INTRODUCTION: A porous implant with adequate pore structure has long been sought as the ideal bone substitute. The optimal pore sizes for porous implants have been studied; estimates vary from 150 to 500 μm [1] and, under non-load-bearing conditions, good bone ingrowth has been achieved with pore sizes ranging from 50 to 125 μm. [2] Generally, these characteristics of pore structures have been based on 2-dimensional (2-D) analysis using cross-sectional micrographs. However, the 3-dimensional (3-D) interconnectivity of each pore may be a more important factor than the size of any individual pore, and these factors are considered. For example, dead spaces (dead pores) are unavailable for tissues, even if these pores possess “optimal” pore sizes. Therefore, description of interconnectivity based on 3-D geometrical considerations is important in the field of porous biomaterials. For this purpose, we have developed a new method to analyze the 3-D network structure of porous biomaterials using high-resolution X-ray micro-computed tomography (micro-CT) with 3-D image processing software. [3] In this study, we investigated the relationship between the 3-D network structure of various porous titanium implants and in vivo bone ingrowth.

MATERIALS AND METHODS: Four types of sintered porous titanium cylinders (6 mm in diameter and 15 mm in length) with different porosities (50% and 70%) and pore sizes (200 μm and 500 μm in average) were manufactured by controlling the amount and size of spacer particles (Fig. 1). These porous titanium implants (ST50-200, ST50-500, ST70-200 and ST70-500) were supplied by Osaka Yakin Kogyo Co., Ltd. The porous structure of these implants was characterized using micro-focus X-ray computed tomography system (SMX-100CT-SV3, SHIMADZU Co., Japan) and specific 3-D image processing software. To obtain high quality data, 3-D data with a voxel size of 13 x 13 x 13 μm were thresholded to obtain binary material images. A specific 3-D image processing software developed for this study, which enabled us to use several 3-D image processing software, such as a “tracing tool” (tracing the voxel surface), a “dilation process” (expanding the voxels) or an “erosion process” (contracting the voxels), was used for the 3-D geometrical analysis. Combining these processes, we performed two types of 3-D analysis—detection of the dead space (% dead pores) and detection of pores with narrow throats of a caliber less than 52 μm (% pores with narrow throats) (Fig. 2).

For animal experiments, each porous titanium cylinder received chemical and thermal treatments that enhance the bioactivity of titanium implants—immersion in 5 M aqueous NaOH solution at 60 °C for 24 h; immersion in distilled water at 40 °C for 48 h; and then heating at 600 °C for 1 h [4]. These implants were inserted into rabbit distal femora and examined histologically after 6 weeks. Eight rabbits were used. This study was approved by the Animal Research Committee, Graduate School of Medicine, Kyoto University, Japan. Bone formation rates (the percentage of available porosity filled with new bone) and bone ingrowth depth (the depth of new bone from the periphery of the implant) were calculated from measurements from two slices from each implant. To analyze tissue differentiation in each pore, each pore was classified into three groups based on histological findings, as shown in Figure 3 [5]. The percent area of each group was also calculated.

RESULTS: Three-dimensional analysis revealed that the % dead pores was 0.218%, 0.182%, 0.007% and 0.018% for ST50-200, ST50-500, ST70-200 and ST70-500, respectively. The % pores with narrow throats was 30.87%, 13.58%, 0.61% and 0.56%, respectively (Fig. 4). The average bone ingrowth depth of ST50-200 (2.59 mm) was statistically inferior to both ST70 implants (3.00 mm). Immature pore area (sum of group 1 and group 2) in ST50-200 (26.5%) was higher than in ST70-500 (13.0%) and both ST70 implants (0%). (Fig. 5) We found no statistical difference in bone formation rate between implants.

DISCUSSION: By using micro-CT imaging with 3-D image processing software, analyses of porous titanium implants based on 3-D geometrical considerations were successfully performed. All porous titanium implants examined possessed an interconnected porous structure with very low % dead pores; however, some of the pores in the ST50 implants, especially ST50-200, had relatively narrow throats. This tendency of lower interconnectivity of the ST50 implants was much improved in the ST70 implants in association with the increased porosity. These results were highly consistent with in vivo bone depth ingrowth and tissue differentiation results, suggesting that future 3-D analysis of pore structure using micro-CT and 3-D image processing software will provide effective information in the development of porous implants.