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Development and Application of Image Analysis Program for Investigation of Pore Characteristics in Transverse Surface of Hardwoods*1

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ABSTRACT

An image analysis program with the function of measuring various quantitative characteristics in the transverse surface of wood was developed using Delphi 2.0. Data on pore characteristics (conditions for image processing, proportion of pores in relationship to other elements, tangential diameter, area, tangential and radial diameter, x and y coordinates of pore center, and geometric coefficients) were saved in text file format. In addition, the pore area histogram in the tangential and radial directions was saved as a BMP (bitmap) type file. Analyses indicated that quantitative characteristics such as the relative radial distribution of pores in a growth ring, pore tangential area histogram, and proportion of pore in lumen area appear to be useful in separating four diffuse-porous woods and four ring-porous woods on the species level.

Keywords : Image analysis, wood anatomy, image processing, quantitative characteristics of hardwoods, vessels tangential area histogram, wood identification

1. INTRODUCTION

Until now, many studies using the image analysis system have been confined to the collection of quantitative data (Gasson, 1985; Fujiwara & Iwagami, 1990; LaPasha & Wheeler, 1990; Butterfield *et al.*, 1993; Peszlen, 1994), based on the list of features for hardwood identification established by the IAWA Committee (IAWA Committee, 1989). This list has been used to modify the coding procedures and identification programs for computer-aided identification, and various proposals for the list and development of identification program have also been presented (Wheeler & Pearson, 1985; Kuroda, 1987; Wheeler *et al.*, 1987). This list of features was believed to be useful in constructing the database of wood anatomical characteristics, and various studies were conducted under this concept (LaPasha & Wheeler, 1987; Wheeler *et al.*, 1987).

Some potential quantitative characteristics of hardwoods for identification purpose can be obtained from new methods and the image analysis system, but they have been neglected in spite of their potential as new types of data. For example, the distribution of the vessel lumen area along the radial position within the growth ring (Fujiwara & Iwagami, 1990), which is an overall expression of

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pore distribution in certain species, can be a new characteristic of wood and may be used for computer-aided identification. Much discussion on the usage and possibilities of potential quantitative characteristics is required for selecting quantitative characteristics for determining reliable quantitative characteristics from new methods.

In this study, a simple image analysis program was developed for collecting various quantitative pore characteristics such as lumen area, tangential and radial diameter, density, sum of vessel area, average lumen area, shape coefficient, proportion of pore per unit area, maximum, minimum, and mean tangential diameter; and tangential and radial area histogram in transverse surfaces of hardwoods. The tangential and radial area histograms and pore distribution along the relative radial position in a growth ring (hereafter called radial growth ring) are discussed as the new potential characteristics for hardwood identification.

2. MATERIALS & METHODS

2.1 Materials

Permanent slides of eight species (four diffuse-porous and four ring-porous) from the Wood Anatomy Laboratory, College of Agriculture and Life Sciences, Seoul National University, were chosen by pattern porosity (Table 1) based on the standard list of IAWA (IAWA Committee, 1989) and Yamabayashi's categories (Lee, 1985). An Olympus BX50 light microscope was used for examining the slides, and the Delphi 2.0 (Borland International) image analysis program was used for developing an image analysis program.

2.2 Methods

Micrographs from 6 or 12 regions in transverse surface per species and 1 photograph of stage micrometer were photographed at 40× magnification. Image files were scanned from 5 by 7 cross-sectional micrographs of 6 or 12 regions per species and were saved on disk. The scanning magnification was 140% for all photographs, and the image file format was BMP type. Image files were analyzed by the image analysis program developed in this study, which had the function of measuring various quantitative pore characteristics, such as area, tangential and radial diameters, density, area sum, area average, area proportion, shape coefficient, tangential lumen diameter (maximum, min-

Table 1. Descriptions of selected species.

	Scientific name	Replications	Description of species
Diffuse-porous woods	*Cornus controversa*	12 sections / 2 individuals (6 sections / 1 individual)	Pores mostly solitary
	Betula platyphylla var. *japonica*	12 sections / 2 individuals (6 sections / 1 individual)	Radial multiples
	Crataegus maximowiczii	6 sections / 1 individual	Pores mostly solitary
	Rhamnus davurica	6 sections / 1 individual	Pores heavily clustered in figured pattern
Ring-porous woods	*Morus alba*	6 sections / 1 individual	Small pore density, evenly diffused outside pore zone
	Ulmus davidiana var. *japonica*	12 sections / 2 individuals (6 sections / 1 individual)	Medium pore density, clustered outside pore zone
	Quercus aliena	12 sections / 2 individuals (6 sections / 1 individual)	Small pore density, solitary pores in radial pattern outside pore zone
	Chionanthus retusa	6 sections / 1 individual	Large pore density, heavily clustered in figured patterns outside pore zone

imum, and mean). The program could also produce tangential and radial histograms of lumen area in the transverse surface.

The results from the image analysis program were saved as text format files containing the condition data for image processing, the sum of pore lumen area, tangential pore diameter, proportion of pore, analyzed area dimension, and all quantitative pore characteristics. Finally, text files were analyzed by Microsoft Excel with the macro functions and some Visual BASIC functions programmed in this study to separate each type of data in a text file.

The results of analysis were expressed by the relative radial distribution of pore in a growth ring, tangential and radial area histograms, and other quantitative characteristics such as pore lumen area, proportion of pore lumen area, pore density, and percentage of conductive area. The graph of relative radial growth ring pore distribution was made to show the pore distribution pattern of each species. First, pore data obtained from the image analysis program were rearranged as the y coordinate of pore reflecting the relative location in the analyzed image. The area of division was the single value of relative radial growth ring pore distribution. If the pore number of a division was greater than 1, the area of the division was represented with the average value of pore areas in that division. For example, in Fig. 1, the x-axis value means the relative position number in a growth ring and the y-axis value means the average pore area of a relative position. Each symbol depicts the average value obtained from replications of certain species.

Tangential and radial area histograms were made to investigate the cumulative tendency of pore lumen area in certain species. Radial area histogram (RAH) and tangential area histogram (TAH) were obtained from radially and tangentially scanned images. Preliminary examination showed that RAH is apparently not useful in expressing the characteristics of each species, whereas TAH is useful as the cumulative area of pores in a growth ring. Thus, TAH was mainly used to characterize species in this study.

3. RESULTS & DISCUSSION

3.1 Quantitative characteristics of diffuse-porous woods: *Cornus controversa*, *Betula platyphylla* var. *japonica*, *Crataegus maximowiczii*, *Rhamnus davurica*

Pore lumen area in *C. controversa* was in the range of 1,379 to 8,614μm^2 and most pores were greater than 5,000μm^2 in a transverse growth ring (Fig. 1). Average pore lumen area of *C. controversa* was 5,841μm^2 , with a standard deviation of 1,436.9μm^2. Radial growth ring pore lumen area was not highly variable because the pores were evenly distributed and did not differ in average lumen size. The TAH showed a tendency of pore lumen area to be distributed along the radial growth ring. The overall outline of TAH was flat (Fig. 2), suggesting that the sum of pore lumen area along the radial growth ring was nearly constant, as shown in Fig. 1.

Pore lumen area in *B. platyphylla* var. *japonica* was 988 to 7,094μm^2 and most pores were less than 5,000μm^2 in a transverse growth ring (Fig. 1). Average pore lumen area was 4,075μm^2 with a standard deviation of 1,153.7μm^2. Radial growth ring pore lumen area was not highly variable because the pores were evenly distributed and had similar lumen areas. The overall outline of TAH was flat (Fig. 2),which means that the sum of pore

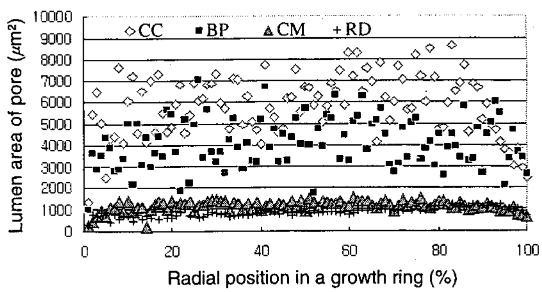

Fig. 1. Variation of pore lumen area in a growth ring in diffuse-porous woods.

Notes; CC : *Cornus controversa*, BP : *Betula platyphylla* var. *japonica*; CM : *Crataegus maximowiczii*, RD : *Rhamnus davurica*.

lumen area in a radial growth ring was nearly constant, as in Fig. 1.

In *C. maximowiczii*, pore lumen area was 222 to 1,547μm^2 and most pores were greater than 1,000μm^2

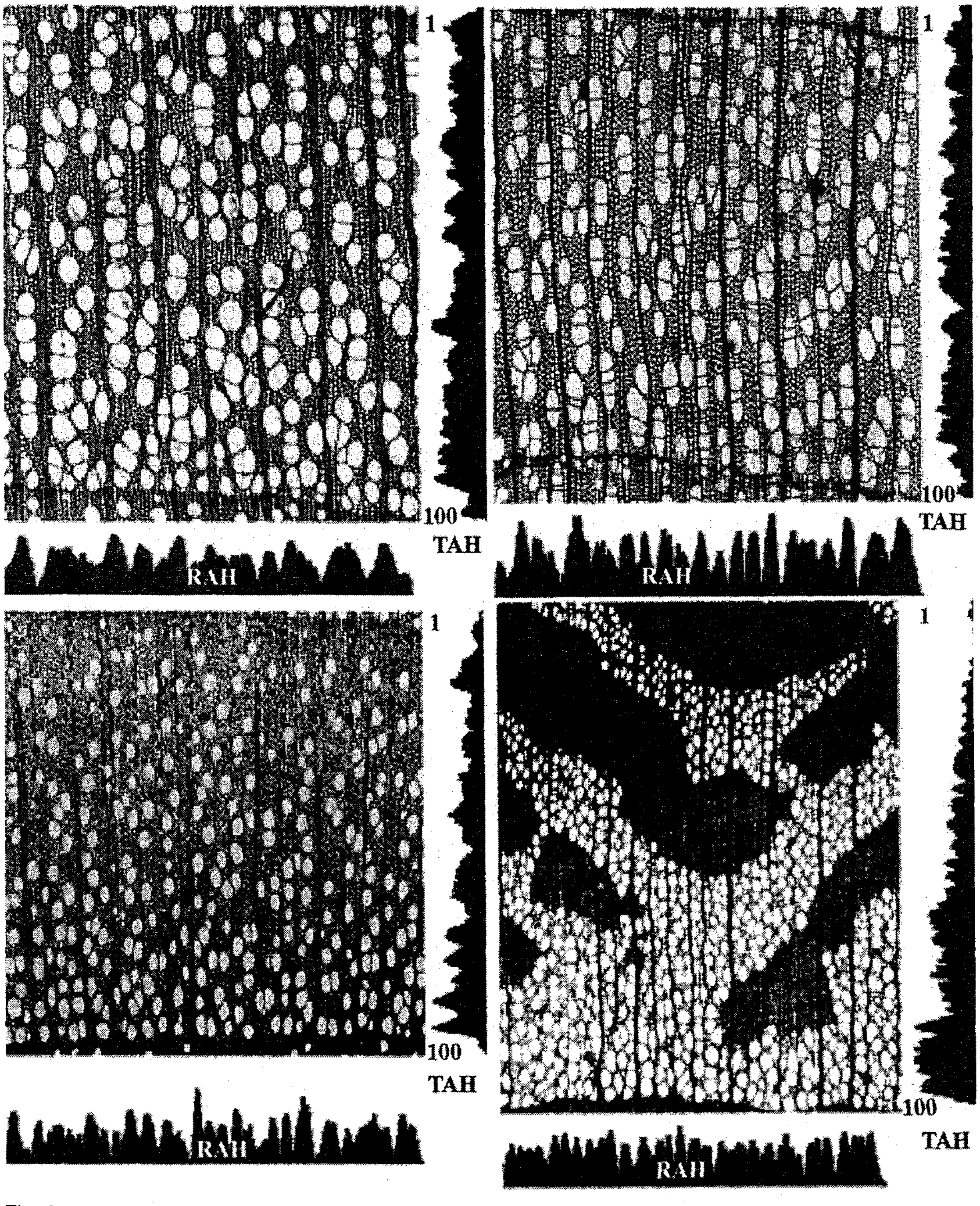

Fig. 2. Typical images and area histograms of *Cornus controversa*, *Betula platyphylla* var. *japonica*, *Crataegus maximowiczii*, and *Rhamnus davurica*.

in a transverse growth ring (Fig. 1). Average pore lumen area was 1,148㎛² with a standard deviation of 248㎛². Radial growth ring pore lumen area was not highly variable because the pores had similar lumen areas. Pore density was high in earlywood and low in latewood (Fig. 2). As revealed by TAH, the sum of pore lumen area tended to increase from earlywood to latewood. This tendency was different from that shown in Fig. 1.

The pore lumen area in *R. davurica* was 324 to 1,271㎛² and most pores were greater than 500㎛² in a transverse growth ring (Fig. 1). Average pore lumen area was 872㎛² with a standard deviation of 192.8㎛². Variation of radial growth ring pore lumen area was not high, but pore lumen area of earlywood was greater than that of latewood (Fig. 2). As shown in Fig. 2, pore distribution was significantly different from that of other diffuse porous woods. As revealed by TAH, the sum of pore lumen area tended to increase from earlywood to latewood.

3.2 Quantitative characteristics of ring-porous woods: *Morus alba*, *Ulmus davidiana* var. *japonica*, *Quercus aliena*, *Chionanthus retusa*

In *M. alba*, normalized pore lumen area ranged between 3, 000 and 17,800㎛² within the pore zone and from 3,451 to 4,052㎛² outside the pore zone. Variation in radial growth ring pore lumen area was very high because the pores within the pore zone were much bigger than those outside the pore zone, as revealed by TAH (Fig. 4). The TAH peak corresponded to the pore zone.

In *U. davidiana* var. *japonica*, normalized pore lumen area ranged between 4,800 and 26,600㎛² within the pore zone and 791 to 1,110㎛² outside the pore zone. As described for *M. alba*, radial growth ring pore lumen area varied greatly. A radial position of about 80 in a growth ring occurred at the end of the pore zone (Fig. 3). TAH revealed this tendency of pore distribution, but it did not clearly show the end of pore zone (Fig. 4). The peak in TAH corresponded to the pore zone.

In *Q. aliena*, normalized pore lumen area ranged between 4,000 and 46,100㎛² within the pore zone and 690 and 2,739㎛² outside the pore zone. Variation in radial growth ring pore lumen area was also very high, as in *M. alba* and *U. davidiana* var. *japonica*. The radial position of about 70 in the growth ring was at the end of the pore zone (Fig. 3). TAH revealed this tendency of pore distribution, but it did not clearly show the end of pore zone (Fig. 4). The TAH peak corresponded to the vessel zone.

In *C. retusa*, normalized pore lumen area ranged between 3,000 and 9,000㎛² within the pore zone and 488 and 605㎛² outside the pore zone. The variation in radial growth ring vessel lumen area was also very high. The radial position of about 90 in the growth ring was at the end of the pore zone (Fig. 3). TAH revealed this tendency of pore distribution (Fig. 4). The TAH peak corresponded to the pore zone.

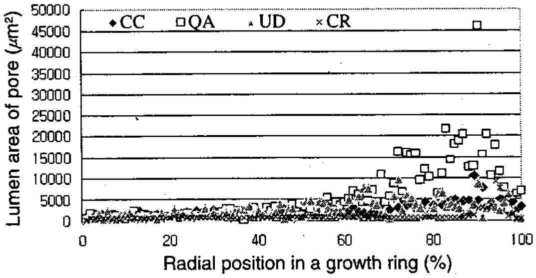

Fig. 3. Variation of pore lumen area in a growth ring in ring-porous woods.
Notes; MA : *Morus alba*; QA : *Quercus aliena*; UD : *Ulmus davidiana* var. *japonica*; CR : *Chionanthus retusa*

3.3 Pore lumen area in diffuse-porous and ring-porous woods

Of the diffuse-porous woods, lumen area was greater in *C. controversa* and *B. platyphylla* var. *japonica* than in *C. maximowiczii* and *R. davarica*; these two groups could be separated by average lumen area. Thus, the average lumen area was thought to be a quantitative characteristic for hardwood identification (Fig. 1).

Of the ring-porous woods, lumen area was

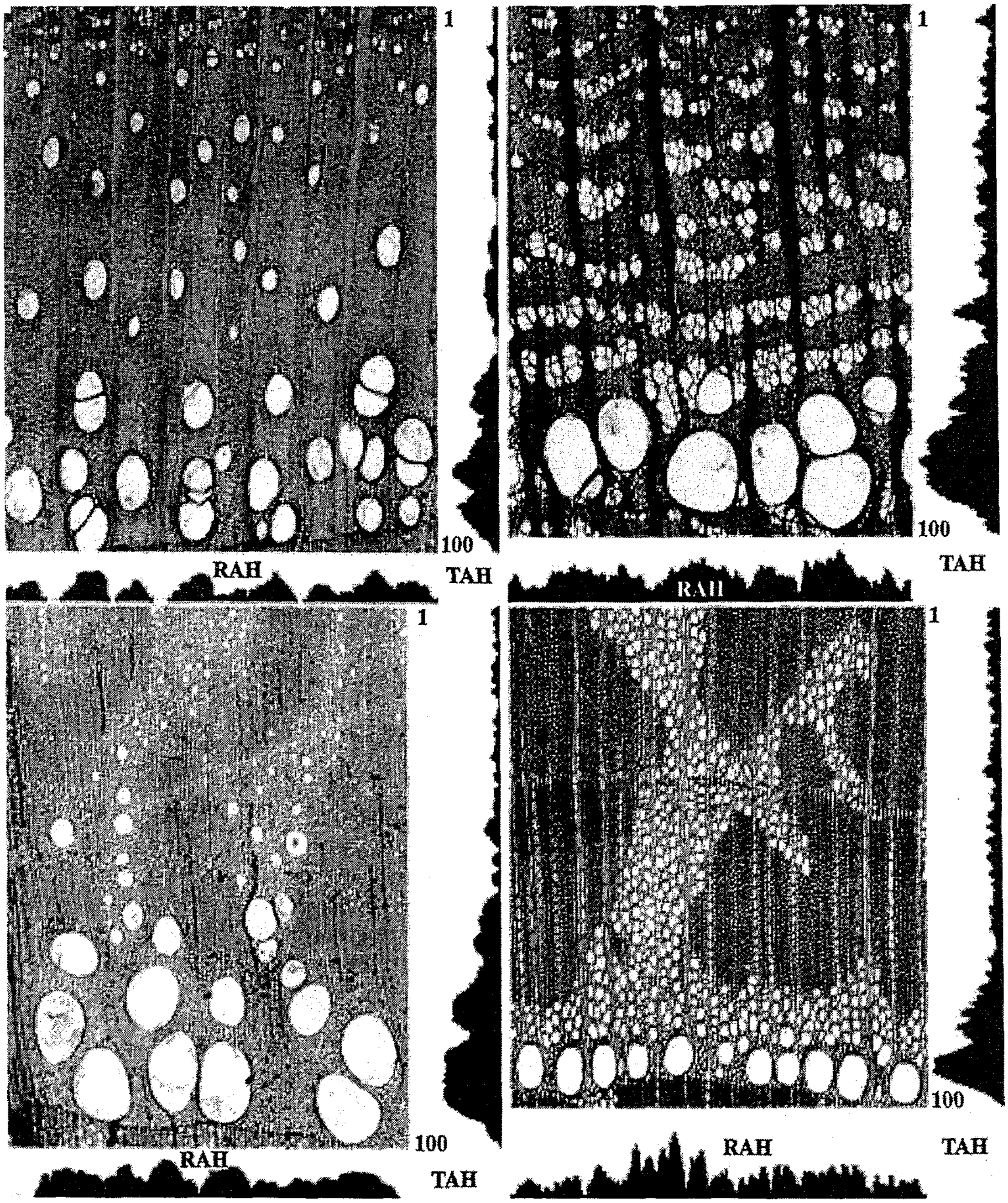

Fig. 4. Typical images and area histograms of *Morus alba*, *Ulmus davidiana* var. *japonica*, *Quercus aliena*, and *Chionanthus retusa*.

greater in *Q. aliena* than in *M. alba*, *U. davidiana* var. *japonica*, and *C. retusa*, with a relative radial position of about 70 (just outside boundary of pore zone) in a growth ring (Fig. 3). Thus, the relative radial growth ring lumen area seemed to be another quantitative characteristic for hardwood identification.

3. 4 Pore density

In the case of diffuse-porous woods, the number of individual pores counted by image analysis was smaller than that counted manually. Lee (1994) reported manual counts of pore density for the following species: *C. controversa*, 92 to 128/mm^2; *B. platyphylla* var. *japonica*, 57 to 80/mm^2; and *C. maximowiccii*, 124 to 292/mm^2. In contrast, by the image analysis program, pore density for these species was as follows: *C. controversa*, 51/mm^2; *B. platyphylla* var. *japonica*, 69/mm^2; and *C. maximowiccii*, 190/mm^2; in addition, pore density for *R. davarica* was 247/mm^2. The differences between image analysis program and manual counts might be the result of biased selection of the counting region in manual work. The species with small pore lumen area showed great pore density (Fig. 5).

3. 5 Proportion of pore lumen area in diffuse-porous and ring-porous woods

The proportion of pore lumen area was greater in diffuse-porous woods than in ring-porous woods, except for *U. davidiana* var. *japonica* (Fig. 6). Among the diffuse-porous species, those with a large lumen area appeared to have a larger conductive area than those with a small lumen area. Ring-porous woods had a smaller conductive area than that of the diffuse-porous woods (Fig. 6). In ring-porous woods, water transport was reported to be almost entirely restricted to the outermost ring, and water flow was 10 times faster than that in diffuse-porous woods (Huber, 1925; Kozlowski & Winget, 1963). Diffuse-porous woods generally have more or less uniform pores in size and distribution in the growth ring. On the other hand, ring-porous woods might need the capacity to transport large quantities of water during the early growing season and thus might require significantly larger pores at the beginning of the growth ring season compared to the end of the season. The results in this study support these explanations for the relationship of water transport to pore size in the growing season.

4. CONCLUSION

The quantitative characteristics of pores in hardwoods were analyzed by an image analysis program developed in this study. The results can be summarized as follows:

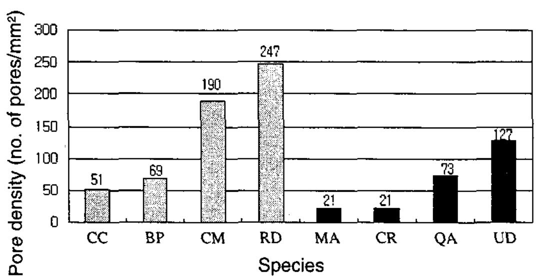

Fig. 5. Pore density.
Notes; CC : *Cornus controversa*, BP : *Betula platyphylla* var. *japonica*; CM : *Crataegus maximowiczii*, RD : *Rhamnus davurica*, MA : *Morus alba*; QA : *Quercus aliena*; UD : *Ulmus davidiana* var. *japonica*; CR : *Chionanthus retusa*

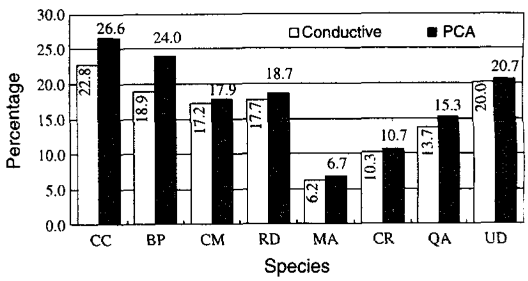

Fig. 6. The proportion of pore lumen area, non-conductive tissue, and cell wall.
Notes; CC : *Cornus controversa*, BP : *Betula platyphylla* var. *japonica*; CM : *Crataegus maximowiczii*, RD : *Rhamnus davurica*, MA : *Morus alba*; QA : *Quercus aliena*: UD : *Ulmus davidiana* var. *japonica*; CR : *Chionanthus retusa*

1. The vessel appears to be a useful characteristic in separating the diffuse-porous and ring-porous woods investigated in this study. This feature can be used to separate some hardwoods in the image analysis program or in an automated identification system with image analyzing and data processing functions.
2. Variation in pore lumen area in a growth ring is another quantitative characteristic for identification of hardwoods. The graph of pore area variation along the radial direction in a growth ring showed average lumen area and the tendency of area size distribution. Especially in the ring-porous woods, the relative radial position that showed a great increase of pore area corresponded to the pore zone, and this position appeared to vary in different species. Thus, this graph could offer information on average pore area and pore distribution pattern in each species and could be processed in an image analysis system or automated identification system for separating hardwoods.
3. The tangential area histogram (TAH) is another characteristic for hardwood identification. TAH was useful in the overall characterization along the radial direction of the eight species in this study, especially in separating the species with a small lumen area in the pore zone from species with a large lumen area in the pore zone. Radial area histograms did not appear to be useful in this respect.

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