Sunitinib inhibits catecholamine synthesis and secretion in pheochromocytoma tumor cells by blocking VEGF receptor 2 via PLC-γ-related pathways

Yuichi Aita,1 Kiyo-aki Ishii,2 Yuria Saito,1 Tatsuhiko Ikeda,3 Yasushi Kawakami,1 Hitoshi Shimano,2 Hisato Hara,3 and Kazuhiro Takekoshi1

1Department of Molecular Laboratory Medicine, Graduate School of Comprehensive Human Sciences, University of Tsukuba, Ibaraki, Japan; 2Department of Internal Medicine (Endocrinology and Metabolism), Graduate School of Comprehensive Human Sciences, University of Tsukuba, Ibaraki, Japan; and 3Department of Breast-Thyroid-Endocrine Surgery, Graduate School of Comprehensive Human Sciences, University of Tsukuba, Ibaraki, Japan

Submitted 27 March 2012; accepted in final form 15 August 2012

Sunitinib inhibits catecholamine synthesis and secretion in pheochromocytoma tumor cells by blocking VEGF receptor 2 via PLC-γ-related pathways. Sunitinib inhibits catecholamine synthesis and secretion in pheochromocytoma tumor cells by blocking VEGF receptor 2 via PLC-γ-related pathways. Sunitinib inhibits catecholamine synthesis and secretion in pheochromocytoma tumor cells by blocking VEGF receptor 2 via PLC-γ-related pathways.

Sunitinib is a rationally designed, oral, small molecule multitargeted receptor tyrosine kinase (RTK) inhibitor with antiangiogenic and antitumor activity that targets platelet-derived growth factor receptors (PDGFRs), vascular endothelial growth factor receptors (VEGFRs), stem cell factor receptor (c-Kit), colony stimulating factor 1 receptor (CSF-1R), and fms-related tyrosine kinase 3 (Flt-3) (1, 2, 9, 13, 19, 21, 32, 43). It has been well established that sunitinib suppresses tumor angiogenesis mainly through VEGFR-2 (KDR/Flk-1), which is expressed on endothelial cells and is known to play a critical role in angiogenesis (9, 13, 19). In addition, sunitinib is reported to have direct antiproliferative and/or apoptotic effects on tumor cells, which express target RTKs (22, 33, 39).

It was previously shown that, unlike other representative RTKs, VEGFR-2 utilizes the phospholipase C (PLC)-γ/protein kinase C (PKC) activity and catecholamine secretion in PC-12 cells and the underlying mechanisms. Sunitinib inhibited TH activity in a dose-dependent manner, and decreased TH protein levels. Consistent with this finding, sunitinib decreased TH phosphorylation at Ser31 and Ser40 and significantly decreased catecholamine secretion. VEGFR-2 knockdown attenuated these effects, including inhibition of TH activity and catecholamine secretion, suggesting that they were mediated by VEGFR-2. Sunitinib significantly decreased phospholipase C (PLC)-γ phosphorylation and subsequent protein kinase C (PKC) activity. Because Ser40 phosphorylation significantly affects TH activity and is known to be regulated by PKC, sunitinib may inhibit Ser40 phosphorylation via the VEGFR-2/PLC-γ/PKC pathway. Additionally, sunitinib markedly decreased the activity of extracellular signal-regulated kinase (ERK), but not c-Jun NH2-terminal kinase or p38 mitogen-activated protein kinase. Therefore, sunitinib may reduce TH Ser31 phosphorylation through inhibition of the VEGFR-2/PLC-γ/PKC/Raf/mitogen-activated protein kinase/extracellular signal-regulated kinase (ERK) pathway as the major signaling pathway. In contrast, Ras is poorly activated in VEGFR-2-related signaling pathways (40, 41).

Advanced-stage malignant pheochromocytomas are resistant to conventional therapy, such as radiation therapy and chemotherapy. However, based on three very recent reports, sunitinib appears to be useful for the treatment of malignant pheochromocytomas (15, 25, 26). Pheochromocytomas often display hypervascularity (5, 14, 27, 35). Therefore, it is reasonable to speculate that inhibition of angiogenesis could be a rational therapeutic target in these tumors, probably through a logical mechanism of action similar to that in other hypoxia-inducible tumors, such as renal cell carcinoma.

However, the antitumor effects of sunitinib in malignant pheochromocytomas have not been clearly established. In particular, it is unclear whether sunitinib acts primarily through only antiangiogenic mechanisms or also directly targets tumor cells. Recent studies revealed that sunitinib markedly reduced plasma catecholamine levels in patients with pheochromocytomas (15, 25, 26). This inhibitory effect of sunitinib on catecholamine strongly suggests the possibility that sunitinib may have direct inhibitory effects on catecholamine synthesis and secretion. To support this, we recently demonstrated that sunitinib directly induced apoptosis through inhibition of the protein kinase B (Akt)/mammalian target of rapamycin (mTOR)/ribosomal protein S6 kinase 1 (S6K1) pathway in PC-12 cells. Additionally, it is of note that VEGFR-2 silencing attenuated these sunitinib-induced effects, indicating that sunitinib exerts its effects through VEGFR-2 (36).

Tyrosine hydroxylase (TH) is a rate-limiting enzyme in the biosynthesis of catecholamine. TH activity is regulated by both short- and long-term mechanisms. Short-term regulation occurs at the posttranslational level. Central to this regulation is...
the phosphorylation of TH, which results in enzyme activation (4, 8, 10, 16, 17, 45). Indeed, TH is phosphorylated and activated by a variety of protein kinases, although phosphorylation of only three serine residues (Ser<sup>19</sup>, Ser<sup>31</sup>, and Ser<sup>40</sup>) is regulated in vivo. The most likely physiological candidates for the phosphorylation of TH at Ser<sup>19</sup>, Ser<sup>31</sup>, and Ser<sup>40</sup> are Ca<sup>2+</sup>/calmodulin-dependent protein kinase II, ERK, and protein kinase A/PKC, respectively. However, only phosphorylation at Ser<sup>40</sup> has a major effect on TH activity. In addition to the short-term regulation of TH activity, long-term control occurs at the transcriptional level (6, 20, 29). Mobilization of Ca<sup>2+</sup> in chromaffin cells is important for the induction of catecholamine secretion. One important mechanism for intracellular Ca<sup>2+</sup> ([Ca<sup>2+</sup>]<sub>i</sub>) regulation is the release of Ca<sup>2+</sup> from intracellular storage sites mediated by inositol 1,4,5-trisphosphate (IP<sub>3</sub>) formation following PLC-γ activation (12, 18).

The aim of the present study was to determine whether sunitinib directly inhibits catecholamine synthesis and/or secretion in undifferentiated PC-12 cells, which are a well-established experimental model of pheochromocytoma. However, it is known that PC-12 cells do not accurately reflect the pathogenesis of malignant cells. Recently, certain neural crest-derived tumors, such as pheochromocytoma and neuroblastoma, were reported to have common genetic background (37, 38). Therefore, we confirmed the effects of sunitinib in a human neuroblastoma cell line, SK-N-SH. An additional objective of this study was to clarify the mechanisms underlying sunitinib-mediated inhibition of catecholamine synthesis and/or secretion in these cells.

MATERIALS AND METHODS

Reagents. Unless otherwise noted, all reagents were purchased from Wako Pure Chemical Industries (Osaka, Japan). Sunitinib was a gift from Pfizer.

Cell culture. The PC-12 cell line (RCB0099) was obtained from the RIKEN Cell Bank (Ibaraki, Japan). The cells were grown in DMEM (Invitrogen) containing 10% horse serum (Invitrogen) and 10% FBS (Invitrogen) in a humidified atmosphere of 5% CO<sub>2</sub> and 95% O<sub>2</sub> at 37°C. The human neuroblastoma cell line SK-N-SH (RCB0426) was obtained from the RIKEN Cell Bank. The cells were maintained in minimal essential medium-a (Invitrogen) containing 10% FBS.

TH activity. TH activity was measured using the method previously reported (3). Cells were incubated with either dimethyl sulfoxide (DMSO) (control) or sunitinib at 37°C for 12 h. The cells were then harvested, homogenized, and incubated for 30 min with 100 μl reaction buffer solution containing a pseudosubstrate and various phospholipids from a commercially available kit (Pep Taq-Non-radioactive PKC activity kit; Promega). The reaction was stopped by heating, and then the reaction mixture was separated into phosphorylated and nonphosphorylated substrates on a 0.9% agarose gel. The band intensities were measured by densitometry.

Effect of sunitinib on TH phosphorylation in PC-12 cells. TH phosphorylation of only three serine residues (Ser<sup>19</sup>, Ser<sup>31</sup>, and Ser<sup>40</sup>) is activated by a variety of protein kinases, although phosphorylation of TH at Ser<sup>19</sup>, Ser<sup>31</sup>, and Ser<sup>40</sup> are 1.5-fold compared with the basal value, respectively. Therefore, we confirmed the effects of sunitinib in a human neuroblastoma cell line, SK-N-SH. An additional objective of this study was to clarify the mechanisms underlying sunitinib-mediated inhibition of catecholamine synthesis and/or secretion in these cells.

RESULTS

Effect of sunitinib on TH activity in PC-12 cells. Because TH is the initial and rate-limiting enzyme in catecholamine biosynthesis, we tested the effect of sunitinib on TH activity. Nicotine is known to stimulate catecholamine synthesis in chromaffin cells. Initially, we confirmed that nicotine (10 μM) increased TH activity ~1.5-fold compared with the basal value in PC-12 cells; thus, this was used as a convenient positive control in this study. As shown in Fig. 1A, sunitinib at 10, 100, and 1,000 nM significantly decreased TH activity to 79, 74, and 68% of the basal value, respectively.

Effect of sunitinib on TH phosphorylation in PC-12 cells. To reinforce the sunitinib-mediated inhibition of TH activity, we

AJP-Endocrinol Metab • doi:10.1152/ajpendo.00156.2012 • www.ajpendo.org
also examined the effect of sunitinib on the phosphorylation of TH at Ser\textsuperscript{19}, Ser\textsuperscript{31}, and Ser\textsuperscript{40}, which functions in the short-term regulation of enzyme activity. Sunitinib significantly decreased TH phosphorylation at Ser\textsuperscript{31} and Ser\textsuperscript{40} in a dose- and time-dependent manner (Fig. 2). In contrast, sunitinib did not affect phosphorylation at Ser\textsuperscript{19} (data not shown).

**Effect of sunitinib on TH protein levels in PC-12 cells.** We also examined the effect of sunitinib on the long-term regulation of TH activity. Cells were treated with sunitinib (1,000 nM), and TH protein level was examined by immunoblotting. As shown in Fig. 3, sunitinib significantly decreased the level of TH protein, to ~60% of the basal value.
Effect of sunitinib on catecholamine release and intracellular catecholamine in PC-12 cells. As shown in Fig. 4A, sunitinib (1,000 nM) significantly inhibited catecholamine secretion to \( \frac{1}{4} \) of the basal level. It is known that the intracellular catecholamine level is correlated with catecholamine synthesis. Therefore, to confirm that sunitinib inhibits catecholamine synthesis, we examined the effect of sunitinib on intracellular catecholamine. As shown in Fig. 4C, sunitinib (1,000 nM) significantly reduced intracellular catecholamine to \( \frac{1}{2} \) of the basal level.

Effect of VEGFR-2 knockdown on sunitinib-mediated inhibition of catecholamine synthesis and secretion in PC-12 cells. To further confirm whether sunitinib exerts its effects through VEGFR-2, we examined the effect of VEGFR-2 knockdown on catecholamine synthesis and secretion. VEGFR-2 knockdown by small-interfering RNA (siRNA) was previously confirmed by immunoblotting (36). As shown in Figs. 1A, 4A, and 4C, VEGFR-2 silencing attenuated sunitinib-induced effects, such as the reduction of TH activity, catecholamine secretion, and intracellular catecholamine, compared with that of the negative control siRNA. These results indicate that these sunitinib-mediated inhibitory effects could be mediated by VEGFR-2.

It is known that sunitinib exerts its effects via multiple RTKs. Indeed, Manley et al. (30) reported that the half-maximal inhibitory concentration (IC\(_{50}\)) values of sunitinib for PDGFR-\( \alpha \) and PDGFR-\( \beta \) are 55 and 35 nM, whereas those for VEGFR-1, -2, and -3 are 15, 38, and 30 nM, respectively. Moreover, sunitinib is also a potent inhibitor of CSF-1R, Flt-3, and c-Kit (IC\(_{50}\) values of 35, 21, and 10 nM, respectively) (30). Consistent with this notion, multitargeted therapies, such as sunitinib, are likely to have more antitumor activities than those targeting a single pathway. Therefore, we determined whether multiple RTKs, such as PDGFR-\( \alpha \), PDGFR-\( \beta \), c-Kit, Flt-3, and CSF-1R, were involved in sunitinib-mediated inhibition of catecholamine synthesis and secretion. As shown in Fig. 1B, mRNA expression was determined by quantitative real-time PCR, confirming the knockdown of target genes by siRNA. In contrast to
what was observed with knockdown of VEGFR-2, knockdown of these other RTKs did not affect the sunitinib-mediated inhibition of either catecholamine synthesis or secretion (Figs. 1C and 4B).

**Effect of sunitinib on PLC-γ and PKC in PC-12 cells.** It is known that VEGFR-2 utilizes the PLC-γ/PKC/Raf/MEK/ERK pathway (40, 41). To clarify the mechanisms underlying sunitinib-mediated inhibition of TH activity, we examined the effect of sunitinib on PLC-γ phosphorylation. As shown in Fig. 5A, sunitinib at 100 and 1,000 nM significantly decreased PLC-γ phosphorylation to ~50% of the basal value. Phosphorylation of TH at Ser40 has a major effect on activity and is known to be regulated by PKC. Combining these findings with the inhibition of TH activity and Ser40 phosphorylation by sunitinib, we examined the effect of sunitinib on PKC activity. As shown in Fig. 5B, sunitinib at 100 and 1,000 nM significantly decreased PKC activity to ~70 and 60% of the basal value, respectively. Therefore, sunitinib may inhibit TH phosphorylation at Ser40 via inhibition of the VEGFR-2/PLC-γ/PKC pathway.

**Effect of sunitinib on mitogen-activated protein kinase activity in PC-12 cells.** Mitogen-activated protein kinases (MAPK) pathways are known to be among the most significant cellular signaling sequences (11). Therefore, we determined whether sunitinib affects the activity of MAPKs, including p44 and p42 MAPK (ERK), p46 and p54 c-Jun NH2-terminal kinase, and p38 MAPK (p38-α, -β, -γ, and -δ), in PC-12 cells. When cells were treated with sunitinib for 12 h, ERK phosphorylation decreased significantly with 100 nM sunitinib, and was ~50% at 1,000 nM (Fig. 6A). Inhibition was evident 12 h after onset of treatment and lasted for at least 48 h (at ~50% of the basal value) (Fig. 6B). In contrast to the sunitinib-mediated inhibition of ERK phosphorylation, sunitinib did not affect the other MAPKs tested (data not shown).

**Effect of sunitinib on IP3 production in PC-12 cells.** Because sunitinib was shown to inhibit PLC-γ phosphorylation (Fig. 5A), we tested whether sunitinib inhibited the production of
IP₃, a messenger for the mobilization of Ca²⁺ from intracellular storage sites. As shown in Fig. 7, sunitinib at 100 and 1,000 nM significantly increased the polarized signal, representing the reduction of IP₃ production in cells.

**Effect of sunitinib on TH activity in a human neuroblastoma cell line.** To confirm the key findings of this study, we examined the effect of sunitinib on TH activity in a human neuroblastoma cell line, SK-N-SH (37, 38). Similar to what was observed in PC-12 cells, TH activity in SK-N-SH cells decreased significantly, to ~60% of the basal value (Fig. 8). In addition, this inhibition was abolished by VEGFR-2 silencing in SK-N-SH cells.

**DISCUSSION**

In this study, we demonstrated that sunitinib directly inhibits catecholamine synthesis and secretion in pheochromocytoma PC-12 cells, indicating that the sunitinib-mediated inhibition of catecholamine secretion observed in a previous paper may be explained, at least in part, through the direct inhibition of tumor cells rather than the inhibition of angiogenesis. Indeed, we demonstrated that sunitinib (10 nM) significantly decreased TH activity (Fig. 1A). Because sunitinib exhibits a similar inhibi-

---

Fig. 5. Sunitinib inhibits phospholipase C (PLC)-γ phosphorylation and protein kinase C (PKC) activity in PC-12 cells. Cells were treated with either DMSO (control) or various concentrations of sunitinib (10, 100, and 1,000 nM) for 12 h. Cell lysates were subjected to SDS-PAGE and immunoblotted with anti-phospho-specific PLC-γ (Try⁷⁸⁴) or anti-PLC-γ antibody (A). PKC activity was assayed as described in MATERIALS AND METHODS (B). Representative data are shown, and these data were reproducible in 3 independent experiments. The value in the histogram represents the mean ± SE of the densitometric measurements of the indicated parameter. Under basal conditions, this ratio was set to 100%. *P < 0.05 vs. the basal value.

---

Fig. 6. Effect of sunitinib on extracellular signal-regulated kinase (ERK) activity in PC-12 cells. Cells were treated with sunitinib at the indicated concentrations for 12 h (A) or at 1,000 nM for the indicated times (B). Cell lysates were subjected to SDS-PAGE and immunoblotted with anti-phospho-p44 and p42 mitogen-activated protein kinase (MAPK) antibody or anti-p44 and p42 MAPK antibody. Details are described in MATERIALS AND METHODS. Representative data are shown, and these data were reproducible in 3 independent experiments. The value in the histogram represents the mean ± SE of the densitometric measurements of the indicated parameter. Under basal conditions, this ratio was set to 100%. *P < 0.05 vs. the basal value.

---

Fig. 7. Effect of sunitinib on inositol 1,4,5-trisphosphate (IP₃) production in PC-12 cells. Cells were treated with sunitinib at the indicated concentrations for 12 h, and IP₃ levels were measured as described in MATERIALS AND METHODS. The polarized signal is inversely proportional to the amount of IP₃. The data shown represent the mean ± SE of 3 independent experiments (1 experiment was performed with 2 samples). *P < 0.05 vs. the basal value.
SUNITINIB INHIBITS CATECHOLAMINE PRODUCTION IN PC-12 CELLS

Fig. 8. Sunitinib inhibits TH activity, and this inhibition is abolished by VEGFR-2 silencing in a human neuroblastoma cell line. SK-N-SH cells were incubated for 12 h with either DMSO (control) or sunitinib (1,000 nM). In other experiments, SK-N-SH cells were transfected with either siVEGFR-2 or siCON, and, 48 h later, the cells were treated with sunitinib (1,000 nM) for 12 h. TH activity was measured as described in MATERIALS AND METHODS. The data shown represent the means ± SE of 3 independent experiments (1 experiment was performed with 2 samples). *P < 0.05 vs. the basal value. #P < 0.05 vs. the value in siCON-transfected cells treated with sunitinib (1,000 nM).

Fig. 9. Proposed model for the direct effects of sunitinib on TH activity and catecholamine secretion in PC-12 cells. Results suggested by the current experiments together with data form the basis of our previous report (36). Sunitinib inhibits components of VEGFR-2-mediated signaling, such as PLC-γ and the PKC/Raf/ERK pathway. TH activity is known to be regulated by phosphorylation at Ser31 and Ser40, and phosphorylation at these sites is decreased by sunitinib (28). Further studies are needed to clarify these points.

The physiological relevance of TH phosphorylation at Ser31 is unclear. However, it was reported that at Ser31 phosphorylation might be required for full TH activation (7). In our experimental system, we demonstrated that sunitinib decreased ERK phosphorylation (Fig. 6). Although the physiological relevance of the differences between MAPKs observed in the present study remains unclear, it suggests that sunitinib may reduce TH phosphorylation at Ser31 through inhibition of the VEGFR-2/PLC-γ/PKC/Raf/MEK/ERK pathway.

Another important point made in this study was that sunitinib inhibited catecholamine secretion from PC-12 cells. Additionally, we demonstrated that sunitinib significantly inhibited IP3 production (Fig. 7). It is well established that [Ca2+]i, is regulated by Ca2+ release from intracellular storage sites mediated by IP3 formation following PLC-γ activation (12). Therefore, we can suggest that sunitinib inhibits PLC-γ phosphorylation and leads to reduced IP3 production, which mediates [Ca2+]i, and is consistent with the notion that sunitinib directly inhibits catecholamine secretion. The precise relationship between VEGFR-2 and Ca2+ mobilization remains obscure. However, it has been previously shown that PLC-γ activation via VEGF stimulation, followed by IP3 production and increased PKC activity, leads to increased [Ca2+]i, in primary endothelial cells (31). The pathophysiological role of RTKs, including VEGFR, in regulating catecholamine secretion in chromaffin cells also remains uncertain (28). Further studies are needed to clarify these points.

It is known that pheochromocytoma PC-12 cells, which are well established and extensively used, do not accurately reflect the pathogenesis of malignant tumor cells. Pheochromocytomas and neuroblastomas are derived from the sympathetic nervous system. Despite their embryologic relationship, a review of the literature suggests the lack of an association...
between them, regardless of the molecular pathogene-
sis, these neural crest-derived tumors reportedly share a common genetic background, such as SDHB and KIF1Bβ (37, 38). Therefore, we confirmed that sunitinib exerted the same effects on catecholamine synthesis in a human neuroblastoma cell line (Fig. 8).

In the clinical setting, sunitinib is reported to significantly inhibit catecholamine secretion (15, 25, 26). This, along with our present findings, suggests that sunitinib directly inhibits catecholamine synthesis and secretion during treatment of malignant pheochromocytomas. In addition, it is of note that TH is strongly activated in pheochromocytomas compared with normal adrenal medullas (24). Therefore, inhibition of TH activity by sunitinib seems to be the rationale for treatment of malignant pheochromocytomas.

Growing evidence suggests that the phosphatidylinositol 3-kinase (PI3K)/Akt/mTOR/S6K1 pathways may play an important role in the pathogenesis of pheochromocytomas. TMEM112, a new tumor suppressor gene reported to be associated with pheochromocytoma development, encodes a protein that suppresses mTOR activation. Indeed, the authors found that S6K1 phosphorylation increased in TMEM112 mutant pheochromocytomas compared with normal adrenal medullas (34, 42, 44). Therefore, activation of the PI3K/Akt/mTOR/S6K1 pathways may also be involved in the pathogenesis of pheochromocytomas.

We recently demonstrated that sunitinib directly induces apoptosis in PC-12 cells by inhibiting the VEGFR-2/Akt/mTOR/S6K1 pathways through modulation of Bcl-2 and Bad (36). Based on this finding along with our present results, it would appear that sunitinib exerts its antitumor effects, at least in part, through direct inhibition of catecholamine synthesis and secretion as well as apoptosis rather than by inhibiting angiogenesis (Fig. 9).

GRANTS
This study was supported in part by a Grant-in-aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology of Japan, No. 21591168 (to K. Takekoshi) and No. 23591889 (to H. Hara).

DISCLOSURES
The authors have nothing to declare.

AUTHOR CONTRIBUTIONS
SUNITINIB INHIBITS CATECHOLAMINE PRODUCTION IN PC-12 CELLS


