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Investigation of defects of artificial BSCC heart valves using radiographic computational methods

Badanie mechanicznych wad sztucznych zastawek serca BSCC przy użyciu radiograficznych metod

***Abstract**. Acute mechanical failure of Björk-Shiley convex-concave artificial heart valves has caused thousands of patient deaths over the past decades. This article focuses on the issue of investigating the inhomogeneities whose presence causes progressive heart valve dysfunction and eventual patient death. The results of radiological inspection and subsequent reconstructive methods, based on digital scanning and computed tomography, are presented to detect artefact defects in a series of artificially produced heart valve implants.*

***Streszczenie**: Ostra awaria mechaniczna wypukło-wklęsłych sztucznych zastawek serca Björk-Shiley spowodowała śmierć tysięcy pacjentów w ciągu ostatnich dziesięcioleci. Niniejszy artykuł koncentruje się na kwestii zbadania niejednorodności, których obecność powoduje postępującą dysfunkcję zastawki serca i ostateczną śmierć pacjenta. Przedstawiono wyniki badania radiologicznego i późniejszych metod rekonstrukcyjnych, opartych na skanowaniu cyfrowym i tomografii komputerowej, w celu wykrycia defektów artefaktów w serii sztucznie wytworzonych implantów zastawek serca.*

Słowa kluczowe: biomateriał, uszkodzenie implantu, metody radiograficzne, przetwarzanie obrazu
Keywords: biomaterial, implant failure, radiographic methods, image processing

Introduction

The study and description of the body's internal structure using non-invasive methods was first carried out at the end of the 19th century and is considered a milestone in contemporary diagnostics. With diagnostic instrument development and technical progress, the development and implementation of surrogate organs and tissues made of materials unknown to modern diagnostics has progressed. For implants, the damage to which often meant a threat to the patient's life, it was necessary to develop methods and procedures that ensured early and accurate identification of possible damage. The development and refinement of modern imaging systems have enabled the advancement of almost all branches of medicine. Imaging systems have also brought new possibilities to treating and diagnosing malignant diseases, for which they are an indispensable tool. In addition to the medical field, X-ray imaging is used in radiation chemistry or defectoscopy [1, 2, 3].

X-rays are ionizing radiation which, when exposed to increased radiation, are characterized by adverse effects on the human body. Computed tomography (CT) systems are characterized by a fundamentally different way of data processing than conventional and digital X-rays, even though their common feature is X-ray imaging. X-ray imaging produces a two-dimensional summation image, whereas CT systems display slices, so-called tomographic planes. If enough of these planes are created using the CT machine, a three-dimensional (3D) scene model can be created with the help of powerful computer technology. In addition to 3D imaging, the importance CT lies in the higher contrast of the imaged object compared to X-rays, and it also provides higher spatial resolution. CT scanning is performed by placing the subject under examination in a gantry consisting of an X-ray tube and a detection array. The resulting image is reconstructed from the detected data using an appropriate mathematical algorithm and displayed on the screen as a set of points (voxels). As the radiation passes through the tissues, its rays are attenuated differently, which allows the individual structures of the imaged area to be distinguished in the resulting image [4, 5].

The Björk-Shiley convexo-concave (BSCC) implant represented a modern and advanced model of heart valve replacement in its time. The design consisted of an inlet and outlet strut fixed on a rim, with an occluder disc sandwiched between the struts. The struts, or separate protrusions, pointing into the valve opening, provide anchorage and guidance for the movable disc. The implant consists of a single disc coated with carbon and housed in a rim made of Haynes 25 alloy consisting of cobalt (Co, 51%), chrome (Cr, 20%), tungsten (W, 15%) and nickel (Ni, 10%). The defective flap model was manufactured and marketed between 1979 and 1986 and represented a proposal to increase the implant's durability against placement influences and the efficiency of its manufacture [6, 7].

One of the design improvements was to weld the BSCC valve outlet strut at an angle that was not parallel to the flange. As a result of this modification, the tension at the strut joint was increased. Moreover, the flange fractured the structure above and caused the patient's sudden cardiac death. For the reasons mentioned above, the complication rate induced by the strut failure was further increased when the disc opening angle was increased from the original 60˚ to 70˚ (Fig. 1).

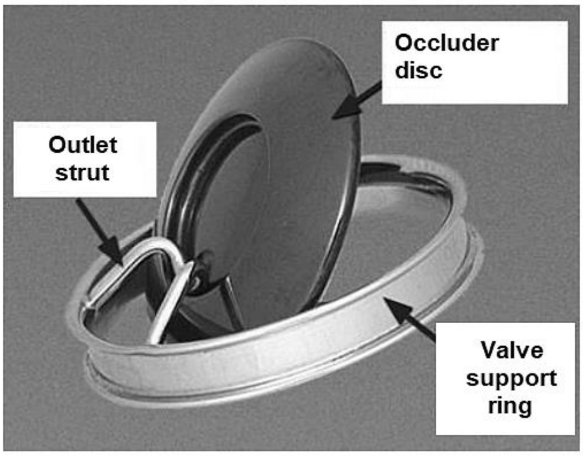

Fig.1. BSCC heart valve implant: basic functional design, [5].

The breakage of the strut typically occurs in two successive processes, with the failure on one side leading to the complete collapse of the strut, and consequently the valve itself, within a few months. It has become a vital diagnostic tool for valve damage, as non-invasive methods have proven effective in detecting damage after one side of the strut has broken off. To maximize the information gleaned, the 'tunnel-view' technique, known for its precision, is employed when imaging the implant, providing a better view of the bases of both sides of the strut. Even when one part of the strut is completely detached, the fractured surfaces can remain in such proximity that detection by electromagnetic methods is highly improbable. However, in certain instances, the residual stresses in the strut cause a deflection at the fracture site, leading to a displacement that can be identified by X-ray-based instrumentation, in conjunction with robust reconstruction algorithms.

This paper highlights the possibilities of diagnosing a series of artificial heart valves using radiographic methods on commercial devices and implemented reconstruction algorithms.

Implementation of measurements determining the rate of damage to BSCC implants

Individual measurements to detect inhomogeneities in BSCC implants were performed in the Kysuce Hospital with Polyclinic in Čadca, the Slovak Republic. In the Department of Radiology, measurements were performed using digital X-ray and CT aimed at the radiographic detection of destructive changes in the struts of BSCC heart valves. The resulting images were evaluated as 2D native tomograms and later reconstructed into 3D structures. The resulting 3D images were processed in the GE Healthcare software (Chicago, IL, USA) and the Slicer software environments, and the results were compared. Each measurement dealing with the description of artificial material defects consisted of imaging structures with a crack and without the presence of a crack in the evaluated structures. On the evaluation pad, the valves were arranged according to the degree of damage located at the outlet strut, which also represents the leading cause of dysfunction of this implant. The individual valves were arranged as follows: valve V0: the absence of artificially created defect (so-called intact sample, 0.0 mm), valve V1: shallow defect (0.2 mm) in the outlet strut near the rim, valve V2: defect up to half (0.5 mm) of the thickness of the outlet strut, valve V3: the deepest defect (0.8 mm) in the outlet strut of the valve simulating the condition before the detachment of a part of the strut.

At the same time, control measurements were taken via conventional X-ray, with valves including all defect depths imaged simultaneously in a single image. The inhomogeneity of the BSCC implants was examined on the X-Frame DR2S System (Italray, Florence, Italy). The system's function is based on semiconductor detectors with amorphous silicon and a scintillator consisting of Gd_2O_2S (gadolinium oxysulfide) or CsI (caesium iodide). This combination provides high-quality X-ray images in real time and at low exposure limits. Like most modern diagnostic devices, the X-ray has several automatic features that allow imaging of even small structures, such as defects on BSCC implants. Such functions include automatic adjustment of the rotational speed of the anode, exposure automation, automatic brightness control, and adjustment of the precise collimation according to the focal length. The resulting image is thus obtained with minimal pixel spacing, resulting in a final image with a matrix of very sharp resolution. In addition to the parameters mentioned above, this instrument uses a 16-bit grayscale and very low-noise electronic circuitry to provide extensive grayscale dynamics, which helps identify even excellent details in the resulting image.

Figure 2 shows the result of imaging the instrument using its exposure automation, with the following parameters: voltage of 65 kV, current through the X-ray tube of 50 mA, and exposure time (incandescent current) of 1 mAs. The measurement results were processed and evaluated in the TomoCon Lite software environment (TatraMed Software, Bratislava, Slovak Republic). At the same time, the damage to the outflow strut is well discernible on all valves. Successful identification of the defect in the acquired image depends on its size and resolution. The pixel size in the resulting image reaches a value of 0.147 mm. In further processing the digital X-ray image, we considered the possibility of identifying the extent of damage to the outlet struts. Using the software, we took measurements of the depth of individual defects compared to the thickness of the outlet strut material.

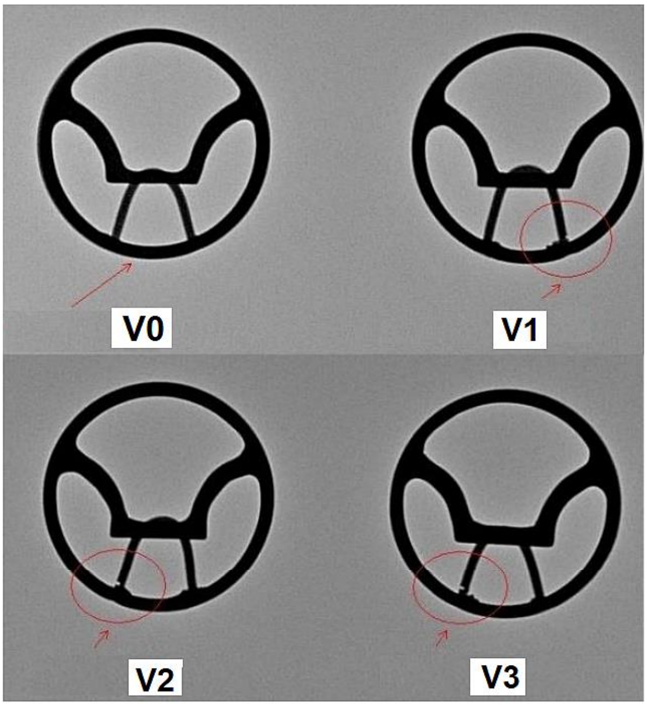

Fig.2. Overview of the placement and design of artificial defects in the BSCC implant (X-ray image).

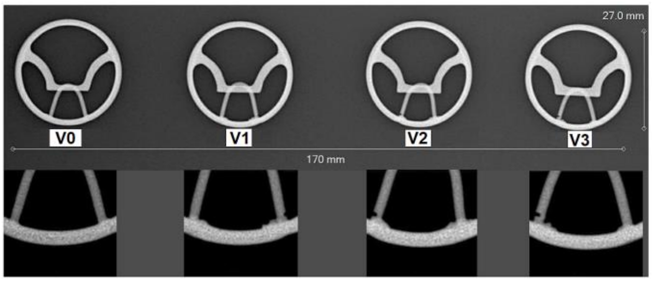

Fig. 3. X-Frame DR2S System results: a comparison of valves with different degrees of damage, with detailed views of outlet struts.

For this purpose, the raw image had to be suitably processed and then significantly enlarged. The measurements of the depth of the inhomogeneities were carried out at an image magnification of 1600%, as shown in Figure 3. The edges and depth of the defects achieve good identifiability due to the high image resolution despite the high magnification level. The resulting dimensions of the inhomogeneities were then stored in the image and checked for the accuracy of the location of the measurement cues at different magnifications. The results of defect depth measurements are summarized in Fig. 4.

Valve No.	Defect depth	Original strut thickness	Percentage of damage
V0	0 mm	1.22 mm	0%
V1	0.34 mm	1.21 mm	28%
V2	0.57 mm	1.22 mm	46%
V	0.68 mm	1.23 mm	55%

Fig. 4. Results of defect depth measurements in the individual BSCC heart valve implants.

Implementation and evaluation of CT measurements

The next series of measurements was carried out using the Optima CT 660 computed tomography scanner (GE Healthcare). Together with the device, diagnostic computers with the reconstruction software were set up and made available on the hospital's premises. Image processing of the heart-valve implants was performed in cooperation with the staff of the radiology department. Various filters were applied to the individual images to remove unwanted metal artefacts from the resulting 3D reconstructions, which affect the quality to such an extent as to make it impossible to identify inhomogeneities in the structures. A series of key images was obtained and adjusted in the software, together with unadjusted data. This data was subsequently processed in the software environments 3D Slicer (software for visualization, processing, segmentation, registration, and analysis of medical, biomedical, and other 3D images and meshes) and wxDicom (software for metal artefact reduction in computed tomography DICOM imaging). Each software's output series of key images was compared, focusing on information value and the ability to assess defects in the heart valve struts qualitatively. Like X-ray imaging, the BSCC implants were arranged from the valve without damage to the valve and the presence of the deepest inhomogeneity, all imaged in a single tomographic series. The uneven positioning and rotation of the flaps in the image, Figure 5, is due to their displacement on the uneven support due to movement during the setup of the scanning table and the scanning itself. A special scanning mode was used to inspect the BSCC implants in all directions, which created a single X-ray plane for defect localization and subsequent graphic image processing after the reconstruction. The CT parameters were set as follows: voltage of 120 kV, current of 49 mA, and exposure time for a complete measurement of 2 mAs.

It can be observed that the inhomogeneities formed in the output struts are impossible to identify from the image and thus modified. Therefore, the obtained unadjusted data were adjusted by 3D Slicer and reconstructed as the 3D images. In this reconstruction, preset fixed filters were not used, but the given structures were filtered sequentially, focusing on preserving the maximum information content. The information value of the images in Figures 5 and 6 is significantly negatively affected by the metal artefacts that have formed around the metallic implant structure during the scanning process. During the formation of metal artefacts during CT scanning, we assume that the geometrically minor defects were smoothed out by the reconstruction algorithm due to the presence of metal artefacts in the later reconstruction, causing them to blend in with the surrounding undamaged strut material. For completeness, it should be noted that the type of Optima instrument used was not equipped with software designed for metal artefact reduction (MAR), which is used in the latest computed tomography scanners.

Then, an instrument equipped with this technology would have reduced the rate of artefacts to the extent that defects in the output struts could have been identified. The MAR reduction software and its modifications are implemented exclusively in the CT output image reconstruction process. They cannot be used to process existing data containing the artefacts in question. To demonstrate image modification using MAR, a new technique of refined metal artefact reduction (RMAR) was used, which allows artefacts to be filtered out even in an existing image. Artefact filtering was performed in wxDicom, where each tomographic slice was separately edited and filtered. Filtering unwanted structures using the RMAR method involves delineating reference contours in each tomographic slice and filtering out the unwanted effect. In Figure 7, it can be observed that the edges of the contours and the struts are irregular, and the information content of the image is greatly affected.

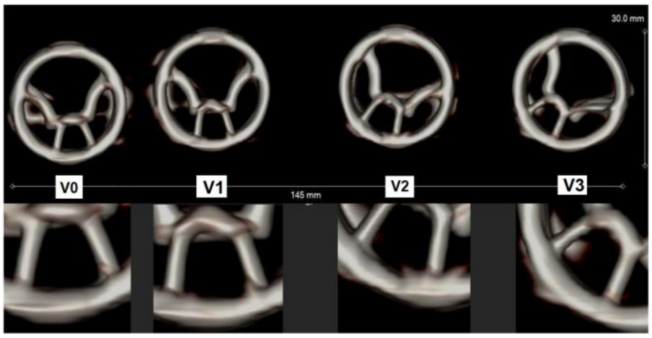

Fig. 5. Overview of reconstructed images created in the GE Healthcare software with detailed views of the output struts.

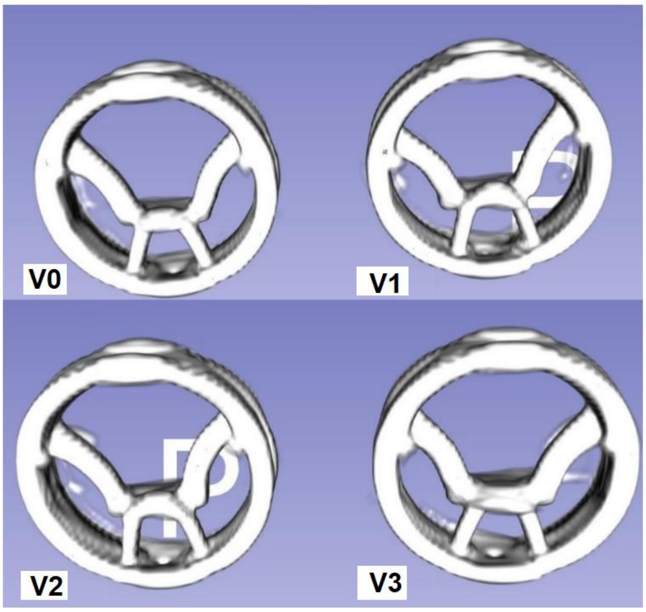

Fig. 6. 3D reconstruction of BSCC implants in Slicer software tool.

When processing the individual tomographic sections using the RMAR algorithm, small parts of the images representing the flap marginal regions were filtered out in the process of extracting metal artefacts, resulting in 3D reconstructions of the implants with incomplete contours. The editing of individual tomographic sections represents a tedious and time-consuming activity, which, however, could have yielded better results in the identification of cracks in the outlet struts of the valves. For these reasons, we do not consider the RMAR algorithm a suitable tool for editing three-dimensional structures affected by the occurrence of artefacts, as the accumulation of partial errors during the editing of individual sections causes the loss of the information content of the resulting 3D reconstruction. The tomogram processing of the BSCC implants, Fig. 8, did not produce the desired result that could be observed in the case of the digital X-ray images. It can be observed in the image that the material was narrowing in the attachment of the outlet struts to the rim. On the implants, defects were created in only one part of the exit strut. However, the narrowing of the material can be observed in the image, indicating the presence of inhomogeneities on both sides of the attachment.

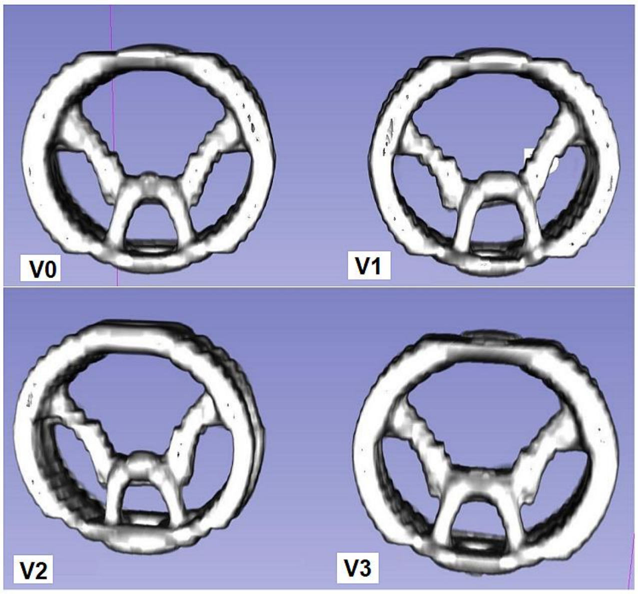

Fig. 7. Overview of BSCC implants after filtering metal artefacts in the program wxDicom and subsequent image reconstruction in the Slicer software tool.

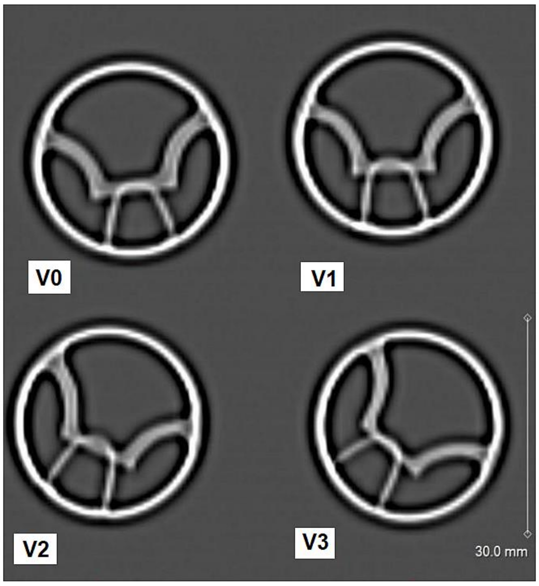

Fig. 8. Tomogram of BSCC implants reconstructed and vizualized in the TomoCon software environment.

From the above, the narrowing of the struts cannot be described as a qualitative defect in the implant. We assume that the inhomogeneities in the image are related to the poor quality of the tomographic section.

Conclusion

The aim of this work was, based on the knowledge of mechanical defects in the outlet struts of BSCC implants, to identify these defects and to describe them qualitatively. The BSCC implants were measured at the Department of Radiology of the Kysuce Hospital with Polyclinic in Čadca using digital X-ray and computed tomography with 3D reconstruction algorithms in commercial medical devices. The measurements performed using digital X-ray have produced images allowing a satisfactory qualitative description of the individual damage to the outlet struts, and this examination represents a favourable choice in terms of invasiveness. The results of the heat valve investigations performed by CT, which was not equipped with an MAR algorithm, may be considered inadequate in terms of qualitative assessment of inhomogeneities due to the low information quality caused by the presence of artefacts that caused complete obscuring of inhomogeneities in the output struts. Based on the evaluation of the results presented in this work, digital X-ray images represent the most advantageous qualitative description and invasiveness method. Examination of implants using a CT scanner without the MAR algorithm represents an unsatisfactory method for identifying the resulting inhomogeneities due to the influence of metal artefacts on the image.

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