Relevance of Conduction Disorders in Bachmann’s Bundle During Sinus Rhythm in Humans

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Background—Bachmann’s bundle (BB) is considered to be the main route of interatrial conduction and to play a role in development of atrial fibrillation (AF). The goals of this study are to characterize the presence of conduction disorders in BB during sinus rhythm and to study their relation with AF.

Methods and Results—High-resolution epicardial mapping (192 unipolar electrodes, interelectrode distance: 2 mm) of sinus rhythm was performed in 185 patients during coronary artery bypass surgery of whom 13 had a history of paroxysmal AF. Continuous rhythm monitoring was used to detect postoperative AF during the first 5 postoperative days. In 67% of the patients, BB was activated from right to left; in the remaining patients from right and middle (21%), right, central, and left (8%), or central (4%) site. Mean effective conduction velocity was 89 cm/s. Conduction block was present in most patients (75%; median 1.1%, range 0–12.8) and was higher in patients with paroxysmal AF compared with patients without a history of AF (3.2% versus 0.9%; P=0.03). A high amount of conduction block (>4%) was associated with de novo postoperative AF (P=0.02). Longitudinal lines of conduction block >10 mm were also associated with postoperative AF (P=0.04).

Conclusions—BB may be activated through multiple directions, but the predominant route of conduction is from right to left. Conduction velocity across BB is around 90 cm/s. Conduction is blocked in both longitudinal and transverse direction in the majority of patients. Conduction disorders, particularly long lines of longitudinal conduction block, are more pronounced in patients with AF episodes. (Circ Arrhythm Electrophysiol. 2016;9:e003972. DOI: 10.1161/CIRCEP.115.003972.)

Key Words: atrial fibrillation ■ Bachmann’s bundle ■ electrophysiology ■ mapping ■ sinus rhythm

About a century ago, Jean George Bachmann examined conduction across a muscular band of parallel, longitudinally orientated muscle fibers running from the right auricle at the superior cavo-atrial junction over the roof of the left atrium (LA) toward the left atrial appendage (LAA). This bundle, which came to be called Bachmann’s bundle (BB), is considered to be the preferential route of interatrial conduction. Whether this is because of the presence of specialized conduction tissue or the parallel-aligned orientation of the muscle bundles remains controversial. In vivo measurements of interatrial conduction velocity in canine hearts demonstrated that the effective conduction velocity across BB is considerably higher compared with other atrial sites. Creation of a surgical lesion across BB resulted in interatrial conduction block and caused biphasic P waves on the surface ECG.

Clinical studies have demonstrated that biphasic P waves predispose to development of atrial fibrillation (AF). It was therefore assumed that conduction disorders within BB play a major role in the pathophysiology of AF, although the exact mechanism is not understood. To date, conduction properties of BB in humans have never been investigated in detail. In this study, we therefore performed direct high-resolution mapping of BB during sinus rhythm (SR) in patients undergoing coronary artery bypass surgery to examine (1) whether conduction disorders are present at BB, (2) the extensiveness of conduction disorders and their impact on LA excitation, and (3) differences in characteristics of conduction disorders between patients with and without AF episodes.

Methods

This study is part of a prospective observational project, entitled Quest for Arrhythmogenic Substrate of Atrial fibrillation (QUASAR), which was approved by the Medical Ethical Committee in the Erasmus Medical Center (MEC 2010–054). The QUASAR project adheres to the declaration of Helsinki principles, and written informed consent was obtained from all patients before the surgical procedure.
WHAT IS KNOWN

- Bachmann’s bundle is an anatomical structure between the right and left atrium and is considered to be the main route of inter-atrial conduction with specialized conduction properties.
- Clinical and experimental studies suggested Bachmann’s bundle plays a role in development of atrial fibrillation.

WHAT THE STUDY ADDS

- Bachmann’s bundle is not only activated from the right side during sinus rhythm, but also from its mid portion (septum) and left side. Moreover, the effective conduction velocity was only approximately 90 cm/s.
- Conduction disorders across Bachmann’s bundle was associated with paroxysmal and early-postoperative atrial fibrillation, suggesting a possible role in AF risk.

Study Population

Epica...
Statistical Analysis

Normally distributed continuous variables are presented as mean±SD and skewed data as median (minimum–maximum). Categorical data are expressed as numbers and percentages. Data were compared using either Student t test, Mann–Whitney U test, χ², or Fisher exact test when appropriate. Correlation between voltage or conduction velocity and patient characteristics was made by using linear Pearson regression model. Adjustments were made for sex, age, body mass index, hypertension, diabetes mellitus, hyperlipidemia, peripheral vascular disease, left ventricular function, and LA dilatation. Multivariate logistic regression models were used to test the relation between slow conduction or conduction block and the same patient characteristics. As a result of the small groups with a high amount of slow conduction and conduction block, univariate analyses were done to select the determinant of interest. Age, sex, a history of AF, hypertension, diabetes mellitus, left ventricular function, and LA dilatation were chosen. In addition, the association between conduction block and PoAF was also investigated with logistic regression models. Because of the limited number of patients with PoAF, univariate analyses were performed to select properties of interest for multivariate analysis for the prediction of PoAF with conduction block. Type of conduction block, age, sex, hypertension, and LA dilatation were included in the multivariate analysis for PoAF. A P value <0.05 was considered as statistically significant.

Patterns of Activation

Figure 2 shows color-coded SR activation maps of BB demonstrating the different types of patterns of activation observed in our study population. Arrows indicate main direction of propagation. In the majority of the patients (N=124, 67%), BB was activated by a single wavefront propagating from the right to the left side of BB as demonstrated in the upper left map of Figure 2. However, in 53 patients (29%), BB was activated by multiple wavefronts entering BB from different sites. In case of multiple different entry sites, wavefronts either collided or were separated by areas of conduction block. The upper right map of Figure 2 shows wavefronts entering on the right side and central part of BB, which was observed in 21% of the patients. Activation of BB from the right, left side, and central part of BB occurred in 8% of the patients. A typical example is given in the lower left map; wavefronts not only enter BB from the right and the left side, but a large wavefront also emerges in the central part of BB (dashed asterisk) and activates a large area more or less simultaneously. In the remaining 8 patients (4%), a wavefront entered in the central part of BB and spread subsequently to both the right and left side of BB (lower right map). There was no difference in incidences of the various patterns of activation between patients without a history of AF and with PAF (P=0.72).

Peak-to-Peak Amplitude of Sinus Rhythm Potentials

Mean voltages of all unipolar SR potentials (N=218±29/patient) were 3.0±1.4 mV and ranged from 0.3 to 7.2 mV. Lower averaged voltages were associated with ageing (P<0.001) and female sex (P=0.046); there were no correlations with a history of PAF, increased body mass index, hypertension, diabetes mellitus, hyperlipidemia, peripheral vascular disease, left ventricular dysfunction, or LA dilatation (P>0.05). Intraindividual variation in voltages across BB was 7.4±3.2 mV (minimum, 0.5±0.3 mV; maximum, 8.0±3.3 mV).

Conduction Velocity

The frequency distribution of the different effective conduction velocities of wavefronts propagating from the right to
the left side of BB is shown in Figure 3 for the right side (left panel), central part (middle panel), and left side (right panel). In all patients, the effective conduction velocity did not differ between the right side (90±24 cm/s), central part (88±16 cm/s), or left side (89±15 cm/s) of BB ($P>0.05$); mean effective conduction velocity over the entire length of BB was 89±13 cm/s (range 57–128 cm/s). Lower conduction velocity was associated with lower voltages ($P=0.002$).

Mean effective conduction velocity was not dependent on age ($P=0.35$) and was comparable between patients with PAF (97±15 cm/s) and patients without a history of AF (89±13 cm/s; $P=0.09$). Areas of slow conduction were observed in the majority of the patients (N=172; 93%); the median amount of slow conduction in all patients was 1.8% (0–9.2) and showed a trend toward a higher amount of slow conduction in patients with PAF compared with patients without a history of AF (2.6% [0.9–6.5] versus 1.7% [0–9.2]; $P=0.07$). Furthermore, a high amount of slow conduction (>2% or >4% slow conduction) was not associated with a higher age ($P=0.16$ and $P=0.33$).

Characteristics of Conduction Block
A frequency histogram of the amount of conduction block at BB is illustrated in the upper panel of Figure 4. In all patients, the
median prevalence of conduction block was 1.1% and the mean prevalence was 1.9%. Areas of conduction block were present in the majority of the patients (N=138, 75%); in the remaining 47 patients (25%), conduction block did not occur. In patients with conduction block, the amount of conduction block varied from 0.2% to 12.8% (median prevalence: 1.8%). Conduction block was higher in patients with PAF compared with patients without a history of AF (3.2% [range 0–11.6] versus 0.9% [range 0–12.8]; \(P=0.03\)). Representative examples of the spatial distribution of areas of conduction block in patients with a variable amount of conduction block are depicted in the color-coded activation maps and corresponding conduction block maps in the middle panel of Figure 4. As can be seen in these maps, lines of conduction block occurred not only in the longitudinal direction, but also in the transverse direction of propagation. Electrograms around lines of conduction block showed both double potentials and fractionated potentials (Figure 4, lower panel).

In the entire study population, the prevalence of longitudinal and transverse lines of conduction block ranged from, respectively, 0% to 12.8% (median: 1.3%) and 0% to 12.8% (median: 1.0%; \(P<0.01\)). Patients with PAF had a higher amount of conduction block in both longitudinal (1.1% [0–12.8] versus 4.0% [0–11.7]; \(P=0.03\)) and transverse direction (1.0% [0–12.8] versus 1.9% [0–12.3]; \(P=0.03\)).

As lines of longitudinal conduction block affect the right to left propagation across BB, the maximum lengths of all lines of longitudinal conduction block across BB were measured. Figure 5 shows the relative frequency of the maximal lengths of all longitudinal lines of conduction block observed in patients without a history of AF (left panel) or with PAF (right panel). Patients with PAF had longer lines of longitudinal conduction block than patients without a history of AF (median 8 mm versus 2 mm; \(P=0.03\)).

In most patients without a history of AF (51%), there were no or only small areas (2 mm) of longitudinal conduction block. Long lines of longitudinal conduction block (≥12 mm) were measured in only 12% of the patients (N=20). Although there were only 13 patients with PAF, solely 3 patients had no or small areas of conduction block. Five patients in this group (38%) had long lines of conduction block (≥12 mm). The maximum length of transverse lines of conduction block was also longer in patients with PAF than
without AF (median 6 mm [range 0–20 mm] versus 2 mm [range 0–20 mm], \( P=0.03 \)).

**Impact of Longitudinal Conduction Block on Right to Left Propagation**

The effects of longitudinal lines of conduction block on total activation time of BB and thus arrival time in the LA were determined for all patients mapped with the 192 unipolar mapping array with a single wavefront propagating from the right to left side of BB (N=52). The initial arrival times of these wavefronts at the LAA in relation to initial activation of BB for every patient individually are plotted in the upper panel of Figure 6. As can be seen, there is no effect of the length of the lines of longitudinal conduction block on the time required for right to left activation of BB.

Explanations for this observation are given in the lower panels of Figure 6. The left activation map shows a line of conduction block with a length of 12 mm with no effect on

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**Figure 6.** Impact of longitudinal lines of conduction block. **Top.** The effect of the maximum length of line of conduction block in longitudinal direction and the first activation of the left atrial appendage is plotted for all patients (N=124) with a single right to left wavefront across Bachmann's bundle. **Bottom.** Examples of the effect on the left atrial appendage activation time by different maximum lengths of lines of longitudinal conduction block. The left map illustrates a broad wavefront curving around the line of conduction block. The middle and right map demonstrate a right to left wavefront with a complete line of longitudinal conduction block coexisting with wavefronts entering BB from the central part (white or dashed asterisk) and left side.
Bachmann’s Bundle During Sinus Rhythm

The right to left conduction. The wavefront propagated around the line of conduction block without any conduction delay and arrived at the LAA side 44 ms after the first activation of BB. The middle and right activation maps demonstrate that even a complete line of conduction block (16 mm) across BB did not affect the arrival time at the LAA because in these patients areas behind the lines of conduction block were activated by wavefront emerging from other sites, including the left and central part of BB. As a result, the activation of the LAA site in these patients occurred only 33 ms and 22 ms after the first moment of activation of BB.

Early Postoperative Atrial Fibrillation

During the first 5 postoperative days, AF was observed in 56 patients (30%), including 7 patients (13%) who already had preoperative PAF. The incidence of de novo PoAF is plotted for each patient individually without a history of AF in Figure 7 and ranked according to the intraoperatively determined prevalence of longitudinal conduction block (x axis). There was a large variation in the length of areas of longitudinal conduction block in patients who developed PoAF. Although 10 patients (50%) with long lines of longitudinal conduction block developed PoAF, patients without or only small areas (2 mm) of conduction block in longitudinal direction also frequently developed PoAF (N=20; 23%).

The lower panel in Figure 7 shows the results of univariate and multivariate analyses. A higher age was not related with the occurrence of PoAF in patients without a history of AF (odds ratio 1.0, 95% confidence interval 1.0–1.1; P=0.31). Although an equal amount of conduction block was found in patients with PoAF compared with patients without PoAF (P=0.09, not shown in Figure 7), >4% conduction block was associated with development of PoAF (odds ratio 3.1, 95% confidence interval 1.2–8.1; P=0.02). When analyzing the amount of conduction block for the different orientations separately, there was no difference between the amount of transverse (P=0.06) or longitudinal conduction block (P=0.14) and development of PoAF. Also, a higher risk of development of PoAF was not associated with >4% conduction block in either longitudinal (P=0.28) or transverse direction (P=0.26).

In patients without a history of AF, the length of lines of longitudinal conduction block did not differ between patients with and without PoAF (median 4 mm versus 2 mm; P=0.07). However, patients with PoAF had more often long lines (≥12 mm) of longitudinal conduction block (N=11) compared with patients without PoAF (N=9; P<0.01). Patients with long lines of longitudinal conduction block had a 3 times higher risk (odds ratio 2.9; 95% confidence interval 1.1–8.2; P=0.04) of developing PoAF, whereas patients with lines of conduction block of 12 mm or longer in transverse direction had the same risk of developing PoAF (odds ratio 2.2; 95% confidence interval 0.51–9.9; P=0.28).

Discussion

High-resolution epicardial mapping of BB during SR in patients with coronary artery disease showed that BB was activated by multiple wavefronts entering BB not only from the right side, but also from the left side and central part in a considerable number of patients. The average effective conduction velocity across BB was ≈89 cm/s and did not differ...
between patients with or without AF. Lines of conduction block were found in the majority of the patients (74%) and occurred both in longitudinal and transverse direction. The effect of these lines of conduction block on excitation of the LA was limited. However, a high amount of conduction block and long lines of longitudinal conduction block were associated with the presence of PoAF.

**Preferential, but Not the Only Interventricular Route**

Experimental studies demonstrated that crushing of BB led to significant delay in excitation of the LA. However, in our study population, the presence of long lines of longitudinal conduction block did not result in delayed LA activation because areas behind the lines of conduction block were activated by wavefronts emerging from either the left side or central part of BB.

As demonstrated in previous studies, our observations confirm that BB is not the exclusive route of interatrial conduction and that propagation of electric waves from the right to the LA occurs along other interatrial pathways when conduction across BB is impaired. These other interatrial pathways include the limbus of the fossa ovalis, the coronary sinus, and interatrial bundles both superior and inferior along BB.

Conduction across BB has to date only indirectly been examined by using endocardial and epicardial mapping techniques. In patients who underwent catheter ablation of AF, 3-dimensional electro-anatomic (non)contact mapping techniques were used to examine the first LA activation site during SR. The earliest LA activation was frequently observed at the antero-superior LA, which was assumed to be the end of BB. Activation at this site was either solitary or simultaneously with other interatrial sites, which often included the posteroseptal wall or the limbus of the fossa ovalis. Similar to these findings, we also observed that in the majority of our patients, a single wavefront propagated across BB from the right to the LA, which may initially activate the LA.

In 30% of our patients, BB was activated by wavefronts emerging in the central part of the mapping area. Although some studies observed that BB is isolated from the interatrial septum, others suggested that muscular connections between BB and the interatrial septum are present. It is therefore likely that when right to left conduction along BB is delayed, BB can also be excited by wavefronts conducting faster in other interatrial pathways (eg, limbus of fossa ovalis or coronary sinus), propagating upwards in the interatrial septum and activating the central area of BB.

Interestingly, wavefronts not only entered BB on the right side and propagated leftwards, but also entered on the left side and propagated rightwards. These left-sided wavefronts emerged both early and late in relation to the onset of activation of the right side of BB. This can be explained by the presence of the aforementioned additional bundles parallel to BB, crossing the roof of the LA. When wavefronts propagate faster across these parallel bands than BB, they can enter BB relatively early on the left side and collide with the right to leftwards propagating wavefronts. When conduction across BB is delayed, interatrial conduction occurs in other interatrial pathways, resulting in late excitation at the left side of BB, depending on the length and degree of conduction delay of the pathway taken. Besides that, a wavefront emerging from the left side in BB in the presence of a long line of conduction block could also be explained by turning of a wavefront around the end of the line of conduction block outside the mapping array. However, as the mapping array covers the entire width of BB, this is unlikely.

**Bachmann’s Bundle, the Superconductor?**

Propagation of wavefronts occurs faster in longitudinal than transverse direction. It is therefore assumed that longitudinal parallel orientation of the fibers in BB results in higher conduction velocity, thereby making BB a preferential route of interatrial conduction. In addition, some studies suggest that the fibers of BB have specific characteristics similar to components of the specialized Purkinje fibers, such as a higher resting membrane potential, rapid velocity upstroke of the action potential, distinct overshoot, and a broader phase 2 plateau. However, in contrast to the Purkinje cells, action potentials in BB abbreviated after application of acetylcholine, which suggests BB cardiomyocytes differ from the Purkinje cells of the cardiac conduction system. Altogether, these studies showed that cardiomyocytes of BB have cell characteristics similar to both the specialized conduction system and atrial cardiomyocytes.

The effective conduction velocity across BB measured in animal studies was often faster at BB than other atrial sites. Goodman et al performed mapping in a Langendorff-perfused canine heart with a 5-point electrode array. They observed a maximum conduction velocity of 300 cm/s in BB, which is comparable with conduction velocity in specialized Purkinje fibers. However, in our study population, we measured an effective conduction velocity of only 89 cm/s in BB, which is comparable with conduction velocities at other sites in the atria. Previous studies found higher effective conduction velocities across BB by measuring velocity between only a few points. Conduction velocity in BB could have been overestimated because wavefronts propagating from the right to the LA might fuse with wave fronts entering the central part of BB. This results in a large simultaneously activated areas, which could mimic fast propagation of a single wavefront between the first and last activated site. In our study population, the effective conduction velocity might also have been overestimated because of late merging of wave fronts arising from deeper layers. Only single wavefronts propagating from the right to left site of BB were chosen to minimize the risk of overestimation. Yet, despite the presence of only one single wavefront, a different angle of the wavefront entering BB, which is highly anisotropic in nature, can influence conduction velocity. On the contrary, areas of simultaneous activation (>200 cm/s) were interpreted as central entry sites of wavefronts propagating partially through deeper layers. They were sometimes observed after a line of conduction block, whereas they also collided with a right to left propagating wavefront without being separated by lines of conduction block. In the latter case, the conduction velocity could have been overestimated.
The Role of BB in the Pathophysiology of AF

Waldo et al made surgical lesions in BB of dogs and observed significant changes in the P wave morphology and duration. Delay in BB led to partial interatrial conduction block, whereas complete block of BB caused advanced interatrial conduction block which was characterized by biphasic P waves, particularly in the inferior leads on the surface ECG. Clinical studies have shown that advanced interatrial conduction block increases the risk of developing atrial tachyarrhythmias, including AF.

The role of BB in initiation and perpetuation of AF has been investigated in animal studies. In the goat model of Allessie, initiation of AF episodes was preceded by atrial extrasystolic beats that were blocked at the middle of BB. Subsequently, re-excitation at the same site of the line of conduction block suggested re-entry in BB. Mapping during AF of both atra and the interatrial septum in a sterile pericarditis canine model revealed multiple unstable re-entry circuits involving the interatrial septum. As BB was the most commonly used interatrial pathway for these reentry circuits, the investigators suggested that BB is essential for perpetuation of AF. In this same canine model, complete transection of BB with radiofrequency ablation resulted in termination and noninducibility of AF.

We observed multiple entry sites of BB during SR in patients with and without lines of conduction block. A line of conduction block across the entire width of BB did not result in delayed LA activation and the specific P wave alterations associated with development of AF. These findings differ from the earlier observations of P wave alterations after surgical transection of BB. In case of complete surgical transection of BB, other muscular connections, that is, interatrial septal pathways to BB, may also be disrupted.

According to these earlier studies, BB may play an important role in development of AF, although the exact mechanism remains unclear. Although over 20% of the patients without or with only a small area of conduction block developed PAF, a high amount of conduction block and long lines of longitudinal conduction block were associated with de novo PAF. These results indicate that the length of lines of conduction block facilitate reentry and hence development of AF. Yet, patients without (long) lines of conduction block developed both PAF and PAF as well, suggesting that not only areas of conduction block in BB are involved in development of AF. The amount of conduction block at BB may merely reflect electric disease which is also present elsewhere in the atria. Other atrial sites may contain more extensive areas of conduction block and thus play a larger role in the pathophysiology of AF.

Becker microscopically examined BB, terminal crest, and pulmonary vein areas in 20 postmortem mainly known with coronary artery disease; 10 patients had a history of PAF. In all patients, fibro-fatty tissue and fibrotic patches were found, which may cause conduction disorders as a result of disruption of cell-to-cell connections. These histological changes were more common in patients with PAF, which may explain the higher amount of conduction block in patients with PAF in our study population. As all examined areas—pulmonary veins, terminal crest, and BB—were more affected in patients with PAF, delayed intra-atrial conduction predisposing to development of AF is probably the result of extensive conduction block throughout the atra and interatrial connections rather than conduction block across BB only. In addition, conduction disorder may be further impaired by, for example, atrial extrasystolic beats, which in turn initiate AF episodes.

Study Limitations

Mapping of BB is solely performed at the epicardial surface and does not provide any information of wavefronts propagating partially in deeper layers or emerging from other atrial sites. Hence, only the effective conduction velocity can be assessed. Also, the definition of slow conduction and conduction block remains arbitrary, and slow conduction cannot definitely be excluded. In the individual patient, the exact proportions of BB are unknown, and the mapping array might not always have covered the entire BB. However, previous studies demonstrated that the size of BB equals approximately the size of the mapping array. Also, our study did not provide any information on conduction properties at other atrial sites. Because of the small group of patients with a history of AF, comparison between patients with and without a history of AF was limited. In line with that, a lack of power might explain the absence of a significant relation between slowing of conduction velocity, a higher age, and development of PAF.

Conclusions

High-resolution mapping of BB in humans with coronary artery disease during SR demonstrated that BB may be the preferential route of interatrial conduction, but can be activated from other directions as well. As a consequence, conduction disorders exclusively in BB have limited impact on LA excitation. Despite the longitudinal orientation of BB fibers, BB is not the superconductor as previously suggested. Conduction is blocked in both longitudinal and transverse direction in the majority of the patients. Conduction disorders, particularly long lines of longitudinal conduction block, are more pronounced in patients with AF episodes.

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Disclosures

None.

References

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