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ORIGINAL ARTICLE

New insight into tricuspid valve anatomy from 100 hearts to reappraise annuloplasty methodology

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Abstract

Objective Prosthetic ring annuloplasty plays an important role in tricuspid valve repair. However, discussions regarding the appropriate suturing technique for rigid annuloplasty rings in patients with tricuspid valve anatomical variations are lacking. We aimed to clarify the diversity and pattern of tricuspid valve morphology.

Methods We analyzed tricuspid valve morphology and measured leaflet dimensions in 100 autopsy hearts, which were classified into three groups based on the number of posterior leaflet scallops: single scallop (PLS1) ($n=52$), two scallops (PLS2) ($n=42$), and three scallops (PLS3) ($n=5$). One heart without posterior leaflet was excluded from the statistical analysis. Demographic characteristics were compared between PLS1, PLS2, and PLS3. The linear trends of proportions of each leaflet between PLS1, PLS2, and PLS3 were assessed using linear regression analysis.

Results Median proportion (interquartile range) of the posterior annular length out of the entire annular perimeter in PLS1, PLS2, and PLS3 was 26% (22–31%), 37% (33–40%), and 45% (42–49%), respectively. Linear regression analysis showed a significant increasing trend (p for trend <0.001) of the posterior leaflet annulus proportion from PLS1 to PLS3. Accordingly, the anterior and septal annulus proportions significantly decreased from PLS1 to PLS3.

Conclusions Approximately half of the tricuspid valve has multiple posterior leaflet scallops. The proportion of the posterior leaflet annular length to the tricuspid valve annulus perimeter increases as the number of posterior leaflet scallops increases. These morphologic variations will be fundamental for future discussion about the pathology of a dilated tricuspid valve and methodology of prosthetic ring annuloplasty.

Keywords Tricuspid valve · Leaflet number · Tricuspid valve annuloplasty

Introduction

Increased attention has recently been focused on the treatment of tricuspid regurgitation (TR), especially when the left-sided valves are being repaired. Conservative TR management turned out to negatively affect long-term mortality [1–3]. Progression of TR after correction of left-sided valvular lesion is also common. Furthermore, residual TR after tricuspid valve (TV) repair was shown to be a risk factor for lower survival rate [4, 5]. This evidence implies that high-quality TV repair based on the precise morphologic assessment is important.

Prosthetic ring annuloplasty plays an important role in TV repair. Rigid rings for tricuspid annuloplasty have markers indicating the position of the anteroposterior commissure. However, anatomical variability of the tricuspid leaflet has been reported [6–8], as the number of scallop of the TV is not three in approximately half of the cases, leading to the variability of the anatomical position of the anteroposterior commissure. Meanwhile, the concept of pathological annular dilatation has been discussed in the TV with three leaflets [9], and annuloplasty technique has been described based on this concept. However, only a few studies examined the morphology of the TV, especially focusing on the

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proportion of annulus of each leaflet corresponding to the number of scallops, in a large number [7]. Thus, this study aimed to assess the TV morphology pattern and variation in 100 normal autopsy hearts, which will contribute as basic data for the future anatomical study of the dilated tricuspid annulus and for the discussion of the methodology for tricuspid annuloplasty.

Materials and methods

Object

From 2009 to March 2017, 321 patients were autopsied in our institute. The heart specimen quality was evaluated in the order of autopsy date, and we excluded hearts which did not meet the quality for precise anatomical assessment of TV leaflet. The exclusion criteria were any lack of integrity of anatomical structures of TV, including leaflets, annulus, and subvalvular apparatus. We also excluded the specimens from the patient with any known heart valve disease, decreased ventricular function, and enlarged atrium and ventricular dimension. In that manner, 100 consecutive hearts were selected for the study. Patients' demographic and clinical information, including medical history, cause of death, and echocardiogram if available, was collected from the medical records. The comprehensive consent for the study using autopsy specimen was obtained in each case when we performed the autopsy. This study was approved by the institutional review board (approval number: 3555).

Definition

We followed the definition of each structure in the TV complex, as reported by Silver et al. in 1971 [6]. The summary of the definitions is as follows: (1) commissure is defined as indentation of the leaflets divided by a fan-shaped chorda; (2) fan-shaped chorda forming the anteroposterior commissure arises from the anterior papillary muscle, which is usually the largest; and (3) posteroseptal commissure is defined by the fan-shaped chorda, which arises from the most medially placed papillary muscle on the posterior wall. Some cases have projections of valvular tissue in the commissural area, which was defined as a "miniscallop" by Silver et al. and is described as clearly distinguishable from the true scallops [6] (Fig. 1).

Measurements

We recorded the number of scallops in each leaflet according to the abovementioned definition. The miniscallops were not included in the number of scallops in this study, but were instead regarded as part of a commissure. The commissural point on the annulus was defined as the cross-point of the annulus line and the bisector of an angle formed by the fan-shaped commissural chordae (Fig. 2). The annular length (perimeter of each leaflet) and height of each leaflet or scallop were measured using a digital caliper. Leaflet height was defined as the length of the perpendicular line from the apex of the free margin of the scallop to the annulus line. When there were multiple scallops on the posterior leaflet, the posterior leaflet height was defined as that of the highest scallop.

Analysis design

The autopsy hearts were divided into three groups based on the number of posterior leaflet scallops: PLS1 with a single scallop; PLS2 with two scallops; and PLS3 with three scallops. Then, we examined the difference of each leaflet dimension between PLS1, PLS2, and PLS3.

To evaluate the relationship between the annular length of each leaflet and the number of scallops in the posterior

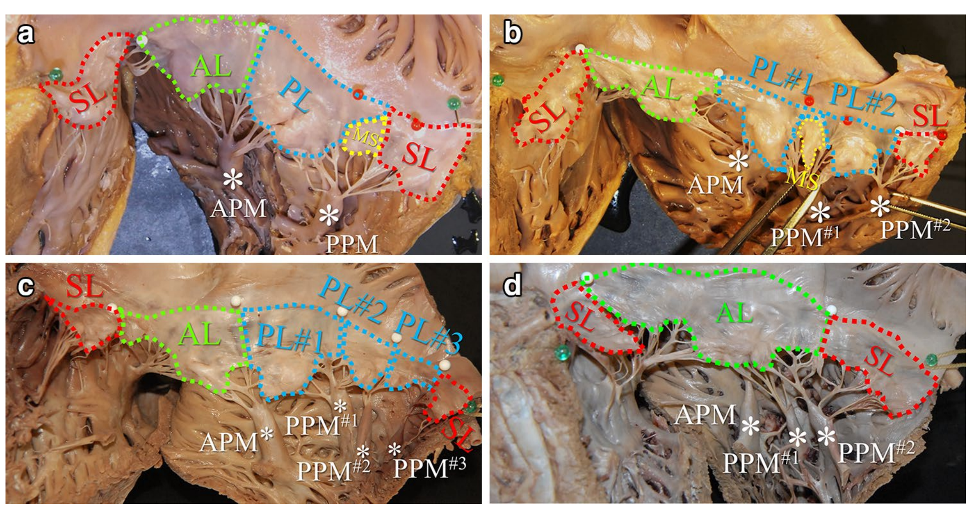

Fig. 1 **a** Single scallop PL. **b** Two scallops in the PL. **c** Three scallops in the PL. **d** Autopsy heart with no PL. *AL* Anterior leaflet, *PL* posterior leaflet, *SL* septal leaflet, *MS* miniscallop, *APM* anterior papillary muscle, *PPM* papillary muscle

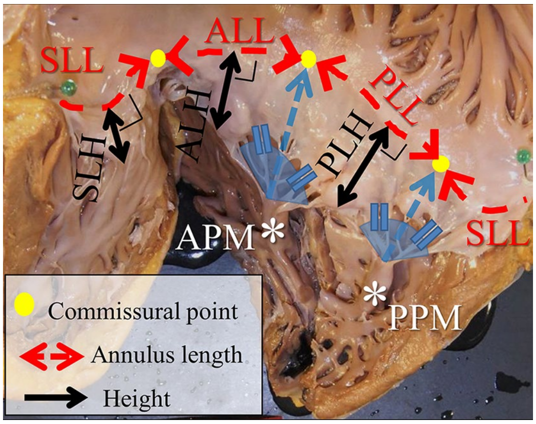

Fig. 2 Definition of each measurement. The commissural point on the annulus (yellow point) was defined as the cross-point of the annulus line and the angle bisector of the fan shape (blue interrupted lines). Leaflet height (black bidirectional arrow) was defined as the distance from the apex of the scallop free margin to the annulus line. *ALH* Anterior leaflet height, *ALL* anterior leaflet annulus length, *PLH* posterior leaflet height, *PLL* posterior leaflet annulus length, *SLH* septal leaflet height, *SLL* septal leaflet annulus length, *APM* anterior papillary muscle, *PPM* papillary muscle

leaflet, we chose the annular proportion of each leaflet (i.e., the annular length of each leaflet divided by the entire annular perimeter) as an outcome variable. The annular length of each leaflet itself could be influenced by the different annulus perimeters, which could differ depending on each patient's cardiac size, sex, or body surface area. To reduce these individual differences, we considered that the proportion mentioned above was appropriate as the outcome variable. We also calculated the index of each measurement, that is, the ratio between the annular length and body surface area, as an outcome measure.

Statistical analysis

Demographic characteristics of the PLS1, PLS2, and PLS3 groups were compared using the Kruskal–Wallis test for continuous variables and Chi-squared test for categorical variables. The median and interquartile range of the annular proportion of each leaflet and the index of annular length were calculated for PLS1, PLS2, and PLS3. Trend tests were performed using a linear regression model by including an ordinal variable representing PLS1, PLS2, and PLS3 with the outcome variable being the annular proportion of each leaflet and the index of annular length separately. Normality of the residuals was confirmed by plotting normal Q–Q plots. Statistical analyses were performed using R version 3.3.2 (R Foundation for Statistical Computing, Vienna, Austria).

Table 1 Patient distribution based on the number of scallops in each leaflet

Total no. of scallops	No. of scallops in leaflet			*n* (100)
	Septal leaflet	Anterior leaflet	Posterior leaflet	
2	1	1	0	1
3	1	1	1	52
4	1	1	2	42
5	1	1	3	5

Results

According to the leaflet definition mentioned above, the number of scallops in each leaflet was counted (Table 1). In one heart, there was no commissural area found in the mural leaflet attached to the right ventricular free wall, and this heart was regarded as having no posterior leaflet (Fig. 1d). Therefore, this heart was excluded from the latter analysis. In the remaining 99 hearts, the anterior and septal leaflets in all hearts had single scallops, whereas the number of posterior leaflet scallop was from 1 to 3. Only 52% of the hearts possess one posterior scallop, namely truly "tricuspid" valve. The 99 hearts were then divided into three groups according to the number of scallops of the posterior leaflet, as follows: PLS1 with a single scallop of the posterior leaflet (tricuspid), accounting for 52% of the hearts; PLS2 with two scallops of the posterior leaflet (tetracuspid), 42% of the hearts; and PLS3 with three scallops of the posterior leaflet (pentacuspid), 5% of the hearts.

Table 2 shows the characteristics of patients obtained from the medical records. There were 63 men. All patients were of Asian ethnicity and were aged between 21 and 93 years. There was no statistically significant difference between PLS1, PLS2, and PLS3 in terms of age, sex, and BSA.

The parameters of each leaflet dimension in PLS1, PLS2, and PLS3 are summarized in Table 3. These results indicate that the posterior leaflet annular length proportion increases as the number of posterior leaflet scallops increases, from 26% of the perimeter in PLS1 to 45% in PLS3 (p for trend < 0.001), whereas the septal and anterior leaflet annular proportions decrease correspondingly (Fig. 3).

Leaflet height was consistent irrespective of the number of the posterior leaflet scallops. No statistically significant associations between leaflet height and the number of posterior leaflet scallops were found.

Table 2 Patient characteristics

Group	PLS1 ($n=52$)	PLS2 ($n=42$)	PLS3 ($n=5$)	Total ($n=99$)	p value
No. of scallop in the posterior leaflet	1	2	3		
Age (year), median (IQR)	69.5 (57.0–76.3)	62.0 (55.0–72.8)	62.0 (46.0–75.0)	66.0 (55.5–74.5)	0.22
Male, n (%)	33 (63.5)	26 (61.9)	4 (80.0)	63 (63.6)	0.83
BSA (m^2), median (IQR)	1.56 (1.41–1.66)	1.65 (1.48–1.72)	1.62 (1.48–1.67)	1.61 (1.46–1.69)	0.23

Age and body surface area (BSA) are expressed as the median and interquartile range (IQR)

Table 3 Summary of parameters of each leaflet dimension in the tricuspid valves

Group	PLS1 ($n=52$)	PLS2 ($n=42$)	PLS3 ($n=5$)	p for trend
No. of scallops in the posterior leaflet	1	2	3	
TV annulus perimeter (mm) median (IQR)	111.5 (102.6–115.5)	112.7 (108.5–119.5)	109.4 (103.8–118.8)	0.21
TV annulus perimeter index[a] median (IQR)	71.7 (64.8–78.7)	69.7 (64.6–74.8)	70.3 (65.5–72.7)	0.92
Leaflet annulus length (mm) median (IQR)				
Anterior leaflet	39.1 (34.7–43.5)	37.7 (33.8–40.1)	34.6 (27.4–36.5)	0.02
Posterior leaflet	27.2 (24.5–34.7)	41.8 (34.5–49.0)	52.7 (46.3–53.3)	< 0.001
Septal leaflet	41.6 (33.8–47.5)	34.5 (31.3–39.2)	28.7 (23.6–35.8)	< 0.001
Leaflet annulus length index[b] median (IQR)				
Anterior leaflet	25.3 (22.4–27.6)	22.7 (20.8–24.7)	21.3 (17.9–24.6)	0.08
Posterior leaflet	17.6 (15.9–22.3)	26.2 (22.1–28.5)	31.5 (27.7–37.9)	< 0.001
Septal leaflet	27.9 (22.0–31.3)	21.7 (18.5–24.3)	17.7 (16.9–21.4)	< 0.001
Leaflet annulus length proportion[c] median (IQR)				
Anterior leaflet	0.36 (0.32–0.39)	0.33 (0.30–0.36)	0.25 (0.25–0.33)	< 0.001
Posterior leaflet	0.26 (0.22–0.31)	0.37 (0.33–0.40)	0.45 (0.42–0.49)	< 0.001
Septal leaflet	0.39 (0.32–0.43)	0.32 (0.26–0.34)	0.26 (0.23–0.28)	< 0.001
Leaflet height (mm), median (IQR)				
Anterior leaflet	23.4 (21.7–26.6)	22.8 (20.6–25.6)	20.4 (18.8–22.8)	0.11
Posterior leaflet	24.0 (21.7–26.1)	23.5 (21.5–25.5)	22.6 (21.5–24.7)	0.62
Septal leaflet	17.3 (15.9–20.6)	16.3 (14.5–19.2)	18.1 (16.8–18.9)	0.30

Each variable is expressed as the median and interquartile range (IQR)

TV tricuspid valve

[a]TV annulus perimeter index = TV annulus perimeter/BSA

[b]Leaflet annulus length index = leaflet annulus length/BSA

[c]Leaflet annulus length proportion = leaflet annulus length/TV annulus perimeter

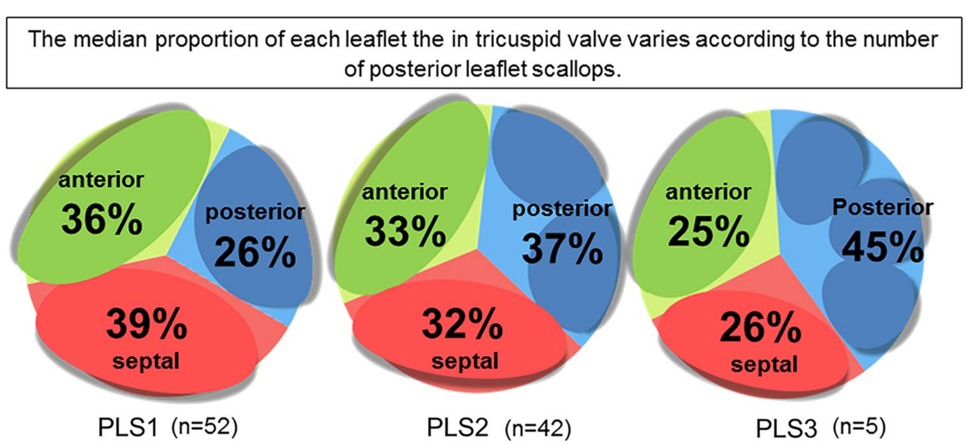

Fig. 3 Comparison of the proportion of each leaflet in the tricuspid valve according to the number of posterior leaflet scallops. The percentage shows the median proportion of each leaflet among each group. The posterior leaflet annular proportion increases, while the septal and anterior leaflet annular proportions decrease according to the number of posterior leaflet scallops

Discussion

The number of scallops in the tricuspid valve

In this study, we demonstrated that the TV is not always "tricuspid," as was previously reported [6–8]. About half of the hearts had three leaflets. The increased number of leaflets is attributed to the multiple posterior scallops. Silver et al. revealed that only 15 out of 50 hearts (30%) had a single scallop posterior leaflet, 21 hearts (42%) had two scallops in the posterior leaflet, and 13 (26%) had three scallops in the posterior leaflet [6]. Although the distribution is different from ours, our results are consistent with their findings that the anterior and septal leaflets are composed of a single cusp, whereas the number of posterior leaflet scallops is variable. The differences in distribution might be due to inter-racial difference, or simply due to the small sample size. Other groups reported the higher prevalence of tetracuspid, pentacuspid, or even heptacuspid valves. Victor and Nayak examined 100 hearts, and they reported that the total number of scallops varies from two to six, and more than 68 hearts had four or more scallops [7]. Kawada et al. assessed 27 hearts, and they described the number of TV scallops as 3–6, and showed that much more TVs (96.3%) have multiple scallops in the posterior leaflet [8]. Both studies counted miniscallops as a leaflet, whereas we and Silver et al. regarded it as a part of the commissure, and not as an independent cusp, which might explain the differences.

The definition of commissure

Tricuspid annuloplasty is the most common procedure for TV repair [10], and identification of the commissures of the TV, especially the anteroposterior commissure, is an integral part of the tricuspid annuloplasty. The previous anatomical studies defined the anteroposterior commissure as an indentation supported by a fan-shaped chordae arising from the anterior papillary muscle [6, 11], and according to this definition, anterior leaflet was revealed to be always a single scallop. We adopted this definition and our result of 100 hearts was consistent with the previous studies. We occasionally encounter a "cleft-like" indentation in the anterior portion of TV. However, in our study, this "cleft-like" indentation was always accompanied by the anterior papillary muscle and fan-shaped chordae, leading to the identification as an anteroposterior commissure. In such a case, the posterior leaflet has multiple scallops and the proportion of posterior leaflet annular length is increased, resulting in a counter-clockwise shift of the anteroposterior commissure (Fig. 4). The reason for the discrepancy of recognition might be attributed to the inconsistent terminology.

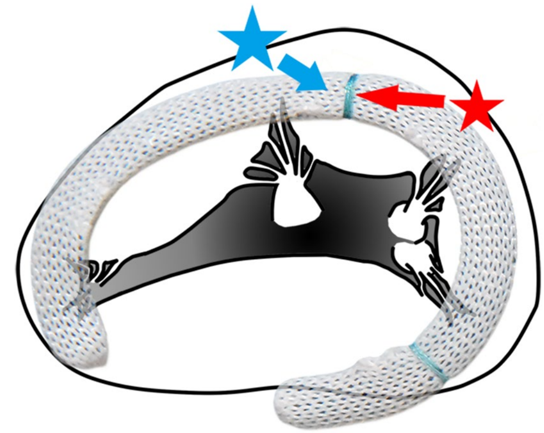

Fig. 4 Comparison of a tricuspid valve with multiple scallops posterior leaflet with the annuloplasty ring, Physio Tricuspid (Edwards Lifesciences, Irvine, CA, USA). The anteroposterior commissure (blue star) shifts counter-clockwise and could be misidentified as a "cleft of anterior leaflet," or the intra-posterior leaflet commissure (red star) could be misidentified as an anteroposterior commissure. The conventional technique for suturing annuloplasty ring may lead to the clockwise shift of the anteroposterior commissure (blue arrow), or misidentification of the commissure may cause deformation of the posterior leaflet (red arrow)

Tricuspid commissure has been defined as an area, a line, or a point by each researcher. From the surgical point of view, the definition as a commissural point might be most useful, because the markers on the prosthetic ring are defined as a point. Victor et al. and Kawada et al. defined the transition point of the anteroseptal and posteroseptal commissures as the first indentation on both ends of the septal leaflet. On the other hand, we followed the definition of the commissure adopted by Silver et al. and Anderson and Becker [6, 11]. Fan-shaped commissural chordae arising from the anterior and posterior papillary muscles are identified, which define the anteroposterior and posteroseptal commissures, respectively. The midpoint of each commissure was labeled as commissural points. The definition of the commissural point had not been fully discussed when the suturing technique for every prosthetic ring was shown. Even if any definition is adopted, we completely agree with the point proposed by Kawada et al. that the commissural points have to be taken into consideration during the future discussion of the technical aspect of the tricuspid annuloplasty.

Proportion of each leaflet in the tricuspid valve

To the best of our knowledge, this is the first report to clearly demonstrate that the proportion of the posterior leaflet annular length to the perimeter of the TV positively correlates with the number of posterior leaflet scallops. Silver et al. reported the width of each scallop of the posterior leaflet, which seemed to have a similar tendency, although the sum of the width of each scallop and its proportion to the perimeter of the TV was not clearly shown. Deloche et al. reported that the mean length of the anterior, posterior, and septal leaflet annuli was 38.7, 37.8, and 35.9 mm, respectively, in the normal human hearts, without taking the number of leaflets into consideration, and the anterior leaflet was the largest among the leaflets [12]. On the other hand, according to Kawada et al., they were 32.3, 41.4, and 32.3 mm, respectively, showing that the posterior leaflet was the largest [8]. However, their definition of the commissural point is different from others, which makes the comparison between studies difficult. In either study, the relationship between the numbers of the posterior leaflet scallops and PLL annular length was not taken into consideration.

Surgical implications

The concept of the TV annular dilatation has been as follows: dilatation of the TV annulus is only recognized in its anterior and posterior aspects, corresponding to the free wall of the right ventricle [9]. Each rigid annuloplasty ring for the TV has a marker indicating the suturing position of the anteroposterior commissure. However, there is no previous anatomical study that focused on the proportion of the anterior and posterior leaflet annular lengths. In this study on normal hearts, we demonstrated that these proportions vary corresponding to the number of scallops in the posterior leaflet. This suggests that the location of anatomical anteroposterior commissure does not always fit to the marker on the annuloplasty ring (Fig. 4). We previously reported the concept of "shoulder point fitting repair" as a universal technique to overcome this anatomical variation [13]. To confirm this concept, a further study on the dilated tricuspid annulus is currently in progress (institutional review board approval number: 3556).

Limitations

The current study had several limitations. First, this study had a retrospective, observational design and was conducted in a single center. Consequently, the cohort size was small and only included a Japanese population, which may limit the results' generalizability. Second, we aimed to assess the morphology of the normal hearts, but the cohort could potentially include patients with conditions complicated with cardiac disorders due to incompleteness of medical information. Third, we examined the normal hearts and could not comment on the morphology of the hearts with tricuspid annular dilatation. It still remains unclear whether the number of scallops or the proportion of each leaflet in the hearts with dilated tricuspid annulus is the same as that of the normal hearts. Further study is warranted to assess the anatomy and dimension of the leaflets with a dilated tricuspid annulus. Finally, we mentioned about the problem in the conventional suturing technique for the annuloplasty ring, but we cannot indicate the universal and optimal method from this study, as this is beyond the scope of this study and should be addressed after expanding our concept from the normal tricuspid annulus morphology to the diseased tricuspid annulus morphology. We are currently working on the next clinical study, in which we will measure the annular length of each leaflet and its correlation with the number of posterior leaflet scallops in the dilated TV annulus during surgery.

Conclusion

We showed that the posterior leaflet of the TV has multiple scallops in almost half of the population. The annular length proportion of the posterior leaflet is increased as the number of the posterior scallops increases. Identification of the correct commissures and assessment of the proportion of each leaflet would be fundamental for future discussions about the optimal methodology of tricuspid annuloplasty.

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Compliance with ethical standards

Conflict of interest Yoshito Sakon has no conflict of interest; Takashi Murakami has no conflict of interest; Hiromichi Fujii has no conflict of interest; Yosuke Takahashi has no conflict of interest; Akimasa Morisaki has no conflict of interest; Kokoro Yamane has no conflict of interest; Masahiko Ohsawa has no conflict of interest; Ayumi Shintani has no conflict of interest; Toshiko Seki has no conflict of interest; Toshihiko Shibata has no conflict of interest.

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