D. students and industrial researchers to oversee the area. After the publication of focused state-of-the-art reviews on special BioVis and MedVis topics, such as visual computing for radiation treatment planning [551], visual analytics for public health [485], and visualization of biomolecular structures [320], we aim to provide a broader picture.

We observe that throughout the history of BioMedical Visualization, there have been three interesting tendencies. Firstly, *advances of the visualization field* progress along with

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imaging modalities, such as the visualization of the multiscale, multimodal, cohort, or computational biology data, as well as the emergence of Visual Analytics with the increasing incorporation of artificial intelligence and "human-in-the-loop" concepts. Secondly, we witness the *re-emergence of topics* once every few years, such as the use of augmented and virtual reality for educational purposes. Thirdly, research makes its way *from general towards more specialized solutions*. While in the past, general solutions were developed (e.g., vessel visualization or virtual endoscopy), nowadays research tends towards special problems or diseases (e.g., aneurysms).

With this book, we set out to answer the following questions: *What are the overall trends through the years? How are the topics evolving with the course of time? Where is the field heading in the upcoming decade?* Our book aims to make the following **contributions**:

- an extensive historical search of the papers related to BioMedical Visualization;
- a taxonomy of BioMedical Visualization, i.e., of the topics and the people/groups working on these, along the course of time;
- a characterization of more than 3,800 papers, and
- an online, interactive repository accompanying the book, where our collection of papers and taxonomy is made available to the community for further use at https://biomedvis-book.fi.muni.cz/.

1.1 Literature Search and Scope

The book has an unusually broad scope, leading us to consider more than 3,800 publications. This broad scope poses several challenges with regard to the extent of the search and the resulting taxonomy. We conducted an extensive search of literature databases, using consistently the following search term to discover previous work in visualization, visual analytics, and augmented and virtual reality on recurrent topics or applications in BioVis and MedVis:

```
("molecular" OR "biological" OR "medical" OR
"anatomical" OR "biomolecular" OR "biochemical" OR
"chemical" OR "biomedical" OR "bioinformatics" OR
"biomechanics" OR "cell" OR "cellular" OR "microbiology"
OR "genetics" OR "histology" OR "pathology" OR
"histopathology" OR "neuroscience" OR "pharmacology" OR
"physiology" OR "surgical") AND ("visualization" OR
"visualisation" OR "visual analytics" OR "visual
computing" OR "visual analysis" OR "virtual reality" OR
"augmented reality" OR "mixed reality" OR "graphics" OR
"human computer interaction")
```

For the literature search, we considered the sources in Table 1.1. When possible, e.g., in PubMed or IEEE Xplore, logical search operators were used to directly apply the aforementioned search term. Otherwise, e.g., in the Eurographics Digital Library, where the search is limited, the considered journals or proceedings were reviewed manually on a one-to-one basis. The searches were not filtered with regard to publication time and all years were considered—spanning even back to 1969 until April 2024. In IEEE Xplore, an initial search

Table 1.1 Sources and respective numbers of identified papers

Source	Papers
IEEE Transactions on Visualization and Computer Graphics (TVCG)	386
EG DigLib (excl. EG VCBM and CGF)	276
EG Visual Computing in Biology and Medicine (VCBM)	261
Computer Graphics Forum (CGF)	240
Computers and Graphics (C&G)	193
IEEE VIS and SciVis	167
IEEE Computer Graphics and Applications (CGA)	134
IEEE Information Visualization (IV)	122
Bioinformatics	101
IEEE Virtual Reality (VR)	98
BMC Bioinformatics	92
International Journal of Computer Assisted Radiology and Surgery (JCars)	74
The Visual Computer	70
IEEE ISMAR	58
IEEE PacificVis	55
Nature (Methods, Biotechnology, Communications, ...)	53
IEEE Access	52
IEEE Visual Analytics in Healthcare (VAHC)	46
ACM SIGGRAPH, SIGGRAPH Asia	45
IEEE Symposium on BioVis	45
IEEE Trans. on Medical Imaging (TMI)	44
IEEE Trans. on Biomedical Engineering (TBE)	42
Book Sections (Springer)	40
Graphics Interfaces (GI)	26
IEEE Visual Analytics Science & Technology (VAST)	26
Nucleic Acids Research	25
ACM Virtual Reality Software & Technology (VRST)	22
Other various	1063
Total	**3856**

yielded more than 70,000 results. Therefore, we decided not to search the entire database, but to restrict the search to the most significant sources, which are indicated in Table 1.1. For the easy storage and further management of the findings, we used reference management software to manage bibliographic data and related materials. This allowed us to import all relevant works easily, check for duplicates, and further identify out-of-scope works.

Papers, where the term visualization was used to denote pure imaging or processing methods, data mining or data management tools, databases, simple plots of findings, or packages with standard viewers (e.g., in R), were discarded. Only works with a core visualization, visual analytics, or virtual/augmented reality focus were considered. Results were also considered out of scope if they only matched the search term due to titles in the reference list or author biographies, and if they were not within our specific BioVis and MedVis scope. We also restricted our search to papers written in English. The initial search yielded more than 4,000 candidates, which were reduced to 3,856 during a second thorough pass conducted iteratively by multiple co-authors. The numbers in Table 1.1 are those resulting from this second pass. As a companion to this book, which contains only 690 selected key publications, a searchable website with all publications we analyzed is provided at https://biomedvis-book.fi.muni.cz/.

Figure 1.1 shows the number of the considered BioMedVis papers published across time overall (a) and for six prominent venues (b). Since the data for the year 2024 were incomplete at the time of publication, we only included data up to the year 2023 in the timeline graphs in the book. It can be noted, that there is a sudden spike from 172 papers in 2018, to 416 in 2019, and to 337 in 2020, which can be justified by the appearance of a multitude of papers that deal with multimodal, multi-parametric, multi-subject, multiscale data, as well as a multitude of contributions in the fields of rehabilitation (also with VR/AR), omics, and molecular visualization.

1.2 Taxonomy: Overview and Dimensions

Our taxonomy is built upon five dimensions, as illustrated in Fig. 1.2. Given the vast number of papers covered in this book, it is unfeasible to follow a method-based taxonomy. This would yield an unmanageable number of distinct categories, which would not be comparable to each other. We, therefore, decided to focus on general characteristics that are present in all kinds of visualization designs: the **data**, the **stakeholders**, the **tasks**, the **scale**, and the **application field**. For the manual categorization of the literature based on the aforementioned five dimensions, the authors read all abstracts (if this was not sufficient, also the papers) and decided on a one-to-one basis how to categorize them. During the categorization, we also considered the integration of information regarding the evolution and how topics have formed, disappeared, and/or re-emerged since 1969, when the oldest included paper was published. Figure 1.3 depicts the distribution of papers for the five dimensions of the manual categorization.