Kinetic assessment of the intimal flap in acute or chronic aortic dissection using cine CPR and MPR images acquired by ECG-gated CT

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Purpose

Aortic dissections (AD) are serious fatal aortic conditions. Their treatment strategies largely depend on the extent of the dissection. Cases with aortic dissection involving the ascending aorta are fundamentally treated by prompt open surgical replacement of the ascending aorta or the aortic arch because of the high mortality rate during the onset of the disease.

Dissection of the descending aorta without complication has a relatively lower initial mortality rate, with classical disease management being stand-alone medical therapy such as antihypertensive therapy.

However, the mortality rate becomes higher once complicated by rupture, aneurysmal dilatation or malperfusion. The reported incidence of developing such complications is around 50% of medically-treated patients(1).

Malperfusion is a serious and fatal condition wherein the dissected false lumen compresses the true lumen, resulting in flow impairment in the distal part of the true lumen. While it is well known that the collapse of the true lumen occurs under the dynamic motion of the intimal flap, assessment of its movement throughout the dissected aorta has been difficult on any modality, and thus, its kinetics and the mechanics of a collapse were not fully recognized.

The recent invention of retrospective electrocardiographically (ECG)-gated CT enables 4D image acquisition of the whole dissected aorta and clear visualization of the dissected intima by eliminating the influence of motion artifacts due to pulsation. Furthermore, we have developed dedicated software for the 4D analysis of the aorta in cooperation with a software maker (AZE, Tokyo, Japan), whereby qualitative or quantitative assessment of the motion of the aorta on curved multiplanar reconstruction or cross-sectional images is possible.

Meanwhile, endovascular entry closure using stent-grafts has become an attractive alternative to stand-alone medical therapy or invasive open surgery for complicated AD in the descending aorta(2-4). In stent-graft placement, detailed analysis of the anatomy is a prerequisite and includes determination of proximal and distal aortic diameters to achieve precise stent-graft sizing and exact planning of its landing part. The current standard measurement is based on non-gated CTA, which impairs image and measurement quality in AD because of intimal motion.
The purpose of this study is to analyze the images of the intimal flap in AD of the descending aorta on retrospective ECG-gated CT using cine curved planar reformation (CPR) and cross-sectional multiplanar reformation (CSMPR) and to characterize and define the kinetics of the intimal flap in acute or chronic aortic dissection.
Methods and Materials

Patient selection

Seventeen consecutive cases with DeBakey type # AD that underwent ECG-gated CT angiograms from January 2010 to June 2012 in our institute were enrolled in this evaluation (2 women, 15 men; mean age 61.5 years (range 46 - 77 years)). The population consists of 2 cases with DeBakey type #a and 16 cases with DeBakey type #b. Six cases had a history of open replacements of the aorta (5 with ascending and total arch replacement and 1 with descending aortic replacement) and classification of these cases were based on the post-operative status. Patient demographics and clinical characteristics are summarized in Table 1 on page 8.

The extent of the AD was indicated based on "zone classification", which is explained in Fig. 1 on page 6.

Retrospective ECG-gated CT

#Image acquisition:

All CT was performed with 32- or 64-detector row CT (Aquilion32 or 64, Toshiba Medical Systems Company, Tokyo, Japan). The scan parameters adopted are as follows: helical pitch 3.2, 120 kVp, 300mA, 0.5 s rotation time and 1mm collimation.

Under 3 liter/min oxygenation via a nasal tube, images were acquired after intravenous administration of 100 ml of iodinated contrast medium (Iomeprol 350) at a flow rate of 3 ml/s applying the bolus tracking program implemented on the scanner. Bolus timing was achieved using an automated triggering technique with a threshold of 200 HU within a region of interest (ROI) placed in the ascending aorta. Scans were performed from the level of the supraaortic vessels to iliac arteries.

#Image reconstruction and postprocessing

Multiphase image reconstruction was conducted in terms of retrospective ECG-gating, wherein the images were reconstructed at 10% intervals from 0-90% of the R-R interval (total 10 phases) with a slice thickness of 1mm and 1mm increment. These 10 volume data sets per patient were transferred to a dedicated workstation for analysis (Fig. 2 on page 6).
CT Data sets corresponding to the 0% phase of the R-R interval were initially used for semi-automatic centerline extraction of the true lumen of dissected aorta. CSMPR perpendicular to the centerline and the straightened CPR were then generated (Fig. 3 on page 7). After which, the 3D centerlines were copied to the remaining 9 volume data sets, and CSMPR and straightened CPR were repeatedly reconstructed according to the centerlines. Vessel analysis software (AZE, Tokyo, Japan) was able to visualize the cyclic motion of the intima either on straightened CPR at any given plane or on CSMPR at any given aortic levels. Confirmation of the level of entry and re-entry sites was conducted using CSMPR under consensus among two experienced radiologists and one medical student. Entry or re-entry sites were defined as apparent communication measuring more than 1mm between the true and false lumen detected in most static phase on CSMPR.

**Quantitative analysis of the true lumen**

To assess alteration of the diameter of the true lumen during cardiac cycle, the semi-automated diameter measurement function on CSMPR of the vessel analysis software was used since this allows the estimation of the mean diameter of the true lumen at given cardiac phase and aortic level.

To assess the rate of the change in diameter of the true lumen during the cardiac cycle, the ratio of internal diameter change ($R_{max}$) was defined using the following formula,

$$R_{max} = \frac{D_{max} - D_{min}}{D_{max}}$$

where $D_{max}$ was defined as the maximum value of the diameter during the cardiac cycle and $D_{min}$ was defined as the minimum value of the diameter during the cardiac cycle:

To assess the kinetics of the intima in the dissection the following parameters were assessed: the average diameter of the true lumen in each cardiac phase calculated at designated levels, the average of $R_{max}$ at each level, the average of $D_{min}$ at each level, and the differences in $R_{max}$ between acute (defined as those with less than 30 days from onset) and chronic cases.
Fig. 1: Modified zonal classification of the aorta Zone 0-3: zone 0 (from the ascending aorta to the brachiocephalic trunk), zone 1 (from the peripheral brachiocephalic artery to the bifurcation of the left common carotid artery), zone 2 (from the left common carotid artery to the left subclavian artery), zone 3 (from the left subclavian artery to the superior edge of Th4 (thoracic spine)). Zones Th4 to L4 correspond to each level of the spine. Zone C is the common iliac artery. Zone E is the external iliac artery.

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**Fig. 2:** Retrospective ECG-gated CT Scanning followed by reconstruction on the basis of R-R interval of the cardiac cycle

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Fig. 3: CSMPR perpendicular to the centerline and the straightened CPR. a. semi-automatic centerline extraction of the true lumen of dissected aorta. b. Straightened CPR Image of the true lumen of the whole aorta. c. Measurement of true lumen diameter in CSMPR image. d. Graph of true lumen diameter during the cardiac phase.

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<td>Chronic</td>
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</tr>
</tbody>
</table>

**Table 1:** Patients' characteristics

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Results

Entry sites were located in zones 3 (n=2), Th4 (n=5), Th5 (n=3), Th6 (n=1), Th7 (n=3), Th8 (n=2), and L1 (n=1). Single or multiple re-entry was detected in 15 cases while two cases had no re-entry. The color map explaining the site locations of entry or re-entries in each case is shown in Fig. 4 on page 12.

Quantitative analysis of the diameter of the true lumen

The average diameter of a true lumen during the cardiac cycle at every zone2 level of the aorta was shown in Fig. 5 on page 12. While the size of the true lumen in the proximal thoracic aorta reaches its peak during the early systolic phase, the maximum diameter in lower thoracic or abdominal appears in the later cardiac phase. Then, a gradual and delayed wavelike movement of the peak toward the distal abdominal aorta is observed.

The greatest Rmax, which was 34% on average (range 3-79%), was frequently observed at the level of the lower thoracic aorta or abdominal aorta (Fig. 6 on page 13).

The Dmin was 11.3mm on average (range 2.3-27.5mm), and was frequently seen at the L3 level (Fig. 7 on page 14).

In the assessment of the images, collapse of the true lumen in the abdominal part was frequently seen in cases having no re-entry sites that were lower than L3. Therefore, we classified the 12 cases with AD at the L3 level into the following two groups based on the status of the false lumen:

- **Closed end group**: Cases without re-entry sites lower than L3 and thus having dead-end false lumen at the lower abdomen or iliac arteries

- **Open end group**: Cases with single or multiple re-entry sites lower than L3 and thus having open false lumen at the lower abdomen or iliac arteries

Diameter change in each cardiac phase for each group was shown in Fig. 8 on page 15 and Fig. 9 on page 16, which reveals that the "closed end" group showed collapse of the true lumen at the early systolic phase while the "open end" group showed relatively stable diameter change.

Differences of the Rmax in terms of duration from the onset
The comparison of the Rmax between acute and chronic phases is presented in Fig. 10 on page 17.

At the L3 level, acute aortic dissections have a significantly higher Rmax than chronic aortic dissections.
**Fig. 4:** The location of entry or re-entry sites. Blue (dark and pale) areas indicate extent of dissection. Yellow areas indicates level of entry or re-entry sites.

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**Fig. 5:** Ratio of diameter of the true lumen (D/Dmax) during the cardiac cycle at each aortic levels. True lumen diameter change in the proximal thoracic aorta reaches its peak during the early systolic phase, and the maximum diameter in the lower thoracic aorta or abdominal aorta appears at a later cardiac phase. We observed a gradual and delayed wavelike movement of the peak toward the distal abdominal aorta.

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Fig. 6: Alteration of the diameter of the true lumen during cardiac cycle (Rmax) at each level. Maximum diameter change (Rmax) was gradually increased up to 27.8% at the L3 level.

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**Fig. 7:** Minimum diameter of true lumen at each level. True lumen diameter was substantially decreased at L3 level.

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**Fig. 8:** Diameter change in each cardiac phase for the open and closed groups. Blue line indicates open group (n=9), red line indicates closed group (n=3). During the late systolic phase (reconstructed phase 30% and 40%), there is a significant difference between the two groups.

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Fig. 9: External diameter of the two groups (closed end and open end group). There is no significant difference between the two groups.

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Fig. 10: Differences in Rmax by stage. At the L3 level, acute ADs have a significantly higher Rmax than chronic ADs.

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Conclusion

Discussion

Contrast-enhanced CT has been essential in the assessment of the condition of AD, which includes the extent of dissection, blood flow of the true and false lumen, location of entry or re-entry sites, and circulatory impairment of abdominal organs. However, it is well known that there is a complicated motion of the intimal flap during cardiac pulsation, which leads to the inaccurate estimation of the entry site and diameter of the true lumen using conventional CT. Recent adaptation of ECG-gated CT has merits not only in eliminating the influence of motion artifact, but also in offering 4D images which allows the assessment of the kinetics of the intima in AD.

Previous investigations for ADs using ECG-gated CT has been confined to the thoracic aorta (5-8); however recent advances in technologies regarding ECG-gated CT enabled us to obtain whole aortic volume data sets during one breath hold, which allowed us to perform systemic analysis of the motion of intimal flap throughout the aorta. Our study is the first investigation of the motion of the intima throughout the descending aorta in dissected cases.

Quantitative analysis of diameter change of the true lumen during the cardiac cycle revealed that the diameter of the true lumen in the proximal thoracic aorta reaches its peak in early cardiac cycle at around 30%. There is then a gradual and delayed movement of the peak toward the distal abdominal aorta. These results seem to be reasonable when we speculate the dynamic force of blood flow generated in systolic phase makes a wavelike pressure transfer in the true lumen of the dissected aorta.

Rmax of the true lumen gradually increased at levels lower than Th10, which means diameter alteration of the true lumen during the cardiac cycle is measurable in the lower thoracic or abdominal aorta. These results indicate conventional CT or prospective ECG-gated CT in certain phases may lead to inaccurate estimations of the diameter of the intima. When we need to assess the diameter of the true lumen in the lower thoracic aorta as a distal landing zone for stent-graft placement, the systolic phase was preferable since the largest diameter was given. However, in the assessment of true lumen collapse to predict malperfusion, the diastolic phase in the lower thoracic aorta and the systolic phase in the abdominal aorta is desirable for accurate estimation. These phenomena also explain the fact that malperfusion of the leg is more common than that of abdominal organs because perfusions were mainly achieved in the systolic phase, wherein collapse of the true lumen of the abdominal aorta tends to occur.
This study revealed the "closed end" false lumen in the distal dissected area could be a cause of true lumen collapse at the abdominal aorta (Fig. 11 on page 22). We may speculate the mechanism of the true lumen collapse is as follows. The pressure within the true or false lumen can dynamically divert during the cardiac cycle due to dynamic flows through the entry or re-entry sites and motion of the wall. Communications between true and false lumen through re-entry sites has an effect of reducing the pressure difference between them, which may lead to the relatively static state of the intima. Since the "closed end" false lumen in the abdominal aorta has no communication between the true and false lumen in the distal aorta, the pressure of the false lumen in a certain cardiac phase does not escape, which may result in the compression of the true lumen (Fig. 11 on page 22, Fig. 12 on page 22, Fig. 13 on page 23, Fig. 14 on page 24 and Fig. 15 on page 25).

This study also revealed that the duration from the onset of the dissection can be a factor of the stability of the intima. According to our results, the intimal motion is significantly less in the chronic phase when compared to the acute phase especially in the abdominal aorta. However, we found no significant difference in the motion of the intima in other parts of the aorta. While further studies with larger populations are needed, using this method will help to evaluate intra-aortic hemodynamics and lumen behavior with dissection.

Summary of Discussions

1. In the lower thoracic aorta, the diastolic phase is better for the assessment in terms of stent-graft planning in distal landing, while systolic phase is better for the prediction of malperfusion.

2. In the lower abdominal aorta, wherein collapse of the true lumen can occur, the late systolic phase is desirable for accurate estimation of malperfusion.

3. "Closed end" false lumen which has no communication between the true and false lumen in the distal aorta can easily compresses true lumen and lead to the collapse of the true lumen.

Conclusion

We characterized the complicated and dynamic motion of the intima in the whole aorta in AD using retrospective ECG-gated CT.
The location of the re-entry sites, extent of the dissection and duration from the onset can substantially affect the wall motion and could be a clue for comprehending the kinetics of the intima. Furthermore, precise and adequate evaluation using retrospective ECG-gated CT could help in determining treatment strategies for AD.
Fig. 11: Scheme of false lumen hemodynamics. Closed end: There is no communication between the true and false lumen in the distal aorta, the pressure of the false lumen in a certain cardiac phase does not escape, which may result in the compression of the true lumen. Open end: Communications between true and false lumen through re-entry sites has an effect of reducing the pressure difference between them, which may lead to the relatively static state of the intima.

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Fig. 12: The kinetics of the intimal flap in "closed end" group on cine straightend CPR image. "closed end" group showed collapse of the true lumen at the early systolic phase.

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Fig. 13: The kinetics of the intimal flap in "closed end" group on cine CSMPR image. "closed end" group showed collapse of the true lumen at the early systolic phase.

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Fig. 14: The kinetics of the intimal flap in "open end" group on cine straghtened CPR image. "open end" group showed intimal flap was relatively static.

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Fig. 15: The kinetics of the intimal flap in "open end" group on cine CSMPR image. "open end" group showed intimal flap was relatively static.

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