Non-Destructive Investigation of a Georgian Codex Binding Using a Portable Computed Tomography Scanner

Philipp Paetzold (Hamburg) & Samaneh Ehteram (Hamburg),
Lars Krämer (Heidelberg), Fabian Isensee (Heidelberg),
Andreas Schropp (Hamburg), Christian G. Schroer (Hamburg),
Jost Gippert (Hamburg)

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philipp.paetzold@desy.de || ORCID: 0009-0004-1752-3913
samaneh.ehteram@desy.de || ORCID: 0009-0009-4811-2312
lars.kraemer@dkfz-heidelberg.de || ORCID: 0000-0002-0586-8357
f.isensee@dkfz-heidelberg.de || ORCID: 0000-0002-3519-5886
andreas.schropp@desy.de || ORCID: 0000-0002-8846-8585
christian.schroer@desy.de || ORCID: 0000-0002-9759-1200
jost.gippert@uni-hamburg.de || ORCID: 0000-0002-2954-340X

Abstract: This study demonstrates a non-destructive approach to investigating the structure of bookbindings in historical manuscripts using high-resolution X-ray computed tomography (CT). We applied the portable CT scanner ENCI to a Georgian codex from the Graz University Library, MS 2058/1, the famous Sinai Lectionary. Three-dimensional reconstructions reveal the complex arrangement of the spine, cords, threads, and gatherings of folios. Individual characters written in vermilion and iron gall ink can be digitally segmented and distinguished. These results highlight the potential of X-ray tomography as a powerful, non-invasive tool for the structural and textual analysis of delicate manuscripts, offering new opportunities to study fragile or partially damaged books while preserving their physical integrity.

Keywords: Computed Tomography, Bookbinding, Georgian manuscripts, Graz collection, Digital humanities, ENCI

1. Introduction

For many centuries, books have served as one of the most important media for recording and transmitting information across generations. By writing down knowledge, people have been able to preserve it from antiquity to the present day. However, beyond the written content itself, the materials used in book production, as well as the techniques employed in their manufacture, can offer rich insights into the history of these artefacts.

Since the beginning of the first millennium, the codex has become the dominant form of the book. Codices consist of folded sheets bound together along a spine, which serves as the structural backbone of the volume. This spine, typically composed of organic material, tends to degrade over time, eventually compromising the structural integrity of the book and leading to its gradual deterioration. To counteract this decay, books were often rebound throughout history, a task typically undertaken in monasteries. In many cases, fragments of older manuscripts were repurposed during the rebinding process. As a result, not just the textual content, but the bindings themselves, can reveal valuable and sometimes hidden clues about a book's provenance and history.

There are several ways to access this embedded historical information. One conventional method involves the careful disassembly of the spine to examine its structure and materials. However, this approach is inherently invasive and destructive, posing the risk of losing critical information that cannot be recovered or visualized through physical means alone. In recent years, numerous non-destructive analytical techniques rooted in physics and chemistry have been developed to study cultural heritage objects. These include active and passive infrared thermography (IRT) and X-ray fluorescence (XRF) spectroscopy.[1] While such techniques offer the advantage of portability and in situ applicability, they are often limited in the depth of information they can provide, for instance, in cases where thick leather bindings are involved. In the case of XRF, large-area scans with high spatial resolution can also require prohibitively long acquisition times.

More recently, researchers have explored the use of X-ray computed tomography (XCT) to investigate book structures non-destructively.[2] XCT provides volumetric datasets that reveal both surface and internal features of a sample in three dimensions. However, traditional CT systems are typically located in research institutions or medical facilities, and transporting fragile, historically significant books to such locations is often not feasible due to conservation regulations that prohibit the removal of artefacts from museums or archives.

This study presents a non-destructive approach to examining the structural features of a historical Georgian codex from the Graz collection (University Library, MS 2058/1) using a portable, high-resolution X-ray computed tomography scanner known as ENCI (Extracting Non-destructively Cuneiform Inscriptions). Originally developed for on-site analysis of encased clay tablets, ENCI is the product of a collaboration between the Cluster of Excellence “Understanding Written Artefacts” at the University of Hamburg (UHH) and the Deutsches Elektronen-Synchrotron (DESY). Here, we demonstrate how ENCI enables detailed structural analysis and virtual exploration of historical bookbindings in situ. This approach opens up significant new possibilities for cultural heritage research by making advanced volumetric imaging accessible within the secure environments of museums and archives, without compromising the integrity of the artefacts themselves.

2. Methods

Unlike conventional X-ray radiography, computed tomography collects multiple projections from different angles. These data are reconstructed into a three-dimensional volume that reveals internal structures through cross-sectional views.

Commercial CT scanners, such as those used in hospitals or industrial settings, typically weigh several tons and are thus immobile and unsuitable for on-site cultural heritage analysis. Transporting delicate artefacts to such stationary scanners is often not feasible due to conservation constraints. To address this challenge, ENCI was developed as a portable, high-resolution X-ray CT system specifically designed for use in museums, libraries, and archives. Weighing 420 kg in total, ENCI is composed of eight modular units, enabling rapid deployment in sensitive heritage environments. It features an integrated shielding system, eliminating the need for additional radiation protection infrastructure at the scanning site. The device includes an X-ray source with adjustable accelerating voltage ranging from 30 to 180 kV and a maximum power of 80 W, allowing for the examination of even dense inorganic materials.

[1] See Mercuri *et al*. 2011 and 2013 for IRT and Duivenvoorden *et al*. 2017 for XRF spectroscopy.
[2] See Seales *et al*. 2016; Stromer *et al*. 2018; Kumpová, Vavřík & Vopálenský 2018; Dilley *et al*. 2022; Ensley *et al*. 2023; Sargan *et al*. 2022; Vavřík *et al*. 2024.

ENCI has already been successfully deployed at major institutions, including the Louvre in Paris and the Museum of Anatolian Civilizations in Ankara, where it has been used to investigate encased cuneiform tablets in situ.

This study explores whether the ENCI scanner is also suitable for the analysis of other types of written artefacts beyond its original application. As a case study, we selected a Georgian codex from the Graz University Library, catalogued as MS 2058/1. This manuscript has been proven to be the oldest known linguistic and literary monument in the Georgian language and originates from the Monastery of St. Catherine on Mount Sinai, dating to the 5th or 6th century CE. Recently, a radiocarbon analysis has yielded a dating between 433 and 574 CE for the codex. Historical evidence indicates that the book was rebound at least three times, with the third binding, carried out in 983 CE, attributed to the Georgian Christian monk Ioane Zosime. Notably, a previous investigation revealed the presence of parchment fragments from a Greek majuscule manuscript used in the binding. Further details on the manuscript and its history can be found in the work of Zammit Lupi.[3]

For the analysis, the codex was gently curved and mounted in ENCI's sample holder to accommodate the limited space within the scanner. X-rays were applied using a tube voltage of 60 kV and a current of 200 µA. A 0.2 mm aluminium foil between source and sample was used to filter the lower part of the X-ray spectrum and reduce beam hardening artefacts. A total of 720 radiographs (also referred to as projections) were acquired over a full 360° rotation, with an exposure time of 0.5 seconds per projection. Including both acquisition and motor movement, the full scan duration was roughly 15 minutes.

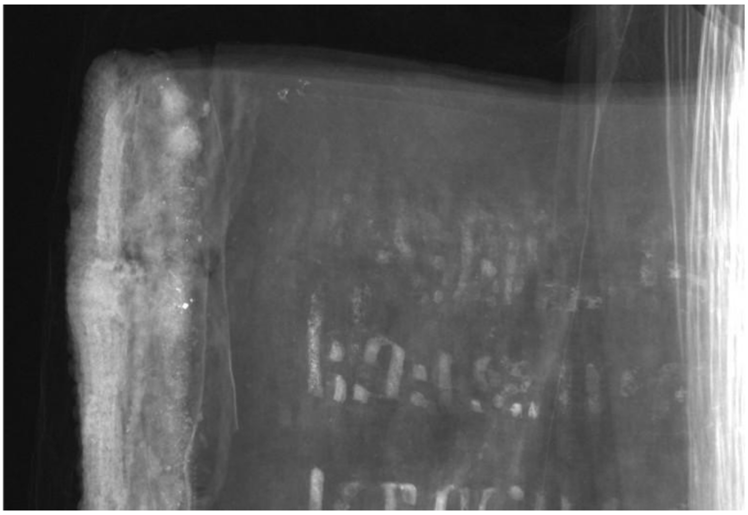

Fig 1: X-ray transmission projection of MS 2058/1 with spine on the left side and folios with letters on the right side.

3. Results and Discussion

The X-ray projection (Fig. 1) already provides valuable insight into the internal structure of the codex. On the left side, the complex bookbinding is clearly visible, consisting of several distinct structural elements. Moving toward the right, the individual pages become apparent, and even

[3] See Zammit Lupi 2023: 124–125; see also Gippert forthcoming: 24–26 and in this volume.

separate lines of text can be distinguished. At the right edge, some pages appear slightly curved, a result of adjusting the book's dimensions to fit inside ENCI's sample chamber.

To gain a clearer understanding of the book's structure, and particularly the configuration of its spine, it becomes evident that the reconstructed volume must be examined in detail. While features overlap in a single projection, a full three-dimensional reconstruction obtained through XCT provides cross-sectional images of the sample. In the following, these tomograms are used to explore the internal architecture of the book in greater detail. From left to right, the individual structural components are examined and described more closely.

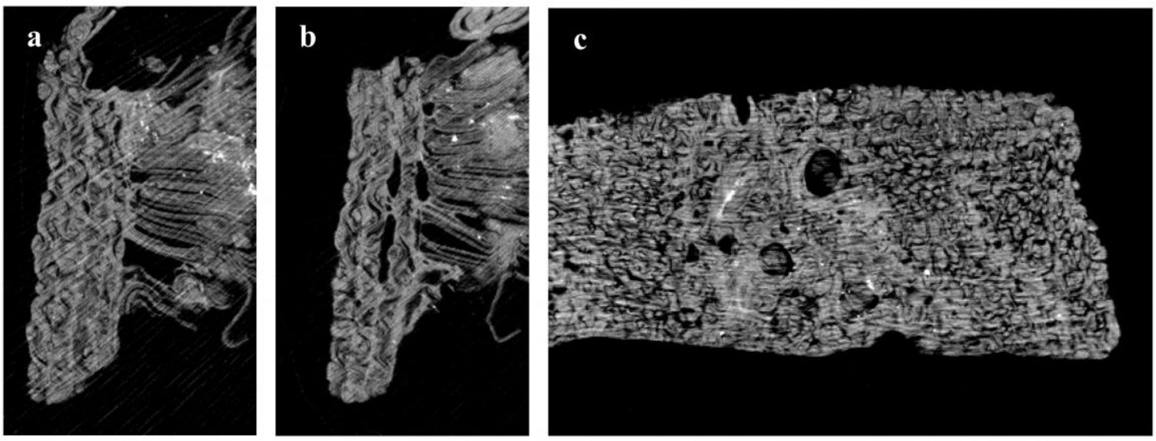

Fig 2: (a) Linen cloth lining of the cover. (b) Different slice revealing the three-layer structure of the linen. (c) yz-slice highlighting the characteristic texture and appearance of the linen lining.

For the protection and stability of the binding, the outermost component is the spine cover, which is made of linen. This cover is preserved only along the spine, while the front and back boards are missing. In the tomogram (Fig. 2), the cover can be readily identified by its characteristic appearance. Figures 2a and b show the axial plane according to the nomenclature of Sargan et al.,[4] while Fig. 2c presents the spinal plane through the entire cover, where the texture of the linen fabric is particularly visible. Furthermore, Fig. 2b reveals that the linen cover consists of three layers, designed to provide maximum robustness. This observation is consistent with the findings reported by Zammit Lupi.[5]

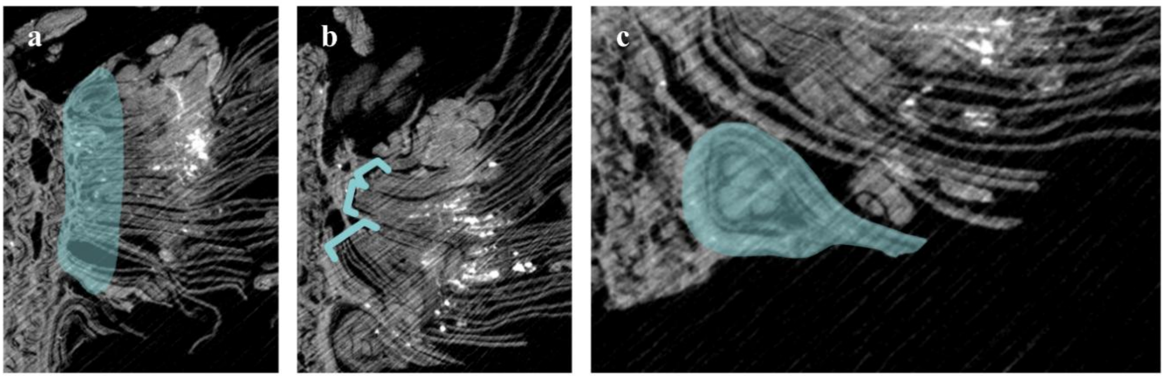

Fig 3: Manually highlighted: (a) single and bifolio units attached to the spine, (b) folios arranged in three main groups, and (c) removed pages and stays located at the front of the book.

[4] See Sargan *et al*. 2022: Fig. 3.

[5] See Zammit Lupi 2023: 131 and Gippert forthcoming: 25.

Additional information can also be derived from the analysis of the folios within the book. Owing to the high spatial resolution of less than 50 µm achieved with ENCI, the individual pages can be clearly resolved. As shown in Fig. 3a, most of the pages were bound as bifolios, meaning that a larger piece of parchment was folded in the middle and then sewn into the binding. Fig. 3b presents a cross-sectional slice taken at a different height of the volume, revealing that the folios were bound in three distinct gatherings. In addition, several single leaves can be observed outside these main stacks (Fig. 3c). At the front and back of the book, as well as in its central part, truncated pages referred to as stays are visible. At least two single folios were removed from the codex before it arrived in Graz. They later reappeared in Paris (National Library of France, géorgien 30) and Birmingham (Cadbury Research Library, Mingana Collection, Georg. 7). The tomograms reveal further truncated pages, which may indicate the loss of additional folios. However, there appears to be no missing textual content. It is therefore likely that these stays were intentionally integrated into the spine to reinforce the binding structure.

Although the individual pages can be well separated in most areas, there are regions where the pages are very closely packed, making separation more challenging. Moreover, streaking artifacts notably reduce the quality of the tomographic reconstruction, as is particularly evident in Fig. 3c. These artifacts arise from an insufficient number of projections, which leads to streaks and noise because the reconstruction algorithm lacks enough information to accurately represent the object. This phenomenon, often referred to as angular undersampling, results in fine streaks. This indicates that 720 projections are not sufficient, and future scans should include a higher number of projections to improve the reconstruction quality.

Of particular interest is how the pages are held together and connected to the spine. To investigate this, the highly complex structure of the spine must be analyzed. Due to the intricate arrangement and the interaction of numerous components, it is necessary to examine the cross-sectional images from the paginal plane, axial plane (Fig. 4a and 4b), and spinal plane (Fig. 4c). This analysis reveals a variety of structural elements.

One especially prominent feature is a cord composed of three threads, which can be readily identified in many of the tomograms (Fig. 4a). To trace its exact course, the reconstructed volume was visualized in three dimensions using the Python program napari.[6] The napari plugin nnInteractive was then employed to segment the cord.[7] nnInteractive is a state-of-the-art, promptable deep learning-based framework for three-dimensional image segmentation, providing an intuitive human-computer interface. A core principle of nnInteractive is enhancing usability by bridging the gap between intuitive two-dimensional annotation and full three-dimensional segmentation: a feature of interest can be manually marked using points, scribbles, boxes, or lasso prompt, and nnInteractive then automatically generates the corresponding three-dimensional segmentation. The three-dimensional visualization reveals that the cord extends along the entire length of the scanned region and is attached to the spine at two distinct points.

At the upper end, four additional cords composed of two threads each are visible, three of which were semi-automatically highlighted using nnInteractive (Fig. 4b). In the reconstructed volume alone, these cords can only be followed to a limited extent. However, segmentation provides

[6] Software and documentation can be found at https://napari.org/. This and all other URLs quoted in this article were last accessed on 29 December 2025.

[7] See Isensee, Rokuss, Krämer *et al.* 2025; the project page can be found at https://github.com/MIC-DKFZ/nnInteractive.

an excellent insight, revealing that the cords converge at a single point in the spine, where they are knotted.

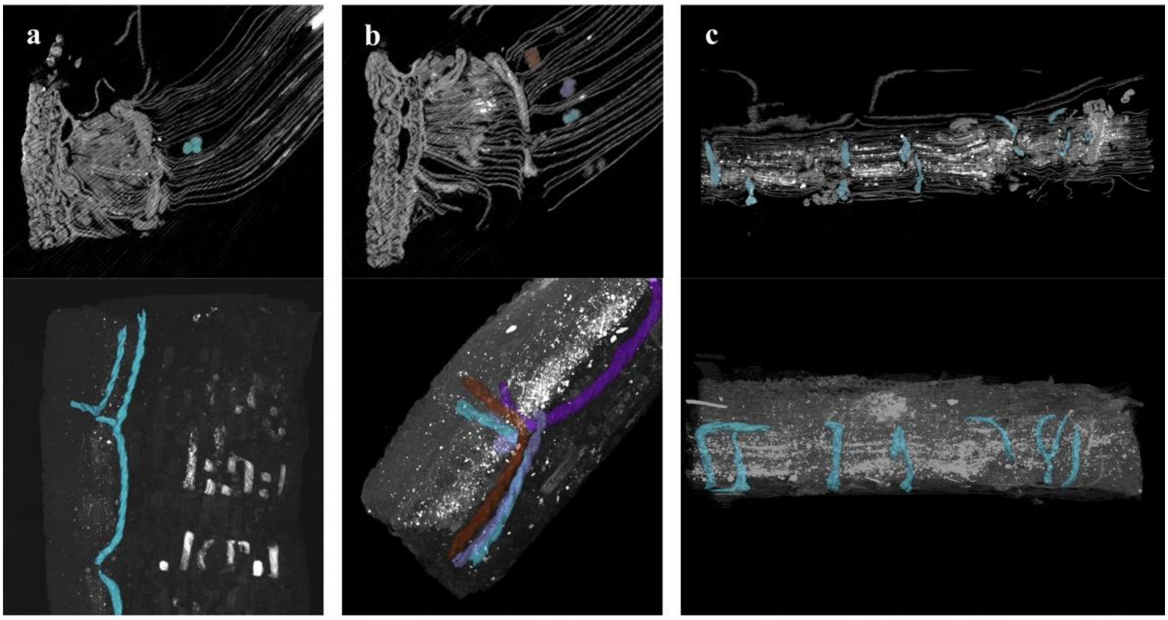

Fig 4: (a) Prominent cord extending along the entire length of the book. (b) Four cords originating at the top of the book and converging in a single knot. (c) Threads running perpendicular to the spine, showing the sewing of the folios.

Furthermore, several threads running perpendicular to the spine can be observed at different heights within the binding (Fig. 4c). These are likely part of the sewing that holds the pages together. A precise classification as components of stab sewing, overcast sewing, or supported sewing on hemp cords is, however, difficult for us to determine.

Another important insight can be gained from examining the folios. The tomograms reveal variations in gray values, which correspond to differences in density and thus indicate different materials (Fig. 5a). Three distinct gray levels can be identified. First, the parchment itself, which constitutes the support material. Second, very bright regions correspond to ink, which is highly absorbing (Fig. 5, marked in red by nnInteractive). In this scaling, these inked areas may appear thicker than the page itself due to beam hardening artifacts from the polychromatic X-ray source. Applying appropriate X-ray filtering could reduce these artifacts in future analyses. A third intermediate gray value can also be observed, which likely represents a second type of ink (Fig. 5, marked in blue by nnInteractive). This interpretation aligns with Zammit Lupi's observation that both a red ink made from vermilion, which is powdered cinnabar and therefore mercury-based, and a reddish-brown iron gall ink were used.[8] It is important to note that mercury has an atomic number of 80 and therefore absorbs X-rays much more strongly than iron, which has an atomic number of 26. A third, carbon-based ink applied later cannot be detected with the ENCI setup, as the contrast between carbon-based parchment and carbon-based ink is insufficient.

In addition, individual characters on the folios were segmented. The segmentation of characters written in vermilion is much easier due to the higher contrast. Letters written in iron gall ink can also be segmented, although with greater effort, provided that the pages are not too closely spaced. The results demonstrate that the text from different pages can be segmented and

[8] See Zammit Lupi 2023: 128 and Bosch & Kvirkvelia, this volume.

visualized separately. In the given case, the book can still be opened and read without tomography. In other cases, where manuscripts are poorly preserved or have deteriorated over time, this method allows the text to be made visible and readable.

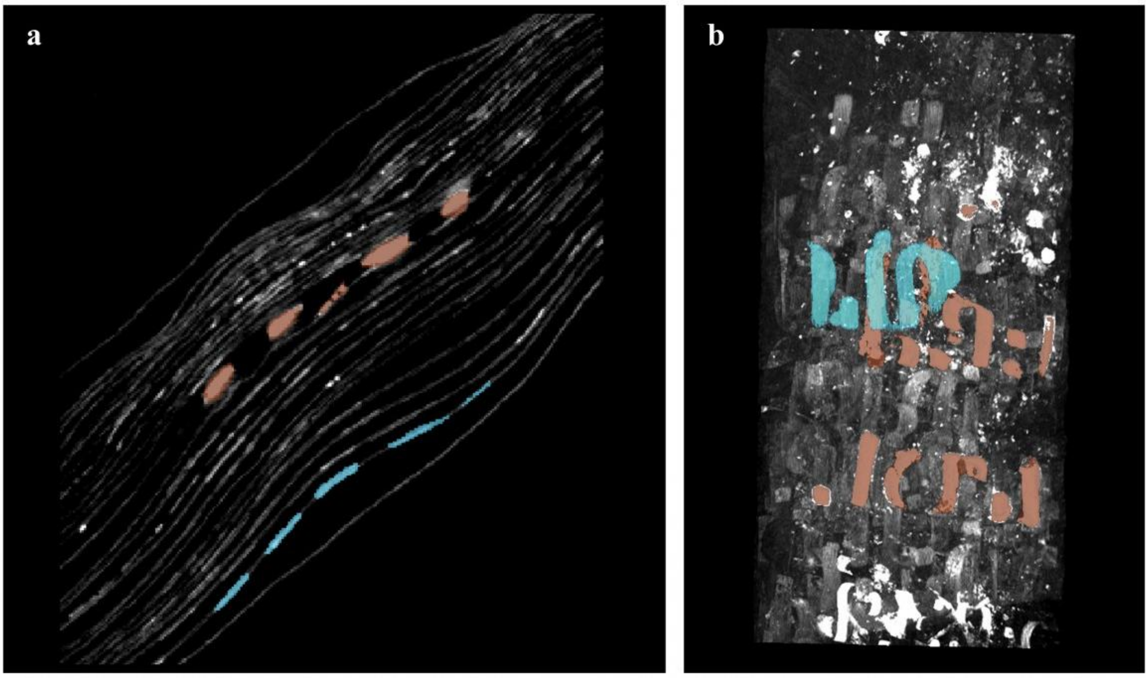

Fig 5: (a) Axial tomographic slice showing pages with variations in gray values corresponding to different inks, with blue indicating iron gall ink and red representing vermilion. (b) Segmented individual characters from two different pages.

4. Conclusion

In conclusion, XCT provides unprecedented insight into the construction and organization of the Graz codex. The three-dimensional analysis reveals a sophisticated spine and binding system, with cords, threads, and stays interacting to support complex gatherings of folios. High-resolution imaging resolves individual pages and enables the digital separation of closely packed text, making it readable without physically opening the book.

These results demonstrate that X-ray tomography is a powerful, non-invasive tool for studying historical manuscripts. It allows detailed investigation of structure and text, offering new possibilities for examining fragile or partially lost books and providing a deeper understanding of historical bookbinding practices.

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ქართული კოდექსის არამრღვევი მიდგომა პორტატული კომპიუტერული ტომოგრაფიის სკანერის გამოყენებით

ფილიპ პეცოლდი (ჰამბურგი), სამანე ეთერამი (ჰამბურგი), ლარს კრემერი (ჰაიდელბერგი), ფაბიან იზენზეე (ჰაიდელბერგი), ანდრეას შროპი (ჰამბურგი), კრისტიან შროერი (ჰამბურგი), იოსტ გიპერტი (ჰამბურგი)

DOI: https://doi.org/10.62235/dk.4.2025.10509
philipp.paetzold@desy.de || ORCID: 0009-0004-1752-3913
samaneh.ehteram@desy.de || ORCID: 0009-0009-4811-2312
lars.kraemer@dkfz-heidelberg.de || ORCID: 0000-0002-0586-8357
f.isensee@dkfz-heidelberg.de || ORCID: 0000-0002-3519-5886
andreas.schropp@desy.de || ORCID: 0000-0002-8846-8585
christian.schroer@desy.de || ORCID: 0000-0002-9759-1200
jost.gippert@uni-hamburg.de || ORCID: 0000-0002-2954-340X

წინამდებარე სტატიაში მოცემულია არამრღვევი მიდგომა ისტორიულ ხელნაწერებში წიგნის სტრუქტურის შესასწავლად მაღალი გარჩევადობის რენტგენის კომპიუტერული ტომოგრაფიის (CT) გამოყენებით. პორტატული კომპიუტერული ტომოგრაფიის ENCI სკანერი გამოვცადეთ გრაცის უნივერსიტეტის ბიბლიოთეკაში დაცულ ქართულ კოდექსზე (MS 2058/1-ის), ცნობილ სინას ლექციონარზე. სამგანზომილებიანი რეკონსტრუქციები აჩვენებს წიგნის ყუნწების, თოკების, ძაფებისა და ფოლიოების კოლექციების რთულ განლაგებას. კომპიუტერული ტომოგრაფიის შედეგად შესაძლებელია წითელი და რკინის ნაღვლის მელნით დაწერილი ცალკეული სიმბოლოების ციფრული სეგმენტირება და გარჩევა. მიღებული შედეგები ხაზს უსვამს რენტგენის ტომოგრაფიის პოტენციალს, როგორც მძლავრ, არაინვაზიურ ინსტრუმენტს იშვიათი ხელნაწერების სტრუქტურული და ტექსტური ანალიზისთვის, რაც ახალ შესაძლებლობებს გვთავაზობს მყიფე ან ნაწილობრივ დაზიანებული წიგნების შესასწავლად მათი ფიზიკური მთლიანობის შენარჩუნებით.