Protective Effect of the KCNMB1 E65K Genetic Polymorphism Against Diastolic Hypertension in Aging Women and Its Relevance to Cardiovascular Risk

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Abstract—The E65K polymorphism in the β1-subunit of the large-conductance, Ca2+-dependent K+ (BK) channel, a key element in the control of arterial tone, has recently been associated with low prevalence of diastolic hypertension. We now report the modulatory effect of sex and age on the association of the E65K polymorphism with low prevalence of diastolic hypertension and the protective role of E65K polymorphism against cardiovascular disease. We analyzed the genotype frequency of the E65K polymorphism in 3924 participants selected randomly in two cross-sectional studies. A five-year follow-up of the cohort was performed to determine whether cardiovascular events had occurred since inclusion. Estrogen modulation of wild-type and mutant ion channel activity was assessed after heterologous expression and electrophysiological studies. Multivariate regression analyses showed that increasing age upmodulates the protective effect of the K allele against moderate-to-severe diastolic hypertension in the overall group of participants (odds ratio [OR], 0.35; P=0.006). The results remained significant when analyses were restricted to women (OR, 0.18; P=0.02) but not men (OR, 0.46; P=0.09). This effect was independent of the reported acute modulation of BK channels by estrogen. A five-year follow-up study also demonstrated a reduced age- and sex-adjusted hazard ratio of 0.11, 95% CI, 0.01 to 0.79 of K-carriers for “combined cardiovascular disease” (myocardial infarction and stroke) compared with EE homozygotes. Our study provides the first genetic evidence for the different impact of the BK channel in the control of human blood pressure in men and women, with particular relevance in aging women, and highlights the E65K polymorphism as one of the strongest genetic factors associated thus far to protection against myocardial infarction and stroke. (Circ Res. 2005;97:1360-1365.)

Key Words: BK channel ▪ estradiol ▪ hypertension ▪ KCNMB1 gene ▪ cardiovascular risk ▪ sex ▪ age

Hypertension is not only a disease but also the most prevalent risk factor for heart, brain, and kidney diseases, present in ≈30% of adults.1,2 Augmented rates of hypertension are seen with increasing age,3 and the incidence of hypertension is higher in men 30 to 50 years of age compared with women of similar age and in postmenopausal compared with premenopausal women.4 The cause of hypertension cannot be identified in 90% to 95% of patients; this type of hypertension is named essential hypertension.5 Typically, essential hypertension is a multifactorial disorder involving abnormalities at different levels, particularly vascular volume homeostasis and vascular tone.6,7 Several association studies have found genetic variations in different genes involved in those homeostasis systems.8 We recently characterized a gain-of-function polymorphism (E65K) in the β1-subunit of the large-conductance Ca2+-dependent K+ channel gene (KCNMB1), which is associated with low prevalence of moderate-to-severe diastolic hypertension.9 Polymorphisms in the KCNMB1 gene have also been associated with the baroreflex function in humans.10 The vascular smooth muscle Ca2+-dependent K+ channel (BK), a key element in the control of vascular tone, is formed by an ion-conducting α-subunit and a regulatory β1-subunit, which couples local increases in intracellular Ca2+ to augmented channel activity11–14 and vascular relaxation.15,16 Mutant E65K channels showed increased Ca2+ sensitivity, which might result in a more efficient negative feedback on vascular smooth contractility.9

Age and sex have been reported to regulate the expression or function of BK channels in vascular smooth muscle cells. A decreased expression of the α1-17; and β1, BK subunits18 with increasing age have been described. Among all sex hormones implicated in the control of vascular tone, estradiol has been linked to the regulation of the BK channel activity in vascular...
smooth muscle cells. Estradiol increases the activity of BK channels by increasing NO availability and subsequent generation of intracellular signaling molecules such as cGMP or direct interaction with the BK channels. Therefore, the aims of the present study were to assess the potential modulatory effect of sex and age on the association of the E65K polymorphism with the prevalence of diastolic hypertension and to determine the protective role of E65K polymorphism against stroke and myocardial infarction.

Materials and Methods

Study Population and Measured Variables
The representative population sample was composed of 3924 participants 25 to 74 years of age: 1973 (50.3%) women and 1951 (49.7%) men. They were randomly selected in two cross-sectional studies performed to establish the prevalence of cardiovascular risk factors in the province of Girona (Spain), in 1995 and in 2000 (the REGICOR study). Full details of recruitment and measured variables are provided by Masia et al. Participants were considered hypertensive when their diastolic blood pressure (DBP) was ≥90 mm Hg or they were under antihypertensive drug therapy. Diastolic hypertensive patients receiving antihypertensive therapy were 38.4% men and 60.1% women, although no individual information on the therapeutic protocol was available. Subjects with DBP <90 mm Hg not receiving antihypertensive therapy constituted the diastolic normotensive group. All participants gave written informed consent. The study was approved by the local ethical committee.

Five-Year Follow-up Study
A five-year follow-up of the 1995 cohort with a personal contact was organized to obtain an ECG and to administer a structured questionnaire to determine whether myocardial infarction events had occurred since inclusion. Finally, it was possible to obtain data on the follow-up and genotype in 1282 participants (73.3% of initial). All cardiovascular events (myocardial infarction and stroke) was evaluated by a five-year follow-up of the 1995 cohort with a personal contact was organized to obtain an ECG and to administer a structured questionnaire to determine whether myocardial infarction events had occurred since inclusion. Finally, it was possible to obtain data on the follow-up and genotype in 1282 participants (73.3% of initial). All ECGs were blindly interpreted and compared with the baseline ECG by the same senior cardiologist to ensure consistency.

The association between the E65K polymorphism and cardiovascular events (myocardial infarction and stroke) was evaluated by a five-year follow-up of the 1995 cohort with a personal contact was organized to obtain an ECG and to administer a structured questionnaire to determine whether myocardial infarction events had occurred since inclusion. Finally, it was possible to obtain data on the follow-up and genotype in 1282 participants (73.3% of initial). All ECGs were blindly interpreted and compared with the baseline ECG by the same senior cardiologist to ensure consistency. All clinical records (ie, hospital and general practitioners') of all hospitalized participants were examined to ascertain the diagnosis. Medical records screening, telephone contacts, and re-examination were used to identify patients with stroke during the follow-up.

E65K Polymorphism Analysis
The E65K polymorphism was identified in the third exon of the KCNMB1 gene as described previously. The E65K polymorphism was analyzed in every one of the 3924 participants by a real-time quantitative PCR using 5’-AGCGTGTGGACCCGGAAT-3’ and 5’-GGCCAGCTGACAGTTGA-3’ primers and FAM-CCCTCTTG-GCCCTACGCTTCTCC-TAMRA and VIC-CACCTTGTGC-CCTCAGCCTCCT-TAMRA probes for the K (A base) and E (G base) alleles, respectively.

Cell Transfection
Human embryonic kidney 293 (HEK-293) cells permanently expressing human BK channel α-subunit were transfected as described previously with plasmids expressing either the wild-type BK channel β1-subunit (β1wt) or the β1 containing the E65K mutation (β1E65K) alone or in combination.

Electrophysiology

Direct Effect of 17β-Estradiol on BK Channels
Ionic currents were recorded from inside-out macropatches held at 0 mV and pulsed from −100 mV to +200 mV in 10-mV steps of 150-ms duration. Tail currents were recorded at −80 mV. The solution filling the patch pipettes (1 to 2 mol/L LiF) and the bath solution contained (in mmol/L): 140 KCl, 0.7 MgCl₂, 3.5 CaCl₂, 5 EGTA, and 10 HEPES (300 mmol/L, pH 7.3; 100 mmol/L free Ca²⁺; calculated using EqCal; Biosoft). A total of 10 mmol/L 17β-estradiol was added to the pipette solution. Currents were recorded immediately after seal formation (t=0 minutes; control) and 10 minutes later (effect of 17β-estradiol). Normalized conductance versus voltage (G/Max-V) curves were obtained from tail currents and fitted to Boltzmann equations from which V1/2 were calculated.

| Clinical Characteristics and E65K Genotypes in Men and Women |
|-----------------------------|-----------------------------|
|                            | Men (n=1951)                | Women (n=1973)               | p   |
|                            |                             |                             |     |
| Age, years                  | 50.7±13.8                   | 50.7±13.3                   | NS  |
| Body mass index, kg/m²      | 27.4±4.3                    | 27.1±5.5                    | 0.022|
| Diastolic hypertension*, n (%) | 594 (30.4)                  | 469 (23.7)                  | 0.001|
| Diabetes mellitus, n (%)    | 273 (13.9)                  | 198 (10.8)                  | 0.001|
| E65K genotypes             |                             |                             |     |
| EE genotype, n (%)          | 1537 (78.8)                 | 1534 (77.7)                 |     |
| K carriers, n (%)           | 414 (21.2)                  | 439 (22.2)                  | NS  |

Continuous variables are shown as mean±SD.

*Subjects under antihypertensive treatment with DBP <90 mm Hg were also included.

Effect of Dibutyril cGMP on BK Channels
Single-channel recordings were obtained from cell-attached patches clamped at several voltages (+40, +60, +80, and +100 mV) before and 20 minutes after exposure to 500 μmol/L dibutyryl cGMP (db-cGMP). The solution filling the patch pipettes (10 mol/L LiF) and the bath solution contained (in mmol/L): 140 KCl, 0.7 MgCl₂, 0.25 CaCl₂, 0.5 EGTA, and 10 HEPES (304 mmol/L, pH 7.26, 100 mmol/L free Ca²⁺; calculated using EqCal; Biosoft). Average BK channel activity (number of channels×single channel open probability [NPo]) was determined from 20-s continuous recordings by fitting the sum of Gaussian functions to an all-points histogram plot at each voltage tested.

Experiments were performed at room temperature on enhanced green fluorescent protein–positive cells. Currents were sampled at 10 kHz and low-pass filtered at 1 kHz.

Statistical Analysis
Deviation from Hardy–Weinberg equilibrium was assessed using a χ² test with 1 df. χ² or Fisher’s exact tests were used as appropriate to compare categorical variables between groups. Continuous variables were compared between groups with the Student’s t test. Adjusted odds ratios (ORs) of moderate-to-severe diastolic hypertension and their 95% CIs were estimated for K-carriers versus EE genotype by unconditional logistic regression analysis. These models were also used to test for interactions between genotype and age, and between genotype and sex.

The association between the E65K polymorphism and cardiovascular events (myocardial infarction and stroke) was evaluated by a five-year follow-up of the 1995 cohort with a personal contact was organized to obtain an ECG and to administer a structured questionnaire to determine whether myocardial infarction events had occurred since inclusion. Finally, it was possible to obtain data on the follow-up and genotype in 1282 participants (73.3% of initial). All ECGs were blindly interpreted and compared with the baseline ECG by the same senior cardiologist to ensure consistency. All clinical records (ie, hospital and general practitioners’) of all hospitalized participants were examined to ascertain the diagnosis. Medical records screening, telephone contacts, and re-examination were used to identify patients with stroke during the follow-up.

Results
The frequency of the K allele was 0.22 and the genotype frequencies were 78.3%, 20.2%, and 1.5% for the EE, EK, and KK genotypes, respectively. The observed genotype frequencies of the E65K polymorphism were consistent with Hardy–Weinberg equilibrium. The clinical characteristics of the participants grouped by sex are shown in the Table. Men were more overweight and more hypertensive, with greater...
prevalence of diabetes than women. The genotype frequencies for the E65K polymorphism were similar in both sexes.

The E65K genotype frequencies of total, moderate-to-severe, and severe diastolic hypertensive subjects were compared with genotype frequencies of the diastolic normotensive group in both sexes (Figure 1). The frequency of the K allele decreased with increasing DBP values in both sexes; however, the differences were statistically significant only in women with moderate-to-severe diastolic hypertension (Figure 1B). In this group, only 10.7% were K-carriers compared with genotype frequencies of the diastolic normotensive group (P=0.047). Moreover, from 12 severe hypertensive women (DBP ≥110 mm Hg), only one was K-carrier.

To assess the influence of age on the relationship between the E65K polymorphism and diastolic hypertension, normotensive and moderate-to-severe hypertensive (DBP ≥100 mm Hg) participants were stratified by sex and age, and 55 years was the cutoff. In subjects <55 years of age, no association between the E65K polymorphism and moderate-to-severe diastolic hypertension was observed. In hypertensive men >54 years of age, there was a decreasing trend of the E65K polymorphism frequency that was not statistically significant. In women >54 years of age the polymorphism frequency shifted from 29.3% in normotensive to 4.8% in moderate-to-severe hypertensive women (P=0.003). Interestingly, there were 10 women >54 years of age with severe diastolic hypertension, but none of them was K-carrier. The ORs adjusted for body mass index and diabetes mellitus in the overall population, and in both sexes stratified by age, all of them with moderate-to-severe diastolic hypertension were estimated for the K allelic variant compared with the EE genotype (Figure 2). Interactions of genotype by age and genotype by sex were also tested. In the overall group of participants (OR, 0.35; 0.17 to 0.72 95% CI; P=0.004) as well as in women >54 years of age (OR, 0.18; 0.04 to 0.77 95% CI; P=0.02), the magnitude of the association was consistent with a protective effect of the K allele against moderate-to-severe diastolic hypertension. Similar logistic regression analysis applied to men >54 years of age showed a relationship between the E65K polymorphism and moderate-to-severe diastolic hypertension that did not reach statistical significance (OR, 0.46; 0.18 to 1.11 95% CI; P=0.08). Analyses of interactions in the overall group of participants demonstrated that the effect of age (P=0.006) on the protective effect of the K allele was more pronounced than sex (P=0.38). The interaction of genotype by age was also significant in women (P=0.02) and nonsignificant in men (P=0.09). Our data shows an age-dependent association between the E65K polymorphism and protection against moderate-to-severe diastolic hypertension, which is only present in women. Because our hypertensive group included subjects under antihypertensive therapy, we set out to discard a possible confounding effect of treatment on the association of E65K polymorphism with DBP. In this respect, we compared the mean values of DBP in hypertensive men and women ≥55 years of age with and without antihypertensive therapy, stratified by genotype (Figure 3). The K genetic variant was associated with a significant reduction in DBP in untreated (P<0.001) and treated (P<0.01) hypertensive women >54 years of age compared with the EE genotype. On the other hand, no significant differences in DBP were observed between genotypes in women <55 years of age and in men of any age, both treated and untreated (data for subjects <55 years of age are not shown).

Estradiol has been linked to the regulation of the BK channel activity in vascular smooth muscle cells via an indirect pathway involving the generation of NO and cGMP and via direct binding to the channel. To evaluate whether sex hormones modulate the protective effect of the E65K polymorphism, we analyzed both direct and indirect estradiol-mediated mechanisms of channel regulation in...
HEK-293 cells expressing the pore-forming α-subunit and different combinations of wild-type and mutant β1-subunits.

Changes in the activity of the BK channels were evaluated by the analysis of the conductance–voltage relationship of the ionic currents generated in cell membrane macropatches expressing the \( \alpha + \beta_{1WT} \), \( \alpha + \beta_{E65K} \), or \( \alpha + \beta_{1WT} + \beta_{E65K} \) subunits in the absence or presence of 10 \( \mu \)mol/L 17β-estradiol. From these curves, the voltage necessary to half activate the channel (\( V_{1/2} \)) can be calculated (Figure 4A). This is a convenient measure to evaluate the effect of modulators of BK channels because \( V_{1/2} \) is directly related to the energy to open the channel.22 In accordance with previous reports,20 addition of 17β-estradiol did not modify the \( V_{1/2} \) of channels formed by just α-subunits but reduced the \( V_{1/2} \) (~10 mV) of channels including the \( \beta_1 \)-subunit, although no significant differences were observed between \( \beta_{1WT} \) and \( \beta_{E65K} \)-containing BK channels.

As mentioned above, estradiol also increases the bioavailability of NO via the activation or increased expression of endothelial23 or inducible (smooth muscle) NO synthase.24 Subsequent activation of NO-dependent guanylate-cyclase will result in increased intracellular levels of cGMP and phosphorylation of BK channels via a cGMP-dependent protein kinase.19 The \( \beta_1 \)-subunit is necessary for the cGMP-dependent activation of BK channels,25 therefore, we evaluated whether the mutant \( \beta_{E65K} \) subunit behaves differently in response to the membrane-permeant db-cGMP.

Single BK channel activity obtained from cell-attached patches of HEK-293 cells expressing \( \alpha + \beta_{1WT} \), \( \alpha + \beta_{E65K} \), or \( \alpha + \beta_{1WT} + \beta_{E65K} \) subunits was measured at different voltages (only results at +80 mV are shown) and represented as the number of channels×Npo; Figure 4B through 4E). No significant differences (ANOVA) in Npo were observed between different BK channels before cGMP application, as reported previously for wild-type and mutant BK channels at intracellular Ca\(^{2+} \) levels in the low nanomole range.29 BK channels formed by α-subunits alone (Figure 4B) did not respond to 500 \( \mu \)mol/L db-cGMP, whereas the presence of \( \beta_{1WT} \) (Figure 4C), \( \beta_{E65K} \) (Figure 4D), or \( \beta_{1WT} + \beta_{E65K} \) (Figure 4E) determined a similar increase in channel activity at each voltage tested. Altogether, our electrophysiological analysis of the BK channel response to estradiol and db-cGMP showed no difference between \( \beta_{1WT} \) and \( \beta_{E65K} \) expressing patches.

In the five-year follow-up study of the first cohort, participants were personally contacted to assess possible cardiovascular events (myocardial infarction and stroke) in this period. The follow-up study showed that 17 of them had experienced a myocardial infarction event and 16 a stroke. Interestingly, only one case of myocardial infarction and none of the 16 strokes reported during the follow-up were K-carriers. Therefore, the proportion of K-carriers presenting a cardiovascular event was significantly lower compared with those free of cardiovascular disease (3% versus 24.0%; \( P=0.003 \)). Compared with EE carriers, K-carriers had a reduced hazard ratio of cardiovascular risk (0.11; 0.01 to 0.79 95% CI; \( P=0.029 \)) in a Cox regression model adjusted for age and sex. Further adjustment for hypertension status had a negligible effect on the hazard ratio (0.11; 0.01 to 0.82 95% CI; \( P=0.031 \)).
Discussion

Essential hypertension is an example of a complex, multifactorial, and polygenic disease that is sexually dimorphic \(^{26,27}\) and with higher prevalence in the elderly population. \(^{3}\) Sexual dimorphism also applied to the pathophysiology of hypertension. Experiments performed in animal models revealed that blood pressure control in males is more dependent on the renin-angiotensin system than females, \(^{28}\) an observation corroborated in a recent study demonstrating the association of the angiotensin-converting enzyme gene polymorphisms with hypertension in males but not in females. \(^{29}\) Other observations offer further support to the view that the pathophysiology of hypertension may differ in women and men. \(^{26,30}\) We recently identified a genetic variation (E65K) in the \(\beta\)-subunit (KCNMB1) of the large conductance, \(\text{Ca}^{2+}\)-dependent potassium (BK) channel that is associated with low prevalence of diastolic hypertension. \(^{9}\) Functional analysis of the mutant channel revealed a gain-of-function consistent with a more efficient feedback mechanism for the control of the vascular tone, compatible with a protective effect of this mutation against the severity of diastolic hypertension. \(^{9}\) No association between the E65K polymorphism and systolic hypertension was found. \(^{9}\) In the present study, we estimated the impact of the K allele in the population stratified by sex and age.

Our epidemiological data showed an age-dependent association between the E65K genotype and protection against moderate-to-severe diastolic hypertension, which is only present in women, although a not significant trend is also seen in men. Furthermore, a significant reduction in DBP levels was observed in untreated and treated hypertensive women >54 years of age carrying the K allele, suggesting that the protective effect of the genetic variant is not affected by antihypertensive therapy.

It has been described that in systolic hypertensive women, DBP is positively and linearly correlated with cardiovascular mortality; \(^{21}\) therefore, it would be interesting to evaluate the cardiovascular protective effect conferred by the K allele in systolic hypertensive patients. At the end of our five-year follow-up study, in the first cohort, we found a markedly reduced age- and sex-adjusted and hypertension-adjusted hazard ratio of K-carriers for myocardial infarction and stroke compared with EE homozygotes. Despite the limited numbers of events, we consider our results (only one cardiovascular event among 33 was documented in K-carriers) of special relevance for the early detection of susceptible subjects enabling prevention and tailored treatment.

Sexual dimorphism in arterial blood pressure appears in adolescence and persists throughout adulthood until the fifth decade. \(^{27}\) Accordingly, the incidence of cardiovascular diseases, including hypertension, is greater in men 30 to 50 years of age compared with women of similar age. This dimorphism could be attributed to the differences in sex hormones, \(^{4}\) environmental factors, \(^{32}\) and the sex chromosomes. \(^{33}\) On the other hand, the prevalence of hypertension in women match in women, although no conclusive evidence exists on this hypothesis.

In summary, our study provides the first genetic evidence for the different impact of the BK channel in the control of human blood pressure in men and women, with particular relevance in aging women, and highlights the E65K polymorphism as one of the strongest genetic factors associated thus far to protection against myocardial infarction and stroke.
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