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The contribution of image processing in the evaluation of guided bone regeneration

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ABSTRACT

One of the most ambitious goals of modern bone surgery is to predict the shape of the bone defect, monitor the progress of bone regeneration, and assess the quantity and quality of newly formed bone. Calcium phosphate biomaterials such as hydroxyapatite and tricalcium phosphate are commonly used as bone substitutes in maxillofacial and dental surgery. The objective of this work is to use cone-beam computed tomography (CBCT) and image processing to assess the spatial (architectural) layout, rate of bone generation and osseointegration of implanted commercial granules (PAH 40%, β-TCP 60%, size 0.5 to 1 mm) in the bone defect generated after tooth extraction. CBCT measurements were performed at 48 hours and 12 months. The analysis of 3D images and the application of appropriate morphological mathematical operations allowed us to evaluate the volume of the cavity to be filled, the volume occupied by the granules and the volume of porosity generated by the random stacking of the granules. The result shows that the bone generation rate reaches a value of 89% after one year of implantation. This study shows that by using 3D image processing techniques CBCT, the same results as classical anatomical and histological studies can be obtained.

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1. INTRODUCTION

Following trauma or infection, the loss of one or more teeth can lead to functional (chewing) or social difficulties. However, the loss of a tooth frequently leads to bone loss and regeneration of the alveolar bone is often necessary before the implant(s) can be placed. The suggested approach is to use a dental implant to replace the missing tooth. Although, the placement of implants requires that the alveolar bone volume is sufficient. This is the case of the guided bone regeneration (GBR) procedure, which has demonstrated its effectiveness in terms of performance and reliability, especially over the long term. Today, this technique is unanimous among clinicians specializing in oral bone regeneration and implantology. GBR techniques are based on the use of a bone substitute biomaterial combined with a barrier membrane.

Granular biomaterials are utilized to fill minor bone imperfections. These granules can be obtained by grinding trabecular bone samples or obtained from the industry as synthetic biomaterials. The granules occupy a 3D space and generate large pores between them that permit vascular and bone cells to infiltrate, provided that the gaps between the granules are greater than 300 µm [1]. Granular bone substitutes prepared from calcium phosphates such as Hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$) and Beta-tricalcium phosphate (β-$Ca_3(PO_4)_2$)

are frequently used in dental surgery for their good biocompatibility and excellent bioactivity [2]–[10]. When the surgeons place granules within a bone defect, it is the voids between the granules that represent the interconnected space available for vascular sprouts and bone cells to invade the grafted area. However, the osteointegration and the behavior of granules in the human body depend on their composition, their microstructure, and their 3D arrangement.

In order to evaluate the microarchitectural parameters of the bone substitute, imaging methods are thought of being quick and non-destructive technologies. X-rays are the most widely used image acquisition techniques in the medical field. The application of cone-beam computed tomography (CBCT) has grown exponentially across dentistry with a clear impact in implant dentistry [11]. CBCT uses voxels that are arranged and analyzed by software to create a 3D image from various angles. In recent years, traditional 2D imaging has been joined by 3D radiographic imaging as viable radiographic modalities. It plays a significant role in the clinical diagnosis of a number of disorders relating to oral health.CBCT provides a suitable solution to analyze and measures the 3D volume, porosity, and microarchitecture of granule implanted in defective bone [12]–[15]. The purpose of this study is to evaluate the microarchitectural characteristics of commercial granules (HA/-TCP) implanted in post-extraction bone defects using CBCT and image processing; an adaptive methodology built on the mathematical morphological processes discussed in earlier research was used to conduct the investigation [14]. The suggested technique enabled us to determine the volume of the cavity to be filled and extract local features, the volume occupied by granules, the porosity generated by the stacking of granules as well as the rate of bone regeneration at 12 months after implantation.

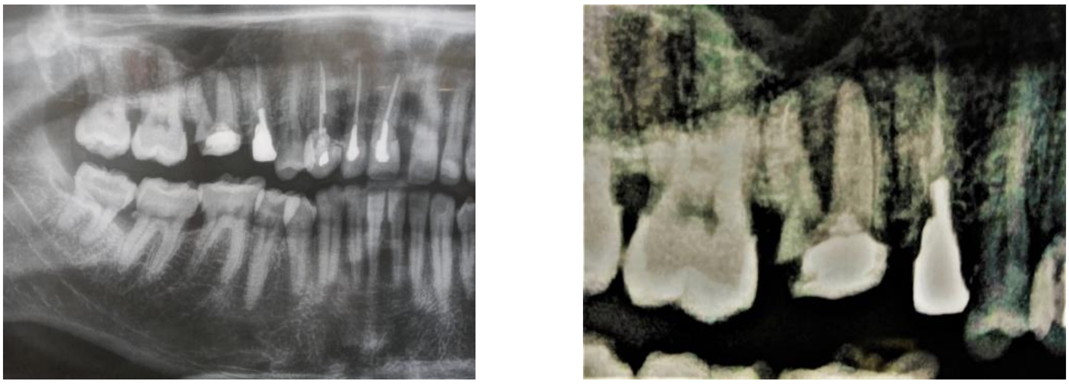
2. METHOD

2.1. Material

To place an implant and fill the cavities generated by tooth extractions, we used commercial calcium phosphate granules composed of 40% HAP and 60% β-TCP and with a granule size between 0.5 and 1 mm. We also used a collagen-based resorbable membrane. The use of barrier membranes has become a standard of care in GBR and guided tissue regeneration for bone augmentation. In this study, we used a CBCT scanner (NTVGiEVO manufacturer model, NewTom VGI) for image acquisition under 10 mA at 90 kV. The scan used is a series of 2D slices (688*688) of spatial resolution and voxel resolution of 0.15 mm. A proposed image processing method will then be used to process the CBCT images.

2.2. Clinical study

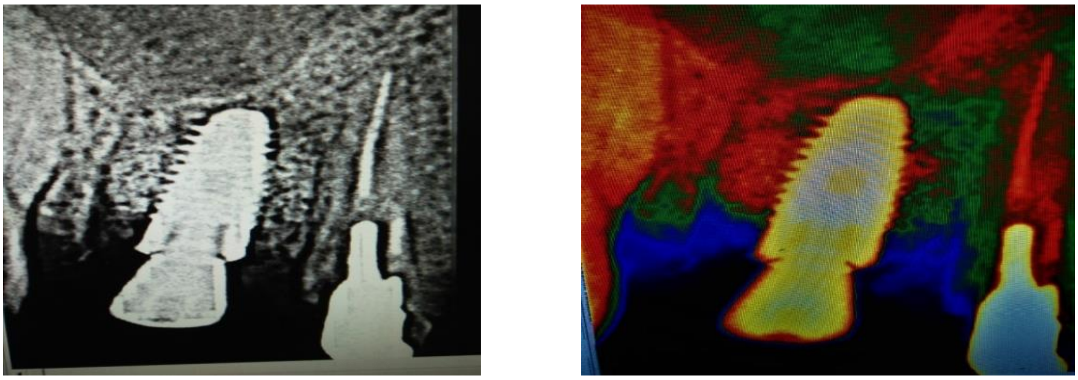
The case presented in this article concerns a 48-year-old patient without general pathology. The reason for consultation is intermittent pain at 16 L. The clinical examination shows a very dilapidated tooth with a defective amalgam filling and damage to the root bifurcation. A panoramic X-ray was requested (Figure 1) which confirmed damage to the inter-radicular bifurcation (Figure 1(a)). Image processing of the bifurcation zone revealed bone damage (Figure 1(b)) which helped us to make the diagnosis of tooth extraction and implant placement.



(a) (b)

Figure 1. Initial panoramic radiography (a) original panoramic and (b) structure of interset

The evaluation of the microarchitectural parameters of the granules inside the cavity is very important to have a precise idea of their biodegradation and then of bone regeneration. As a result, a 2D retro-alveolar X-ray was taken postoperatively (Figure 2(a)) illustrating the placement of the implant and the degree of filling of the alveoli by the granules. It should be noted that the granular stack has a pore microarchitecture closer to trabecular bone (Figure 2(b)). 3D Cone Beam X-ray was taken to allow a case study (Figure 3); control x-rays were taken at 48 hours and at 12 months after implantation with axial and coronal slices (Figures 3 and 4). The analysis of the 3D images and application of the mathematical morphological operations allowed us to evaluate the localization and microarchitecture of granules as well as the evaluation of the rate and quality of the neoformed bone.



(a) (b)

Figure 2. Clinical photograph 2D illustrating implant and granule placements (a) original image and (b) after processing

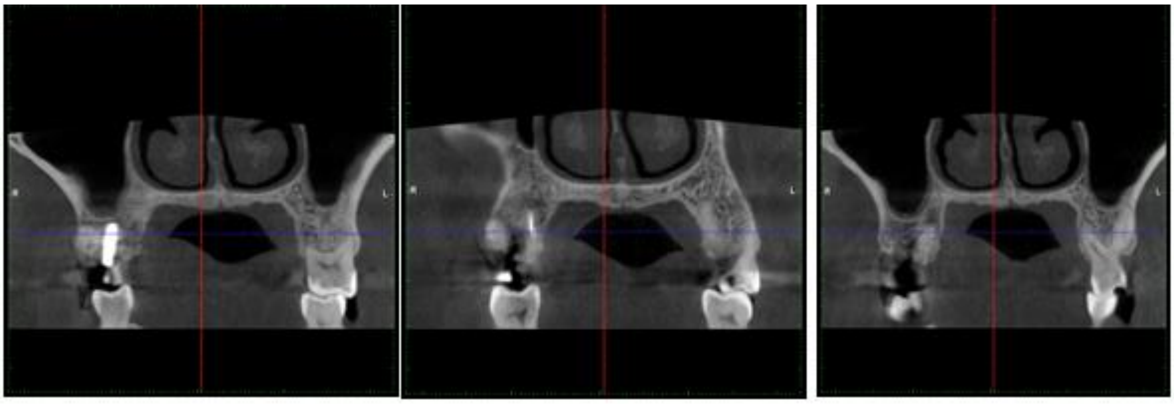


Figure 3. CBCT scan realized 24 hours after implantation

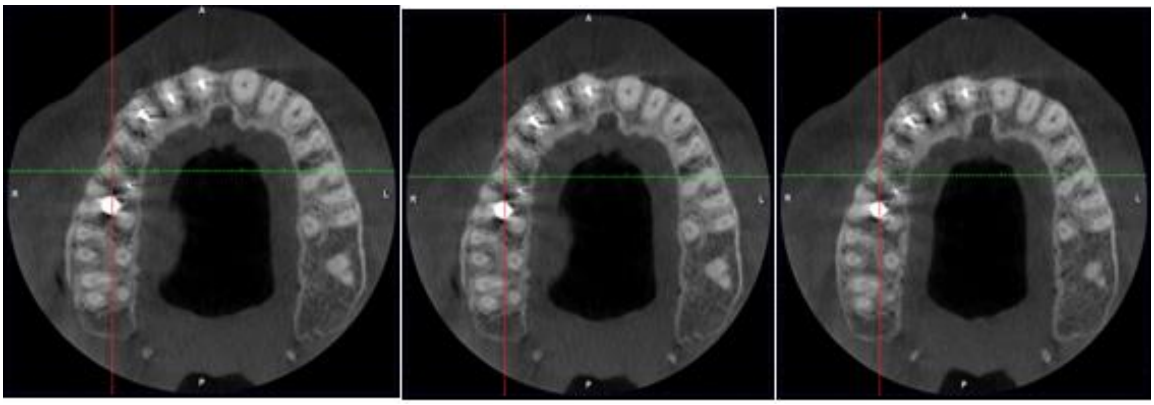


Figure 4. Axial slices

2.3. Image processing

Medical image analysis using image processing has many applications, such as in the detection and diagnosis of tumors, the measurement of anatomical structures, the identification of abnormalities in tissue or organ function, and the monitoring of disease progression or treatment efficacy. Figure 5 shows the steps of image processing used in this study for calculating the hole volume and the following method was used:

Figure 5. Steps of image processing

2.3.1. Filtering

The filter used in this step is the nonlocal mean filter. Non-local means filtering takes a mean of all pixels in the image, weighted by how similar these pixels are to the target pixel, as opposed to "local mean" filters, which take the mean value of a group of pixels surrounding a target pixel to smooth the image. Compared to local mean methods, this yields far better post-filtering clarity and less loss of detail in the image. Many studies use filtering as a processing technique [16]–[18].

2.3.2. Conversion to grayscale images

An intuitive way to convert a numerical image array to a grayscale one is, for each pixel, the average of the red, green, and blue pixel values are used to get the grayscale value. This combines the lightness or luminance contributed by each color band into a reasonable gray approximation.

2.3.3. Thresholding

Thresholding is a method of segmenting images. From a grayscale image, thresholding can be used to create binary images. The thresholding method consists of replacing each pixel in an image with a black pixel. If the image intensity $I_{i,j}$ is less than a fixed constant T (that is, $I_{i,j}<T$), or a white pixel if the image intensity is greater than that constant [19]–[21]. Many studies use threshold as a technique for image segmentation [22]–[24].

2.3.4. Granulometry study

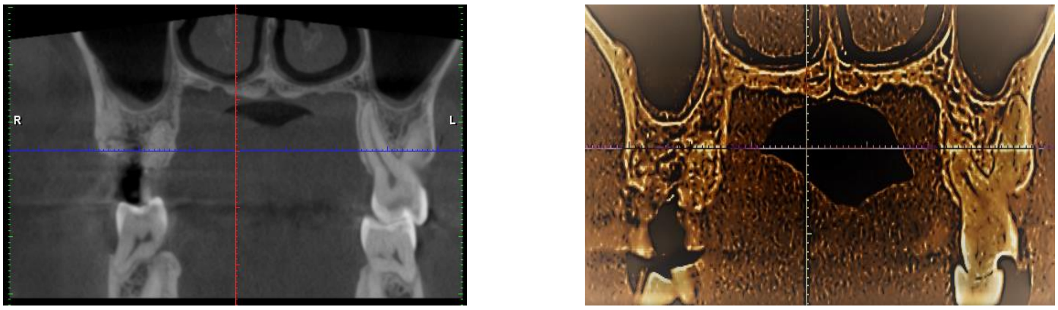
The method used for granulometry calculation is that described in previous work [14]. The effectiveness of the previous technique has been demonstrated both qualitatively and quantitatively using various computed phantoms. Reports and measurements generated provide clear evidence of its efficiency. This suggested method has potential uses for analyzing porous materials utilized in medicine or other industries. This method is summarized in the algorithm presented in Figure 6 (in Appendix) [14].

3. RESULTS AND DISCUSSION

3.1. Radiographic results

Figure 7 present a coronal slice wich provide an important information about the progress and effectiveness of bone regeneration treatment. Coronal slice image of new bone regeneration show a clear and well-defined area of new bone growth in Figure 7(a), with a texture and density similar to the surrounding bone tissue in Figure 7(b). The coronal slice image in Figure 8 shows the contact between the granulated implant and the integrity of the sinus membrane (Figure 8(a)). The image processing of the coronal slice allowed us to observe very precisely this information which is crucial for evaluating the success of the implantation procedure, because it indicates whether the implant has been correctly placed in the event of contact with the membrane (Figure 8(b)), which is essential for good evolution and bone regeneration.

Figures 9(a) and 9(b) shows an axial section showing the closure of the crystal bone defect indicating that the treatment was successful in restoring the integration of the bone tissue to its normal function and structure. The reconstruction of the 3D image from the axial sections taken by CBCT one year after the placement of the pellet shows the closure of the crestal bone defect which is an indicator of successful bone regeneration. Figure 10(a) before implantation and Figure 10(b) one year after laying the granule.

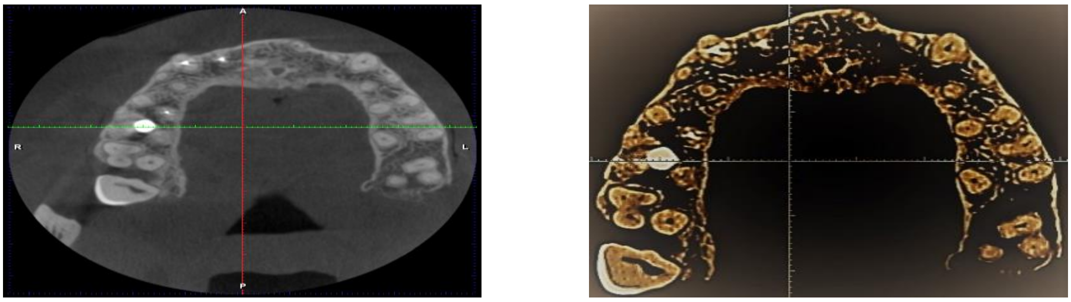


(a) (b)

Figure 7. Coronal slice that highlights new bone regeneration (a) original image and (b) processed image

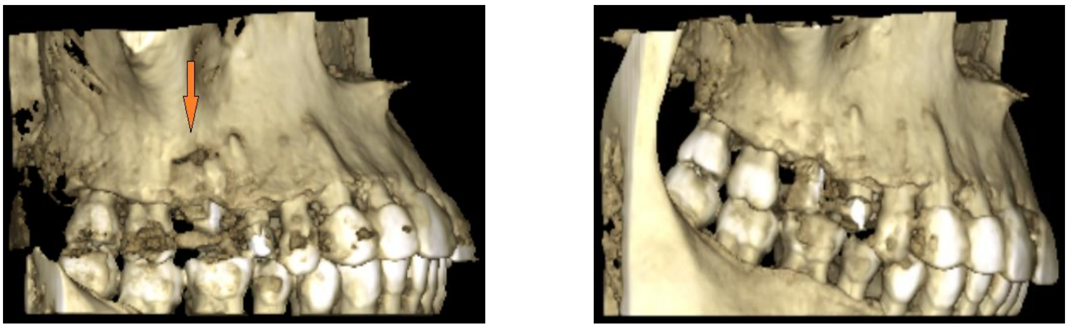
(a) (b)

Figure 8. Contact between granule implant and full sinus membrane (a) original coronal slice and (b) processed coronal slice



(a) (b)

Figure 9. Axial slice show closing of crestrale bone defect (a) original slice and (b) processed slice



(a) (b)

Figure 10. 3D image present closing of crestrale bone defect (a) before implant and (b) one year after laying the granule

3.2. Analyical results

The results of image processing and the application of the mathematical morphological operations are summarized in Table 1. The volume of the cavity to be filled was 531 mm^3, the volume occupied by granules was 358.42 mm^3, and the volume of porosity generated by the arrangement of granules was 119.47 mm^3 after 48 hours after implantation. The rate of bone generation reaches a value of 89% after one year of implantation.

Table 1. Volume of granules, the volume of porosity, and rate of regeneration bone

Times after implantation	Hole volume (mm^3)	Volume of granules (mm^3)	Porosity volume created (mm^3)	Bone generation rate (%)
48 hours	531	358.42	119.47	0
12 months		48.35	-	89

3.3. Discussion

The subtraction and exploitation of the information used during this study were possible through the use of the computer tool and the processing of X-ray images. The radiological and analytical results on the coronal sections taken postoperatively (Figure 7) show that the filling of the three empty alveoli after extractions of the three residual roots of the upper molars by the HAP/β-TCP granules match the shape of the latter and coincides with the location of the sockets by comparing with the opposite side of the arch. We also note the preservation of the integrity of the sinus membrane during the placement of the implant (Figure 8).

The analysis of the axial sections improved by image processing enabled us to highlight the vestibulo-palatine and mesio-distal position of the masses of granules and their relationship with the surrounding periodontal tissues. The fenestration of the cortical at the vestibular apical level next to the extracted tooth was highlighted. We also see the central position of the implant and the contact of the implant with the granules at the level of the two vestibular and palatal roots (Figures 9 and 10). The analysis of the 3D images confirms the existence of a cortical fenestration at the vestibular level next to the apical part of the implant in preoperative. Visualization of 3D images taken after 12 months showing total closure of the fenestration by a regular cortex

The osseointegration and behavior of granules in the human body generally depend on their composition, microstructure, and 3D arrangement [8]. The bone regeneration observed in our case is not total (89%). This may be due to two phenomena: the porosity volume initially created by the granules and their chemical composition. Indeed, the small size of the granules used cannot generate a volume of interconnected macroporosity necessary for the degradation of the granules [25], [26]. Also, the presence of 40% of the HAP phase known for its very low solubility [9] does not allow total resorption of the granules. To confirm this result, it is necessary to test granules of different sizes and compositions.

4. CONCLUSION

Currently, the majority of the studies carried out to evaluate the progression and the results of a bone regeneration guide are based on histological studies. Our objective in this study is to show that by using image processing techniques and 3D CBCT images, we can achieve the same results as anatomical and histological studies without going through conventional histological sections, therefore CBCT was used to evaluate in vivo microstructure and microarchitectural parameters of the implanted calcium phosphate granules (granules of 40% PAH/60% β-TCP between 0.5 and 1 mm) in the human dental bone defect. Appropriate image processing was used to segment the empty cavity and the granules placed in the cavity, to estimate the volume of porosity generated by the stacking of the granules and the rate of bone regeneration 12 months after implantation. The results show that the characteristics of the granules do not allow total bone regeneration. In the future, we aim to increase clinical states and improve image processing. We are interested in testing other sizes and compositions of granules and evaluating the quality of regenerated bone in different anatomical situations.

APPENDIX

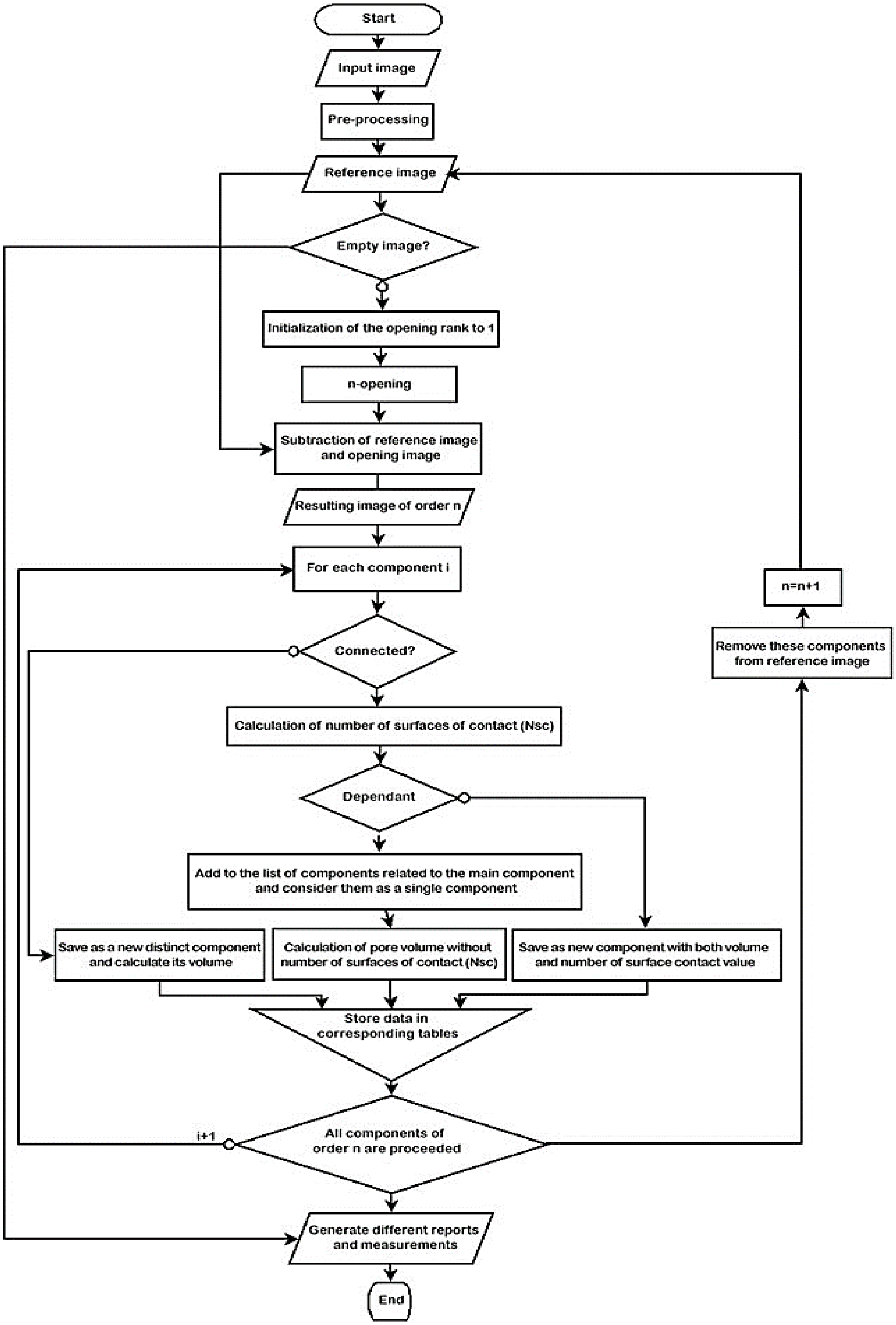


Figure 6. Algorigram for granulometry study [14]

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