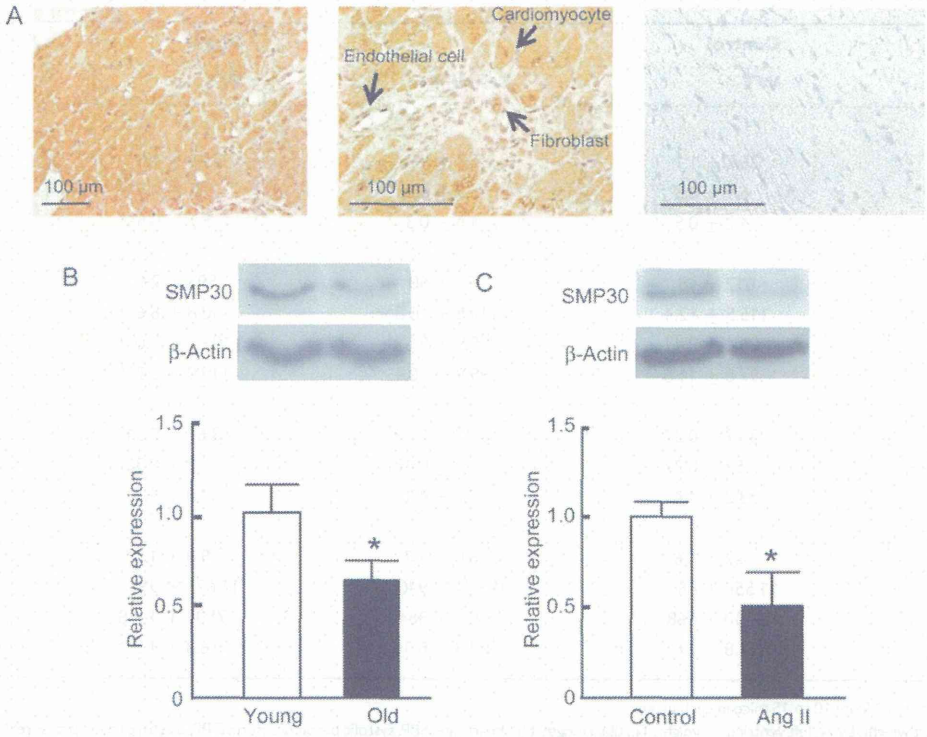

Figure 1 SMP30 expression in heart tissue. (*A*) SMP30 is expressed in cardiomyocytes, fibroblasts, and vascular endothelial cells (left, magnification ×200; middle, ×400). Right panel indicates negative control (×400). (*B*) Cardiac SMP30 expression was significantly decreased by 40% at 12-month-old WT mice (old) compared with 3-month-old WT mice (young). (*C*) Cardiac SMP30 expression was significantly decreased by 50% after Ang II infusion for 14 days in WT mice. Results are mean ± SD from 3 mice in each group. *$P < 0.05$ vs. young mice or control.

2.9 *In vivo* terminal deoxynucleotidyl transferase-mediated dUTP nick end- labellingassay

Apoptosis was detected by the terminal deoxynucleotidyl transferase-mediated dUTP nick end-labelling (TUNEL) method (CardioTACS *In Situ* Apoptosis Detection Kit, Trevigen, Inc., Gaithersburg, MD, USA) according to the manufacturer's instructions. TUNEL-positive nuclei were counted, and then expressed as a per cent of the total nuclei.[28]

2.10 Senescence-associated β-galactosidase activity

Senescence-associated β-galactosidase (SA-β-gal) staining was performed according to the manufacturer's protocol (BioVision, Inc., Mountain View, CA, USA).[29] SA-β-gal-positive cardiomyocytes were visualized as blue colour under light microscopy, and positive cells for SA-β-gal activity were counted.

2.11 Reverse transcription polymerase chain reaction

Total RNA was extracted from the snap-frozen left ventricle using TRIzol reagent (Invitrogen, Carlsbad, CA, USA).[28] Reverse transcription polymerase chain reaction (RT–PCR) was performed using the PrimeScript RT–PCR Kit (Takara Bio, Inc., Otsu, Japan) according to the manufacturer's instructions. Primers were designed on the basis of GenBank sequences (p21, NM_001111099 and β-actin, NM_007393). The optical density of the bands was quantified using the NIH imageJ software.

2.12 Statistical analysis

All data were expressed as mean ± SD. Comparisons of vitamin C levels at basal conditions between WT mice and SMP30-KO mice were performed by an unpaired *t*-test. All other parameters were evaluated by two-way analysis of variance followed by multiple comparisons with the Bonferroni test using SPSS Statistics 17.0 (SPSS Japan, Inc., Tokyo, Japan). A probability value < 0.05 was considered statistically significant.

3. Results

3.1 Vitamin C levels of the heart tissue in WT mice and SMP30-KO mice

First, we measured vitamin C levels of the heart tissue in basal conditions. To avoid vitamin C deficiency, drinking water containing sufficient vitamin C was supplied for SMP30-KO mice because SMP30-KO mice were unable to synthesize vitamin C due to the lack of gluconolactonase.[10] The tissue concentrations of the vitamin C level were not significantly different between WT mice and SMP30-KO mice (45.7 ± 7.0 vs. 44.5 ± 10.2 μg/g tissue).

3.2 SMP30 expression in the heart tissue

Immunostaining revealed that SMP30 was expressed in cardiomyocytes, fibroblasts, and vascular endothelial cells in WT mice on the basis of cellular morphological characteristics (*Figure 1A*).[30] We confirmed the decrease in SMP30 expression with ageing in the WT mouse heart as

Table 1 Gravimetric and hemodynamic data of WT and SMP30-KO mice

	Control		Ang II	
	WT	SMP30-KO	WT	SMP30-KO
Gravimetric data				
BW, g	26.7 ± 1.1	27.8 ± 1.6	25.6 ± 1.5	27.2 ± 2.2
HW/TL, mg/mm	6.1 ± 0.6	6.5 ± 0.5	7.5 ± 0.6**	8.4 ± 1.0**,†
LVW/TL, mg/mm	4.2 ± 0.5	4.6 ± 0.3	5.7 ± 0.5**	6.7 ± 0.9**,††
Telemetry blood pressure				
HR, b.p.m.	612 ± 48	627 ± 50	593 ± 24	607 ± 65
SBP, mmHg	115.5 ± 12.4	114.8 ± 10.8	140.8 ± 8.6**	144.1 ± 13.7**
DBP, mmHg	85.1 ± 9.4	89.9 ± 9.6	129.4 ± 7.0**	128.6 ± 10.6**
MAP, mmHg	97.8 ± 11.6	99.9 ± 10.4	119.0 ± 6.2**	115.2 ± 9.7**
Echocardiography				
LVEDD, mm	3.77 ± 0.37	3.77 ± 0.38	3.68 ± 0.31	4.26 ± 0.21**,††
LVESD, mm	2.52 ± 0.32	2.42 ± 0.42	2.52 ± 0.35	3.12 ± 0.33**,††
FS, %	33.2 ± 4.4	33.7 ± 4.1	31.8 ± 4.7	25.9 ± 5.2**,††
Catheterization				
LVEDP, mmHg	5.2 ± 1.6	6.0 ± 1.7	9.8 ± 1.0*	11.7 ± 3.0**
max dP/dt, mmHg/s	11 556 ± 850	10 977 ± 940	11 675 ± 999	7303 ± 1107**,††
min dP/dt, mmHg/s	8140 ± 668	8247 ± 384	7582 ± 1408	4804 ± 1897*,†
Tau, ms	4.8 ± 2.0	4.3 ± 0.3	6.3 ± 1.9**	8.3 ± 1.9**

Data are presented as mean ± SD from 10 to 15 mice in each group.
BW, body weight; HW, heart weight; LVW, left ventricular weight; TL, tibial length; HR, heart rate; SBP, systolic blood pressure; DBP, diastolic blood pressure; MAP, mean arterial pressure; LVEDD, left ventricular end-diastolic dimension; LVESD, left ventricular end-systolic dimension; FS, fractional shortening; LVEDP, left ventricular end-diastolic pressure; max and min dP/dt, maximal and minimal rates of left ventricular pressure development, respectively; Tau, time constant of left ventricular isovolumic relaxation.
*$P < 0.05$ and **$P < 0.01$ vs. control in the same strain mice; †$P < 0.05$ and ††$P < 0.01$ vs. Ang II-infused WT mice.

described previously in other organs.[4] Cardiac SMP30 was significantly decreased by 40% at 12-month-old WT mice compared with 3-month-old WT mice ($P < 0.05$, *Figure 1B*). Additionally, cardiac expression of SMP30 was significantly decreased by 50% after Ang II infusion for 14 days in 3-month-old WT mice, suggesting that the expression of SMP30 may alter in cardiovascular diseases ($P < 0.05$, *Figure 1C*).

3.3 Effect of SMP30 deficiency on Ang II-induced cardiac hypertrophy and fibrosis

As shown in *Table 1*, heart weight (HW) and left ventricular weight (LVW) corrected by the tibial length (TL) were similar between control WT mice and SMP30-KO mice. After Ang II infusion, the ratios of HW to TL and LVW to TL were significantly higher in SMP30-KO mice than in WT mice ($P < 0.05$ and $P < 0.01$, respectively), although the blood pressure was similarly elevated in both Ang II-infused WT mice and SMP30-KO mice by telemetry blood pressure monitoring (*Table 1*).

Histological examination showed that Ang II-infused SMP30-KO mice had substantial left ventricular hypertrophy with left ventricular dilatation compared with Ang II-infused WT mice, which suggested eccentric hypertrophy in Ang II-infused SMP30-KO mice compared with concentric hypertrophy in Ang II-infused WT mice (*Figure 2A*, top). The cardiomyocyte cross-sectional area was significantly larger in Ang II-infused SMP30-KO mice than in Ang II-infused WT mice (399 ± 17 vs. 372 ± 11 μm^2, $P < 0.01$, *Figure 2A*, middle and *B*). Additionally, *ex vivo* analysis demonstrated that cell width, length, and surface area of isolated cardiomyocytes were significantly greater in SMP30-KO mice than in WT mice after Ang II stimulation (Supplementary material online, *Figure S1*). The degree of cardiac fibrosis was significantly higher in Ang II-infused SMP30-KO mice than in Ang II-infused WT mice (6.4 ± 0.8 vs. 7.5 ± 0.7%, $P < 0.01$, *Figure 2A*, bottom and *C*). These data revealed that the deficiency of SMP30 exacerbates Ang II-induced cardiac hypertrophy and fibrosis, independently of blood pressure.

3.4 Effect of SMP30 deficiency on Ang II-induced cardiac dysfunction

As shown in *Table 1*, there were no differences in cardiac function between WT mice and SMP30-KO mice under basal conditions. Echocardiography showed that left ventricular end-diastolic and end-systolic dimensions were enlarged and fractional shortening was reduced in SMP30-KO mice compared with WT mice at 14 days after Ang II infusion ($P < 0.01$, *Table 1* and Supplementary material online, *Table S1* and *Figure S2*, top). The left ventricular mass was greater in Ang II-infused SMP30-KO mice than in Ang II-infused WT mice, which was concordant with the histological findings ($P < 0.01$). Ang II-infused SMP30-KO mice had significantly higher peak E velocity, *E/A*, and *E/E′* compared with Ang II-infused WT mice (Supplementary material online, *Table S1* and *Figure S2*, middle and bottom). The mitral inflow showed the restrictive pattern in Ang II-infused SMP30-KO mice in contrast to the relaxation abnormality pattern or the pseudo-normalization pattern in Ang II-infused WT mice. These echocardiographic data revealed that left ventricular systolic and diastolic functions were remarkably depressed in SMP30-KO mice compared with WT mice after Ang II infusion.

Haemodynamic assessment by cardiac catheterization showed that max dP/dt and min dP/dt were significantly lower in SMP30-KO mice than in WT mice after Ang II infusion ($P < 0.01$ and $P < 0.05$,

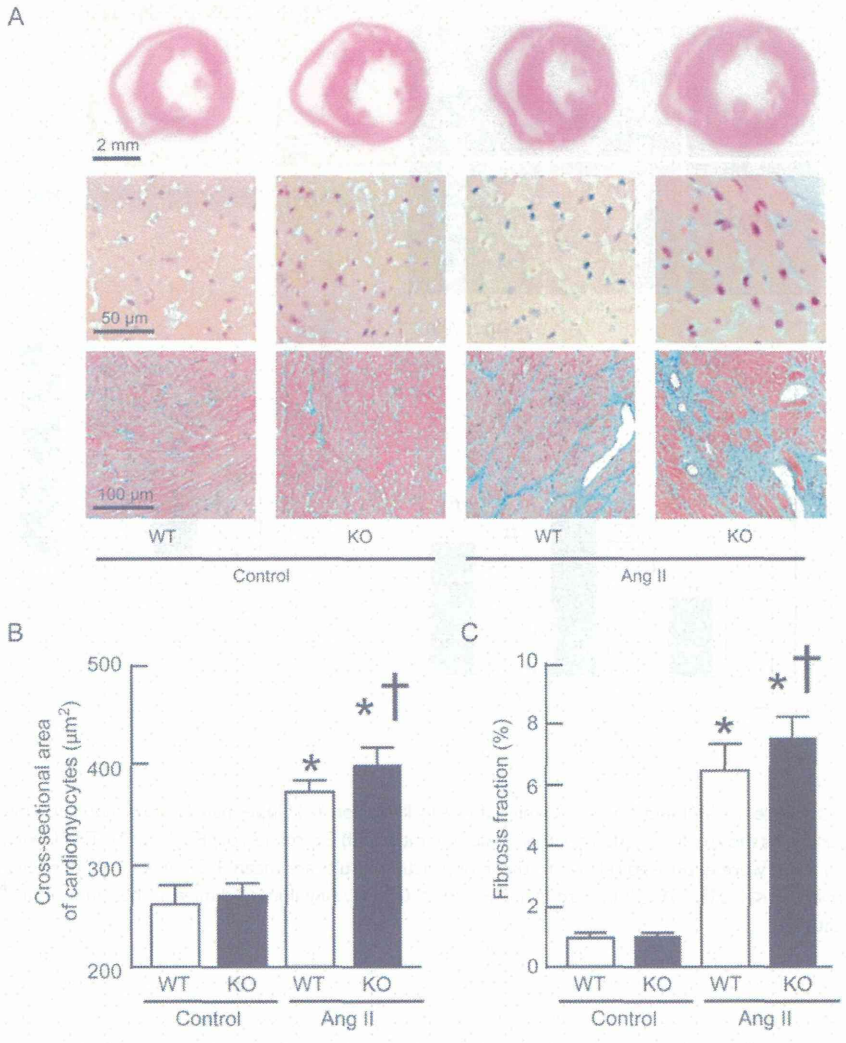

Figure 2 Cardiac hypertrophy and fibrosis in WT and SMP30-KO mice after Ang II infusion. (*A*) Representative images of light micrographs of hearts from WT and SMP30-KO mice with and without Ang II infusion (top). Haematoxylin and eosin staining of myocardial cross-sections (middle). Elastica-Masson staining of myocardial sections (bottom). (*B*) Quantitative analysis of the cross-sectional area of cardiomyocytes from the left ventricle. (*C*) The per cent area of myocardial interstitial fibrosis in the left ventricle. Data are presented as mean ± SD from 6 to 8 mice in each group. $^{*}P < 0.01$ vs. control in the same strain mice; $^{\dagger}P < 0.01$ vs. Ang II-infused WT mice.

respectively), supporting that cardiac systolic and diastolic functions were more severely depressed in SMP30-KO mice (*Table 1*).

3.5 Effect of SMP30 deficiency on Ang II-induced myocardial oxidative stress

We examined myocardial oxidative stress by DHE staining which indicates the O_2levels of living cells because oxidative stress is considered to be one of the important mechanisms of heart failure and cardiac remodelling. Although Ang II infusion dramatically increased the ROS generation in both WT mice and SMP30-KO mice, the ROS generation in Ang II-infused SMP30-KO mice was significantly greater than in Ang II-infused WT mice ($P < 0.01$, *Figure 3A*). In addition, we found that the level of superoxide generation was significantly decreased in Ang II-infused WT mice with apocynin treatment, compared with that of Ang II-infused WT mice without apocynin treatment ($P < 0.01$, *Figure 3A*). As well as WT mice, SMP30-KO mice revealed that Ang II-induced superoxide generation was significantly down-regulated by apocynin treatment ($P < 0.01$, *Figure 3A*).

To investigate the involvement of NADPH oxidase in Ang II-induced ROS generation, we examined the expression of $p67^{phox}$ subunit of NADPH oxidase by western blotting. The expression levels of $p67^{phox}$ were significantly elevated in Ang II-infused SMP30-KO mice compared with Ang II-infused WT mice ($P < 0.01$, *Figure 3B*). These data suggested that the deficiency of SMP30 increased Ang II-induced myocardial oxidative stress via up-regulation of NADPH oxidase.

3.6 Effect of SMP30 deficiency on Ang II-induced apoptosis

As previously demonstrated, SMP30 has anti-apoptotic effects in other organs.[11] We, therefore, checked apoptosis using TUNEL staining

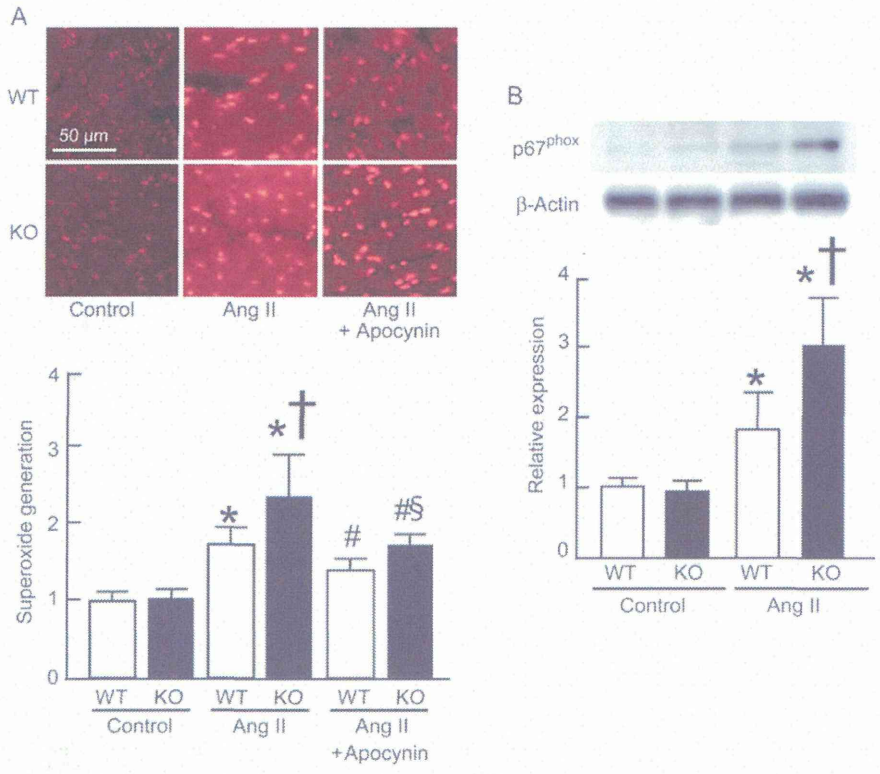

Figure 3 Myocardial oxidative stress in WT and SMP30-KO mice after Ang II infusion. (*A*) Upper panels show representative DHE staining of frozen left ventricular tissues. Lower bar graphs show quantification of superoxide generation. (*B*) Expression of $p67^{phox}$ of NADPH oxidase subunits was analysed by western blotting. Expression levels were expressed relative to those of β-actin. Results are mean ± SD from 6 to 10 mice in each group. $^{*}P < 0.01$ vs. control in the same strain mice; $^{\dagger}P < 0.01$ vs. Ang II-infused WT mice. $^{\#}P < 0.05$ vs. Ang II-infused mice in the same strain; $^{\S}P < 0.05$ vs. Ang II-infused WT mice with apocynin treatment.

(*Figure 4A*). After Ang II infusion, the numbers of TUNEL-positive nuclei including cardiomyocytes and non-cardyomyocytes were increased in both WT and SMP30-KO mice. The numbers of TUNEL-positive nuclei in Ang II-infused SMP30-KO mice were remarkably greater than in Ang II-infused WT mice, as shown in *Figure 4A* ($P < 0.01$).

Then, we examined signalling pathways of Ang II-induced apoptosis in the heart. Caspase-3 is a key mediator of apoptosis, and activation of caspase-3 leads to DNA injury and subsequently apoptotic cell death.[31] The activation of caspase-3 was induced by Ang II infusion in both WT and SMP30-KO mice, and the activation of caspase-3 in Ang II-infused SMP30-KO mice was significantly greater than in Ang II-infused WT mice ($P < 0.01$, *Figure 4B*). After Ang II infusion, Bax expression which functions as pro-apoptotic protein was increased, whereas the expression of anti-apoptotic protein Bcl-2 was decreased in both genotypes of mice. The ratio of Bax to Bcl-2 was significantly higher in Ang II-infused SMP30-KO mice than in Ang II-infused WT mice ($P < 0.01$, *Figure 4C*). Furthermore, we examined the involvement of SAPK/JNK which has a crucial role in cell apoptosis as one main subgroup of the mitogen-activated protein kinase family.[32] Phosphorylation activity of SAPK/JNK in Ang II-infused SMP30-KO mice was significantly increased compared with Ang II-infused WT mice ($P < 0.01$, *Figure 4D*). These findings demonstrated that SMP30 deficiency exacerbates Ang II-induced apoptosis through these signalling pathways.

3.7 Expression of senescence markers in SMP30-KO mice after Ang II infusion

Senescent cells can be identified by the expression of enzymatic SA-β-gal activity in left ventricular tissues (*Figure 5A*). SA β-gal activity was induced by Ang II stimulation. The numbers of SA β-gal-positive cells were significantly greater in Ang II-infused SMP30-KO mice than in Ang II-infused WT mice (1.7 ± 0.8 vs. $0.6 \pm 0.5/mm^3$, $P < 0.01$) as demonstrated in *Figure 5A*.

To evaluate the gene expression of cell cycle inhibitor to confirm senescence of cardiomyocytes, we analysed mRNA expression of p21 gene by RT–PCR (*Figure 5B*). Following Ang II infusion, the expression levels of p21 mRNA were increased in both WT mice and SMP30-KO mice. Compared with Ang II-infused WT mice, Ang II-infused SMP30-KO mice showed a significant increase in p21 expression ($P < 0.01$). These results indicate that deficiency of SMP30 induced cellular senescence after Ang II infusion by the p21-dependent pathway.

4. Discussion

Previous studies have shown that SMP30 acts as an anti-ageing factor, and SMP30 prevents oxidative stress and apoptosis in the liver, lungs, and brain.[11,13,14] However, the role of SMP30 in the heart has not

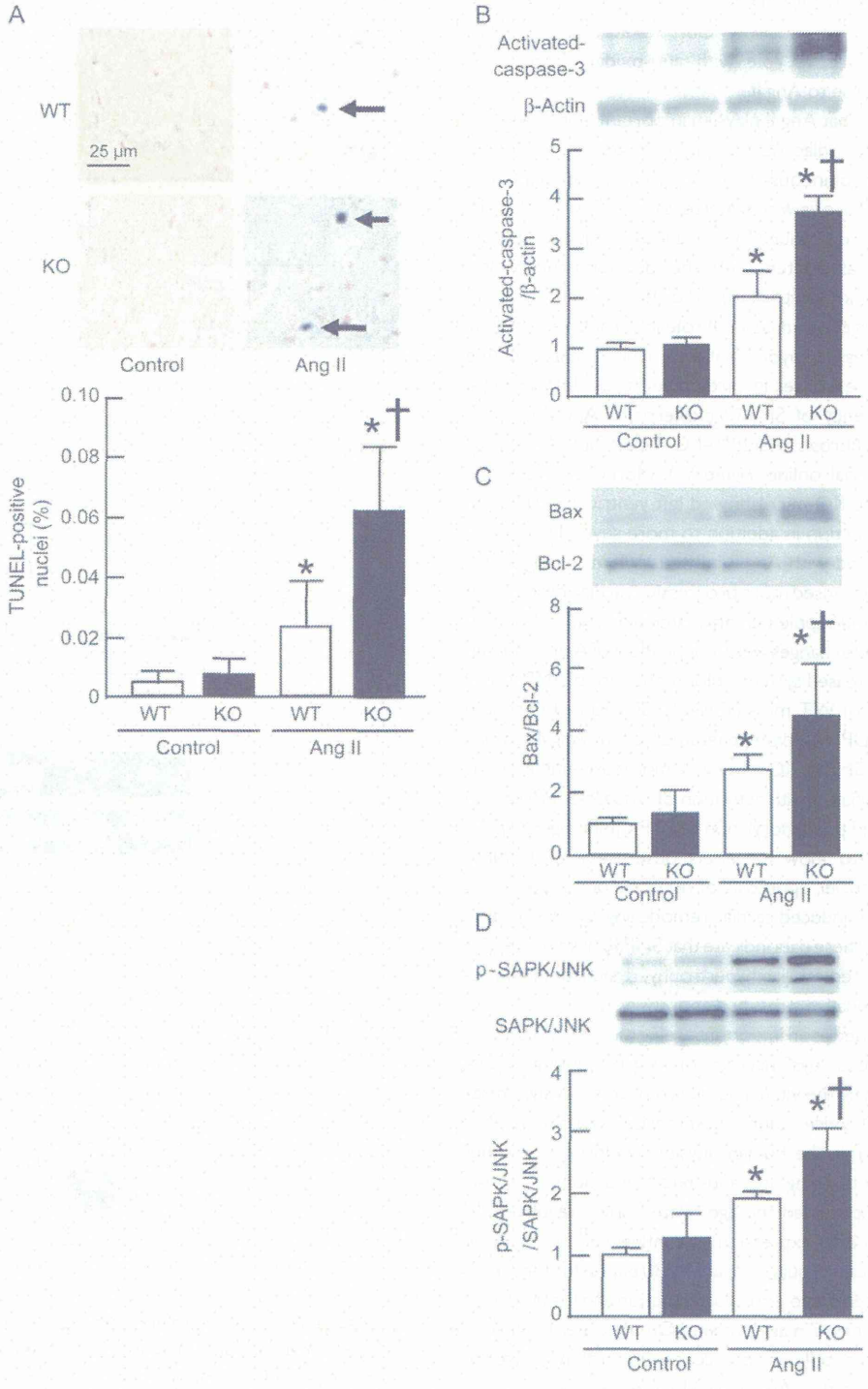

Figure 4 Apoptosis and apoptotic signalling pathways in WT and SMP30-KO mice after Ang II infusion. (*A*) Upper panels show representative images of TUNEL staining of left ventricular tissue sections. Lower bar graph shows the per cent of TUNEL-positive nuclei. (*B*) Activation of caspase-3 was examined by western blotting with anti-activated-caspase-3 antibody using myocardial samples. Expression levels of activated-caspase-3 were normalized by β-actin. (*C*) Expressions of Bax and Bcl-2 were analysed by western blotting. The Bax to Bcl-2 ratio was calculated and presented in the bar graph. (*D*) Phosphorylation activity of SAPK/JNK. Expressions of phosphorylated and total SAPK/JNK were analysed by western blotting. Relative expression levels of phosphorylated SAPK/JNK (P-SAPK/JNK) were expressed in relation to those of SAPK/JNK. Results are mean ± SD from 6 to 10 mice in each group. $^{*}P < 0.01$ vs. control in the same strain mice; $^{\dagger}P < 0.01$ vs. Ang II-infused WT mice.

been investigated. In this study, we demonstrated the first evidence that deficiency of SMP30 exacerbates Ang II-induced cardiac hypertrophy, dysfunction, and adverse remodelling. Our results revealed that SMP30 has a cardio-protective role with anti-oxidative and anti-apoptotic effects in response to Ang II.

It has been well known that Ang II plays an important role in the development of pathological cardiac hypertrophy, remodelling, and subsequent heart failure.[33] Subcutaneous chronic infusion of Ang II induces cardiac hypertrophy and fibrosis with hypertension.[18,34] Ang II also stimulates NADPH oxidase to produce ROS,[35] and consequent myocardial oxidative stress is associated with the development of left ventricular remodelling and heart failure.[36] Furthermore, it has been considered that apoptosis plays an adverse role in cardiac remodelling and contributes to progressive myocardial dysfunction[37] and that Ang II exaggerates apoptotic responses in cardiomyocytes.[38] Interestingly, we observed that deficiency of SMP30 exacerbates Ang II-induced cardiac hypertrophy and fibrosis in SMP30-KO mice (*Table 1*, *Figure 2*, and Supplementary material online, *Figure S1*). Moreover, we found that Ang II-infused SMP30-KO mice showed left ventricular dilatation and depressed systolic function in addition to more severely impaired diastolic function compared with Ang II-infused WT mice, suggesting that the absence of SMP30 caused more progressive cardiac dysfunction and remodelling (*Table 1* and Supplementary material online, *Table S1* and *Figure S2*). These remarkable changes were independent of Ang II-induced hypertension because increased systemic blood pressure of SMP30-KO mice was similar to that of WT mice (*Table 1*). SMP30-KO mice had much more elevated NADPH oxidase-generated ROS by Ang II stimulation (*Figure 3*). In addition, SMP30-KO mice were more susceptible to Ang II-induced apoptosis associated with activation of caspase-3, increase in Bax, decrease in Bcl-2, and phosphorylation of SAPK/JNK (*Figure 4*). Although we were unable to show the direct observation of TUNEL-positive cardiomyocyte nuclei, apoptosis of non-cardiomyocytes plays an important role in Ang II-induced cardiac remodelling and dysfunction as previously reported.[39] These data indicate that SMP30 has a protective role against Ang II-associated cardiac hypertrophy, dysfunction, and remodelling by inhibiting oxidative stress and apoptosis.

SMP30 has been proposed as an important ageing marker, and the lack of SMP30 causes various dysfunctions of organs during ageing process.[11,13–15] Concerning the vitamin C biosynthesis pathway, similar to humans, SMP30-KO mice cannot synthesize vitamin C and SMP30-KO mice may mimic the human physiology closer than other rodents.[40] The potent anti-ageing and anti-oxidative actions of a low-calorie diet effectively suppressed the age-related down-regulation of SMP30, indicating that SMP30 expression was influenced by oxidative stress.[41] These previous reports suggest that SMP30 expression accounts for the age-associated deterioration of cellular function and the enhanced susceptibility to harmful stimuli in aged tissues. On the other hand, very few reports demonstrated cellular senescence of cardiomyocytes *in vivo*.[42,43] We demonstrated that Ang II could increase senescent cells detected by SA β-gal activity *in vivo*. Importantly, Ang II-induced cellular senescence was accompanied with markedly elevated p21 gene expression. SMP30-KO mice showed significantly increased SA β-gal-positive cells with elevated expression of p21 gene by Ang II stimulation, indicating that SMP30 inhibits premature cellular senescence through the signalling pathway of p21 in response to Ang II (*Figure 5*).

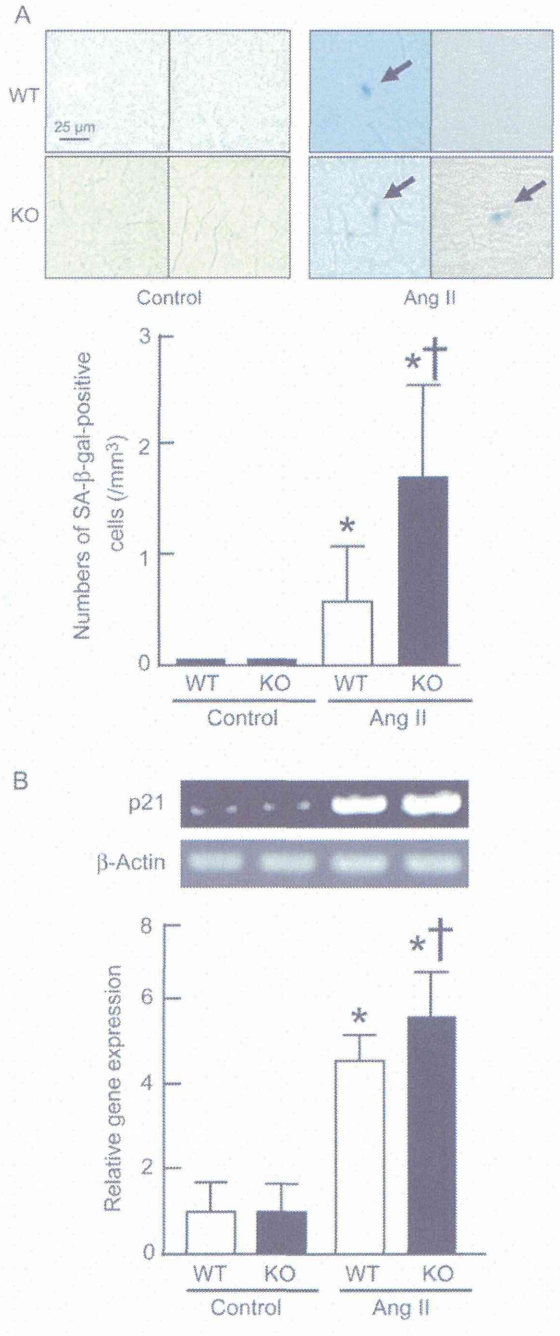

Figure 5 Senescence markers in hearts of WT and SMP30-KO mice after Ang II infusion. (*A*) Senescent cells were detected by SA β-gal staining of left ventricular tissue sections, and the numbers of SA β-gal-positive cells were counted. (*B*) The mRNA expression levels of p21 gene were analysed by RT–PCR. Expression levels of p21 gene were normalized by β-actin. Results are mean ± SD from 6 to 8 mice in each group. *$P < 0.01$ vs. control in the same strain mice; †$P < 0.01$ vs. Ang II-infused WT mice.

There were no differences between WT mice and SMP30-KO mice under basal conditions at 12- to 16-week-old, but we observed that 12-month-old SMP30-KO mice showed exaggerated left ventricular hypertrophy, diastolic dysfunction, and myocardial fibrosis compared with 12-month-old WT mice (Supplementary material online, *Table S2*). One central role of SMP30 in the heart is considered to be the suppressive effect of ROS generation by inhibiting NADPH oxidase activation, as demonstrated in the present study (*Figure 3*). The suppressive role of SMP30 in oxidative stress contributes to the reduction of senescent marker expressions, suggesting that SMP30 prevents myocardial dysfunction from various stresses such as Ang II stimulation and ageing (Supplementary material online, *Figure S3*). Since detailed mechanisms have not been fully clarified, we should evaluate the cellular compartment specific effects of SMP30 in the future study.

5. Conclusions

In summary, deficiency of SMP30 adversely modifies Ang II-induced cardiac hypertrophy and remodelling through increase in oxidative stress and progression of apoptosis. These data provide that SMP30 has a protective role in cardiac remodelling and up-regulation of SMP30 could be a therapeutic target for treatment of heart failure.

Supplementary material

Supplementary material is available at *Cardiovascular Research* online.

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EDITORIAL COMMENTARY

Electrical vagal stimulation and cardioprotection

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When you think of increased vagal tone and its effect on heart rhythm, what comes to mind first is how it slows heart rate and causes atrial fibrillation (AF) with ease, even in the presence of a normal substrate. Paradoxically, it has also been shown that low-level (LL) vagus nerve stimulation (VNS) can decrease AF.[1,2] Clinical[3] and experimental studies[4] have demonstrated that VNS associated with a decrease in heart rate (HR) can also benefit ventricular function. However, much less is known about LL-VNS, when changes in HR are small. This is what, in part, motivated the study by Shinlapawittayatorn et al[5] reported in this issue of Heart*Rhythm,* which focuses on the ventricular benefits of LL-VNS during ischemia reperfusion (I/R).

Main findings

Shinlapawittayatorn et al[5] report several important findings related to the benefits of LL-VNS during I/R. In vivo experiments were performed using swine that underwent left anterior descending artery occlusion (60 minutes), followed by reperfusion (120 minutes). LL-VNS was performed throughout by stimulating the left cervical vagus at a strength that had little to no affect on HR. It is important to note that continuous and intermittent LL-VNS were evaluated. The authors report that LL-VNS during I/R attenuated infarct size, improved ventricular function, and caused a rather dramatic reduction in ventricular tachycardia/ventricular fibrillation (VT/VF) episodes. The functional benefits of VNS have been shown previously,[3,6] but what is interesting from the present study is that similar benefits are reported during LL-VNS in the absence of any significant change in HR. Finally, what might be most interesting to readers is that VT/VF episodes were markedly reduced. Spinal cord stimulation, which can increase vagal tone and decrease sympathetic tone, was shown to reduce ventricular arrhythmias in canines with myocardial infarction.[7] Moreover, Vanoli et al[4] showed that VNS provided significant protection against VF in an animal model of acute myocardial ischemia. Even though HR reduction is often associated with ventricular benefits, in the study by Vanoli et al,[4] protection from VF also was observed during constant atrial pacing, suggesting that reduced HR is not a requirement.

What is the mechanism of reduced VT/VF?

From an electrophysiologic point of view, one of the more interesting questions raised in the study by Shinlapawittayatorn et al[5] is how LL-VNS decreased VT/VF episodes. Like the study by Vanoli et al,[4] reduced HR is not necessary to explain the reduction of arrhythmia vulnerability. VT/VF episodes could be related to the occurrence of premature ventricular complexes (PVCs) (triggers), which, for the most part, was similar. However, it is interesting that with intermittent VNS (with or without atropine), VT/VF during reperfusion did not mirror PVC occurrence. Thus, LL-VNS may be modifying the electrophysiologic substrate in several ways in addition to suppressing triggers (PVCs). VNS can also antagonize sympathetic outflow to the heart, which has well-known proarrhythmic action. Such may be the mechanism whereby LL-VNS can suppress AF. For example, Shen et al[8] showed that left-sided LL-VNS can suppress stellate ganglion nerve activity (LSGNA) immediately and cause neuronal remodeling over time.

There is some evidence that suppression of LSGNA can improve ventricular function[9] and, possibly, suppress ventricular arrhythmias. Gao et al[10] showed that pretreatment with electro-acupuncture can protect against ventricular arrhythmias during I/R due to inhibition of beta-adrenergic signaling and the L-type calcium channel. In addition, reduced LSGNA may attenuate reverse mode activation of the Na^+/Ca^{2+} exchanger, which has been associated with stimulation of $alpha_1$-adrenergic receptors during I/R.[11] These results suggest that reduced LSGNA may prevent arrhythmias during I/R that are due to calcium overload. There are several other possibilities whereby LL-VNS may modify the electrophysiologic substrate, such as that related to reduced reactive oxygen species (ROS)[12,13] (as shown in the present study) or even by preserving myocardial connexin43 expression.[14] Unfortunately, these mechanistic pathways are all speculative, and there is no clear reason

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why LL-VNS decreased VT/VF, as observed in the present study. Of course, one simple explanation is that LL-VNS modified the structural substrate by reducing infarct size, which, from wavelength theory, could explain the reduction of VT/VF episodes observed.

What caused the decrease in infarct size?

Shinlapawittayatorn et al[5] report a significant decrease in infarct size with LL-VNS. This is paralleled by an attenuation of mitochondrial ROS, depolarization, and swelling, all of which may reduce apoptosis. Others have shown that VNS can inhibit the release of proapoptotic signals associated with mitochondria dysfunction and, thus, attenuate cardiac injury.[15] Alternatively, Calvillo et al[16] described the antiinflammatory and antiapoptotic properties of the nicotinic pathway as the primary mechanism underlying VNS-induced decrease in infarct size during cardiac I/R. However, this action by the nicotinic pathway was partial. Therefore, the present study provides some interesting insight regarding the role of muscarinic (ie, atropine sensitive) LL-VNS activation in the reduction of infarct size during I/R. Finally, infarct size during I/R can be reduced by inhibition of inflammasome activation in cardiac fibroblasts.[17] Given that ROS can activate inflammasomes (eg, NLRP3),[18] then this may also be a mechanism by which LL-VNS reduced infarct size, as observed in the present study.

Clinical implications

Independent of the potential causal relationships discussed, the findings reported by Shinlapawittayatorn et al[5] have important clinical implications. First, the results of this study suggest that LL-VNS may be an effective therapeutic strategy for preventing the loss of ventricular function and increased VF episodes that are associated with I/R. Given that VNS is a safe and efficacious treatment of neurologic disorders (eg, seizure prevention and control), utilization for cardioprotection may be emerging. Second, the benefits are achieved by stimulating the left cervical vagus rather than the right. This is ideal because of the greater number of cardiac efferent fibers from the right vagus nerve, including innervation of the sinoatrial node. Accordingly, altered heart rate and other possible undesirable consequences can be avoided. Third, intermittent LL-VNS performed better than continuous. Continuous LL-VNS may have caused tachyphylaxis, which sometimes can result from a marked reduction in the amount of acetylcholine. Alternatively, this can be explained by desensitization of receptors available to acetylcholine, which occurs in response to saturation.[19] In contrast, intermittent LL-VNS seems to not exhibit tachyphylaxis.

Summary

You may be scratching your head and be a bit disappointed if you crave a mechanistic understanding of why LL-VNS decreased VT/VF episodes. However, this does not diminish the potential clinical implications of the findings reported by Shinlapawittayatorn et al.[5] LL-VNS may be an important treatment strategy to prevent VF/VT episodes and preserve ventricular function during acute ischemia. If this can be achieved without undesirable consequences associated with VNS, then this approach could have a significant impact on patients with ischemic heart disease.

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