Chapter 13

Medicinal Chemistry of Vitamin K Derivatives and Metabolites

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Additional information is available at the end of the chapter

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Abstract

Vitamin K acts as a cofactor for γ-glutamyl carboxylase. Recently, various biological activities of vitamin K have been reported. Anti-proliferative activities of vitamin K, especially in vitamin K_3, are well known. In addition, various physiological and pharmacological functions of vitamin K_2, such as transcription modulators as nuclear steroid and xenobiotic receptor (SXR) ligands and anti-inflammatory effects, have been revealed in the past decade. Characterization of vitamin K metabolites is also important for clinical application of vitamin K and its derivatives. In this chapter, recent progress on the medicinal chemistry of vitamin K derivatives and metabolites is discussed.

Keywords: vitamin K derivative, metabolite, antitumor activity, anti-inflammatory activity, steroid and xenobiotic receptor/pregnane X receptor

1. Introduction

Vitamin K is a specific cofactor for γ-glutamyl carboxylase (GGCX), which catalyzes formation of γ-carboxyglutamyl (Gla) residues in vitamin K–dependent proteins (**Figure 1**) [1]. Various other biological activities of vitamin K and its derivatives have also been reported. For example, vitamin K_3 (menadione), a vitamin K homologue that was considered as a synthetic vitamin K, has antitumor activity [2–5], as does vitamin K_2 (menaquinone) [6, 7]. Among the homologues of vitamin K_2, menaquinone-4 (MK-4), which contains four isoprene units, has been intensively investigated. It binds to nuclear receptor human pregnane X receptor (PXR), which is also called steroid and xenobiotic receptor (SXR), and regulates transcription of osteoblastic genes [8, 9]. It also exhibits anti-inflammatory activity by suppressing the NF-kB pathway [10], and has an inhibitory effect on arteriosclerosis [11]. It binds 17β-hydroxysteroid dehydrogenase 4 and

modulates estrogen metabolism [12]. Further, it enhances testosterone production [13, 14], and shows growth-inhibitory activity toward hepatocellular carcinoma (HCC) cells [6, 7]. These biological activities of vitamin K and its analogues are attractive targets of drug discovery, and the activities of vitamin K metabolites have also attracted much interest. A great many natural and synthetic biologically active 1,4-naphthoquinone derivatives (i.e., vitamin K derivatives) have been reported. In this chapter, we will focus on three medicinal-chemistry studies of vitamin K activities.

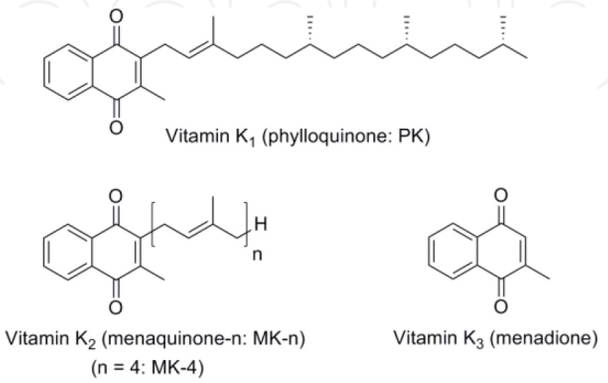

Figure 1. Structures of vitamin K homologues.

2. Menadione derivatives as antitumor agents

The antitumor activity of thioether derivatives is one of the most intensively investigated fields in the medicinal chemistry of menadione derivatives. Several series of naphthoquinone derivatives and benzoquinone derivatives bearing an alkyl, alkoxy, or alkylthio group as a side chain have been synthesized and biologically evaluated by assay of growth-inhibitory activity toward human hepatoma cell line HepB3. Almost all of the tested compounds, as well as the parent menadione, exhibited significant inhibitory activity, and the alkylthio derivatives were more potent than the corresponding alkyl and alkoxy derivatives. Among these compounds, a 2-hydroxyethylthio derivative Cpd 5 (compound 5; NSC 672121) exhibited the most potent activity (**Figure 2**) [15]. Subsequent studies revealed that Cpd 5 irreversibly inhibits growth-regulatory phosphatase Cdc25 by arylating a cysteine residue in the catalytic site, causing cell-cycle arrest [16–19].

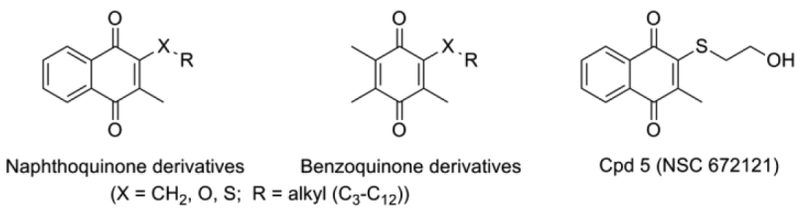

Figure 2. Compounds tested in the initial work on development of Cpd5.

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Based on the finding that Cpd5 inhibits Cdc25 and exerts antitumor activities, various menadione derivatives have been developed as candidate antitumor compounds. Bis(2-hydroxyethylthio)naphthoquinone derivative NSC 95397 (**Figure 3**) showed potent Cdc25-inhibitory activity and inhibited proliferation of several cancer cell lines with greater potency than that of Cpd 5 [20]. Hydroxylated NSC 95397 derivatives exhibited enhanced Cdc25-inhibitory activity and inhibited growth of several cancer cell lines [21]. Fluorinated Cpd 5 was three times more potent than Cpd-5 itself in Hep3B growth inhibition and induced phosphorylation of ERK1/2, JNK1/2 and p38 in HepB3 cells [22]. Calculations suggested that fluorinated Cpd 5 cannot generate reactive oxygen species because of its modified redox profile, and therefore, the compound appears to function as a pure arylating agent [23]. Modification of the core structure afforded a maleimide derivative PM-20 with a submicromolar IC_{50} value for HepB3 growth inhibition. Structure-activity relationship study indicated that the biphenyl structure of PM-20 is essential for activity (**Figure 3**) [24].

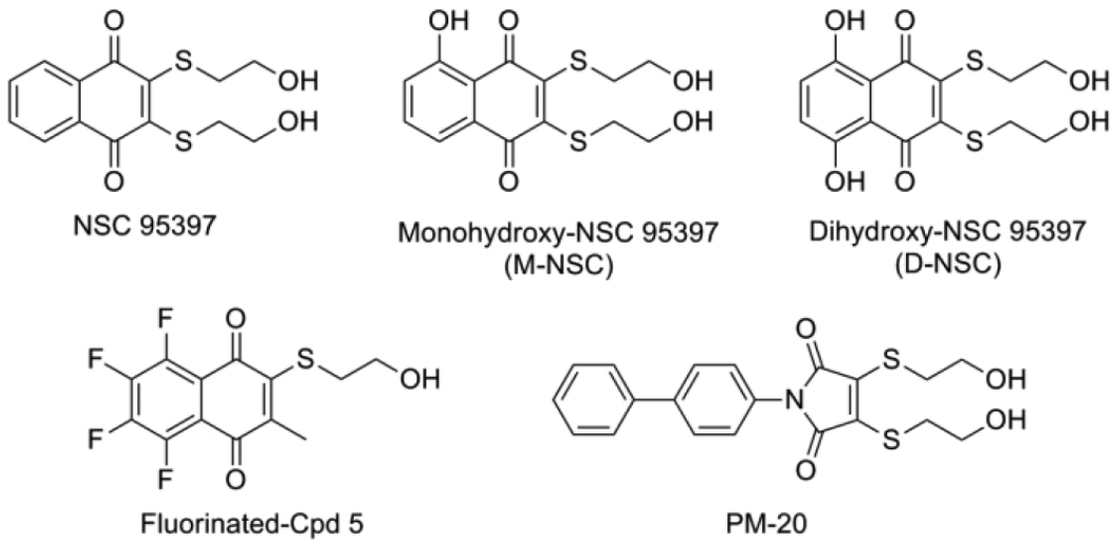

Figure 3. Structures of Cpd 5 derivatives bearing a 2-hydroxyethylthio moiety.

Modification of the hydroxyethyl side chain of Cpd-5 and NSC 95397 was also investigated. Carboxylic acid derivatives such as compounds **1, 3**, and **4** (**Figure 4**) were designed to interact with arginine residues in the catalytic site of Cdc25B, and indeed, they exhibited potent Cdc25B3-inhibitory activity [25, 26]. Though the cytotoxic activities of these carboxylic acid derivatives, especially dicarboxylic acid **4**, were low, prodrug-type benzyl ester derivatives exhibited enhanced growth-inhibitory activity toward HeLa cells. It was also found that Cpd 5 derivatives bearing a modified terminal, such as **6**, showed selective cytotoxicity toward neuroblastoma cell lines, whereas the parent menadione and Cpd 5 exhibited cytotoxicity toward both neuroblastoma cells and normal cell lines [27]. Aminoalkylmenadione derivatives such as **7** showed angiogenesis-inhibitory activity (**Figure 4**) [28].

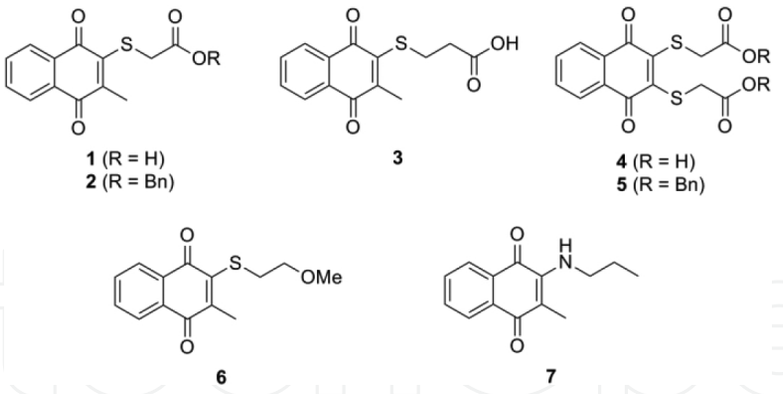

Figure 4. Examples of side chain-modified Cpd 5 derivatives.

A natural product, plumbagin (5-hydroxymenadione, **Figure 5**), shows anticancer and antiproliferative activities [29]. It suppresses the NF-kB activation pathway by modulating p65 and IkBα kinase activation to potentiate cytokine- and drug-induced apoptosis [30]. Structurally related naphthoquinone derivatives juglone and 1,4-naphthoquinone exerted similar TNFα-induced NF-kB inhibitory activities, whereas menadione did not [30]. Another natural product, lapachol, which has a hydroxyl group instead of the methyl group of MK-1, has anticancer activity [31]. A synthetic analogue **8** bearing two isoprene units also exerted antitumor activity (**Figure 5**) [32], and various biologically active lapachol derivatives have been developed [33]. The 2-hydroxy-1,4-naphthoquinone structure has distinct chemistry; for example, it has the characteristics of 1,2-naphthoquinone (e.g., lapachol can cyclize to form α-lapachone or β-lapachone), in contrast to 2-methyl-1,4-naphthoquinone.

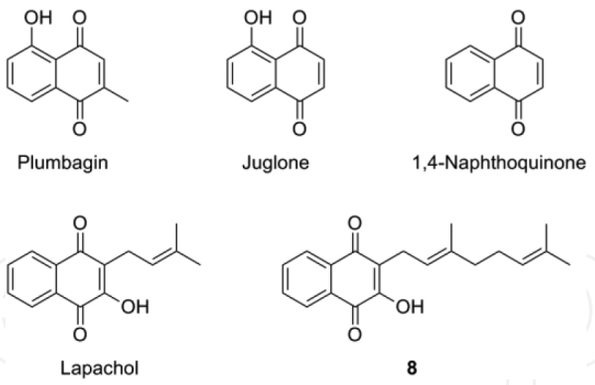

Figure 5. Some vitamin K–related naphthoquinone derivatives with antitumor activity.

3. Structure-activity relationship of MK-4 derivatives as nuclear SXR ligands

In the early twenty-first century, it was found that MK-4 binds a nuclear receptor, steroid, and xenobiotic receptor (SXR), which is a human homologue of pregnane X receptor (PXR), and

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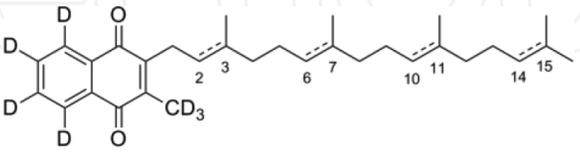
regulates transcription of osteoblastic genes [8, 9]. Structure-activity relationships of MK-4 as an SXR ligand were intensively investigated by Suhara et al., using deuterated derivatives (**Figure 6**). Saturation of double bond(s) in the side chain significantly reduced the SXR agonistic activity. Triene derivative **9** bearing a 6,7-saturated side chain exerted only moderate activity, and diene **10**, monoene **11** (phylloquinone-d_7), and alkyl derivative **12** were inactive. Removal of methyl groups also reduced the activity, but demethylated compounds **13–16** still retained significant activity [34].

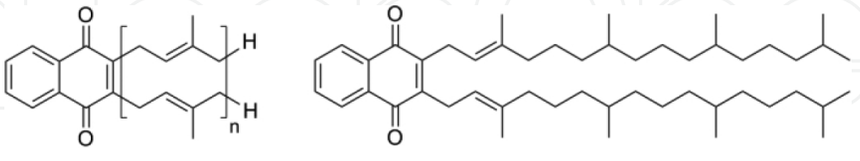


6,7-dihydro : **9** (triene)
6,7,10,11-tetrahydro : **10** (diene)
6,7,10,11,14,15-hexahydro : **11** (phylloquinone-d_7)
2,3,6,7,10,11,14,15-octahydro : **12** (alkyl)

des 3-Me : **13**
des 7-Me : **14**
des 11-Me : **15**
des 15-Me : **16**

Figure 6. Compounds used in SAR study of SXR.

The length of the side chain is important for the SXR activity of menaquinones. MK-1 bearing one prenyl group showed little ligand potency, while MK-2, MK-3, and MK-4 were more active. In the SXR-GAL4 one hybrid assay system, MK-3 was the most potent compound, and MK-2 and MK-4 showed somewhat lower activity. In the assay system using SXRE, MK-2, and MK-3 were the most potent compounds [35]. "Double side chain" vitamin K analogues bearing the same side chains at the 2-position and 3-position of the naphthoquinone ring were also designed and synthesized. MK-1-W and MK-2-W were as potent as MK-3 and MK-4, whereas MK-3-W, MK-4-W, and PK-W showed little activity (**Figure 7**) [35].



n = 1 : MK-1-W
n = 2 : MK-2-W
n = 3 : MK-3-W
n = 4 : MK-4-W

PK-W

Figure 7. Structures of double side chain vitamin K analogs.

Substitution at the terminal of the side chain of menaquinones significantly affects SXR ligand potency. Hydroxylated derivatives MK-2-ω-OH, MK-3-ω-OH, and MK-4-ω-OH showed little activity in the SXR-GAL4 one hybrid assay system, whereas compounds **17** and **18** bearing a

terminal phenyl group exhibited more potent activity than the parent menaquinones (**Figure 8**). Compounds **17** and **18** also exhibited potent activity in the SXRE assay system [36]. Thus, a suitable hydrophobic side chain is essential for SXR activity of menaquinones.

Interestingly, Suhara et al. also found that menaquinone derivatives bearing a terminal hydrophobic substituent have the ability to induce selective neuronal differentiation of neuronal progenitor cells. The most potent compound **19** was twice as effective as the EtOH control, based on quantitation of Map2 mRNA (**Figure 8**) [37].

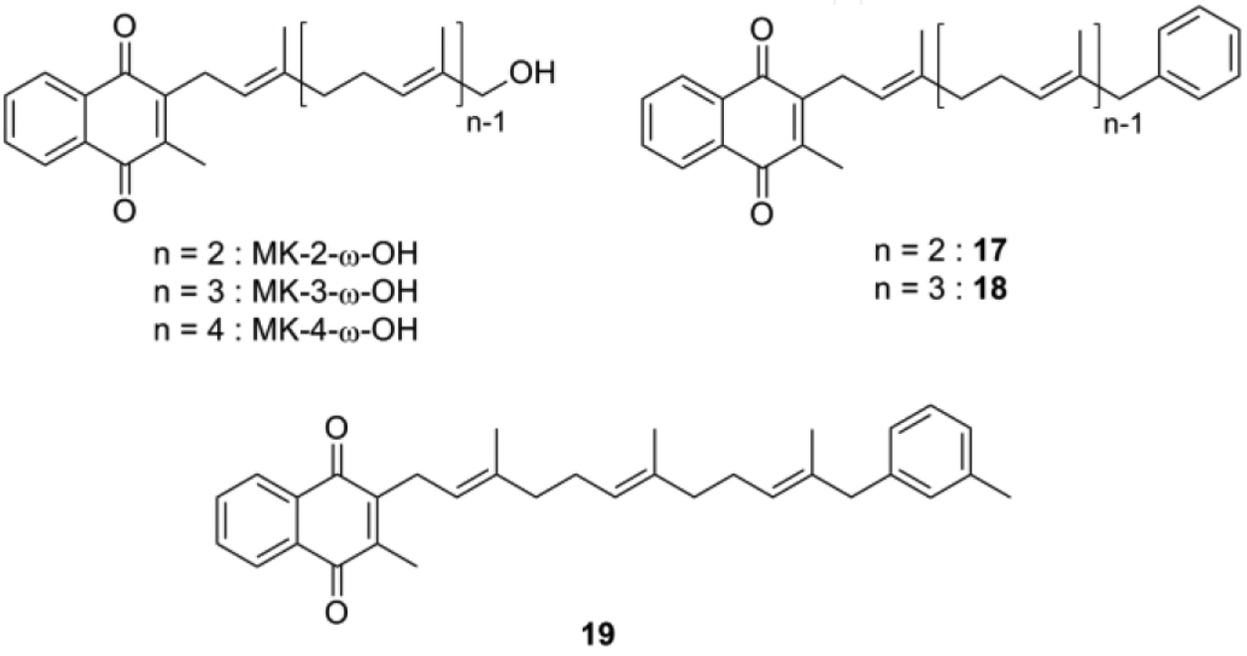


Figure 8. Structures of menaquinone derivatives with modified terminal.

4. Synthesis and biological activity of menaquinone metabolites

The biological activities of metabolites of vitamin K are also important. MK-4 is one of the most interesting vitamin K homologues because of its multifunctional properties, and ω-carboxyl homologues of MK-4 (MK-4-ω-COOH), K acid I, K acid II and their glucuronides have been identified as metabolites [38–42]. It is considered that MK-4 is initially metabolized to MK-4-ω-COOH by ω-oxidation, followed by β-oxidation to afford intermediary carboxylic acids (**Figure 9**) [43]. These carboxylic acids can be categorized into two groups; MK-n-ω-COOH derivatives bearing a α,β-unsaturated carboxy group and MK-n-(ω-2)-COOH derivatives bearing a γ,δ-unsaturated carboxy group. Chemical synthesis of these metabolites is essential for evaluation of their properties, and several synthetic routes have been reported.

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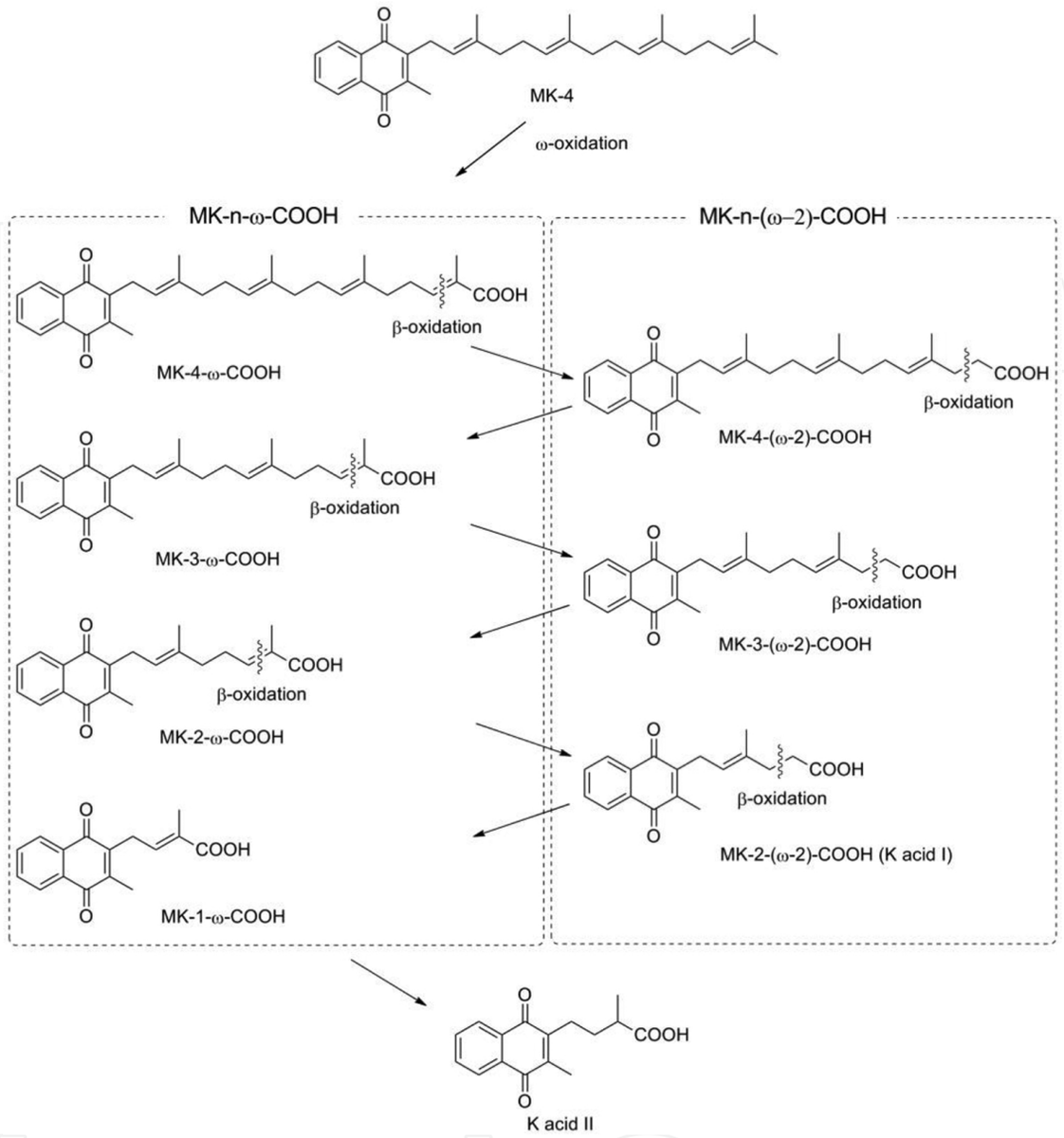

Figure 9. Putative catabolic pathways of MK-4.

4.1. Synthesis of menaquinone metabolites

The MK-4 metabolites K acid I and K acid II are also metabolites of phylloquinone (vitamin K_1). Several chemical syntheses of K acid I and K acid II have been reported. Watanabe et al. synthesized K acid I by direct addition of a carboxy side chain to the naphthoquinone framework using BF_3 etherate [44]. A route involving a malonyl derivative and decarboxylation was also investigated (**Figure 10**) [45]. They also synthesized K acid II. Addition of a side chain moiety by Friedel-Crafts acylation, followed by Clemmensen reduction, afforded naphthylcarboxylic acid, and oxidation of the naphthol moiety using Fremy's salt gave K acid II. Direct alkylation of naphthoquinone using peroxide also afforded K acid II (**Figure 11**) [44].

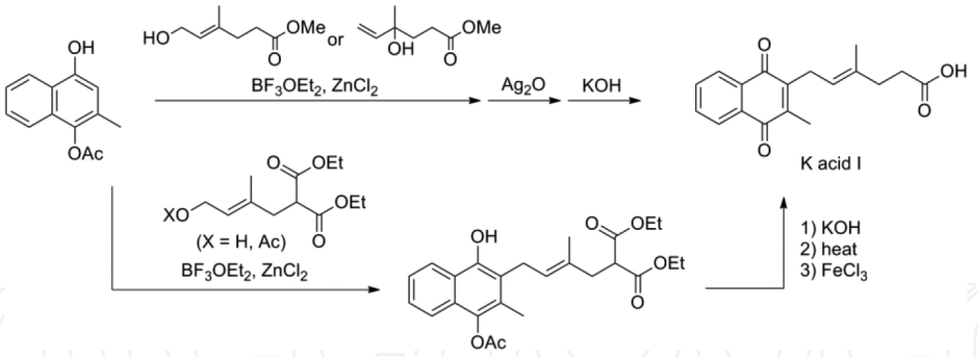

Figure 10. Synthetic route to K acid I (Watanabe et al.).

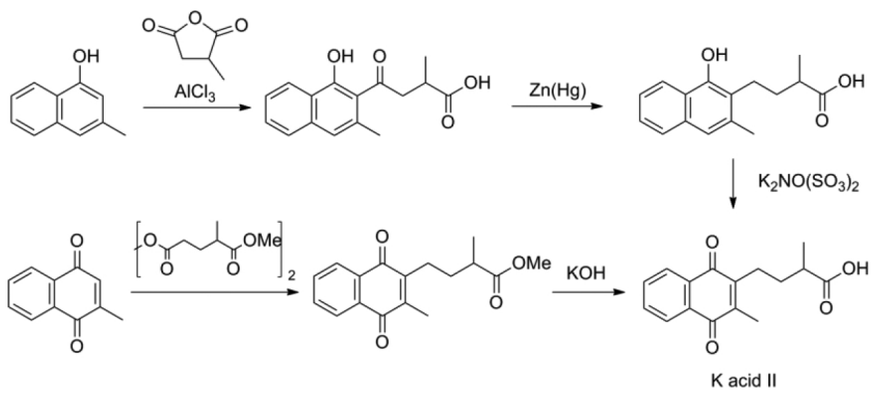

Figure 11. Synthetic route of K acid II (Watanabe et al.).

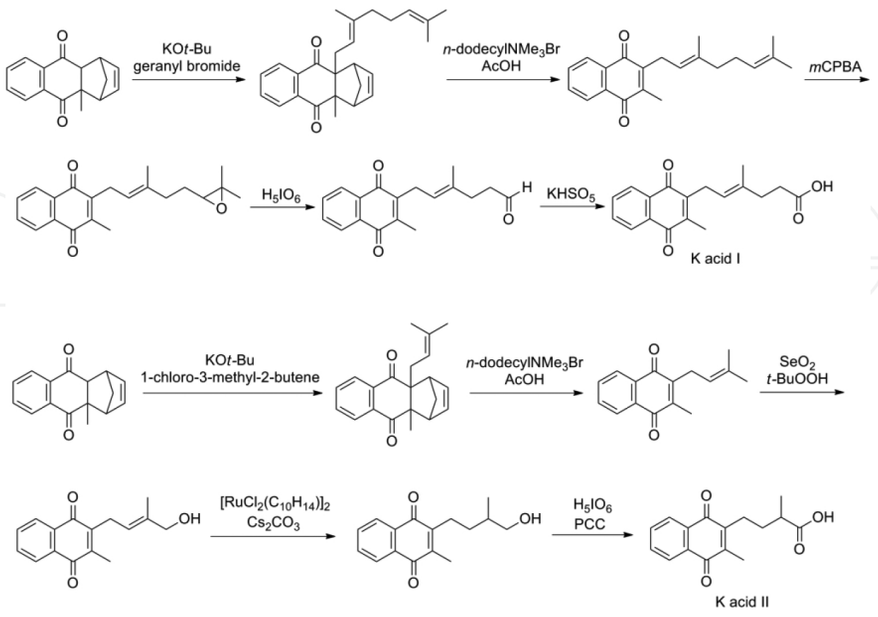

Figure 12. Synthetic routes of K acid I and K acid II (Teitelbaum et al.).

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Teitelbaum et al. synthesized K acid I and K acid II by oxidation of MK-2 and MK-1, respectively. They prepared intermediary MK-n using a menadione-cyclopentadiene adduct as the same starting material (**Figure 12**) [46].

Okamoto et al. synthesized MK-1-ω-COOH by using Wittig reaction as a key step. To prepare the intermediary aldehyde, they employed alkylation and oxidative cleavage (**Figure 13**) [47].

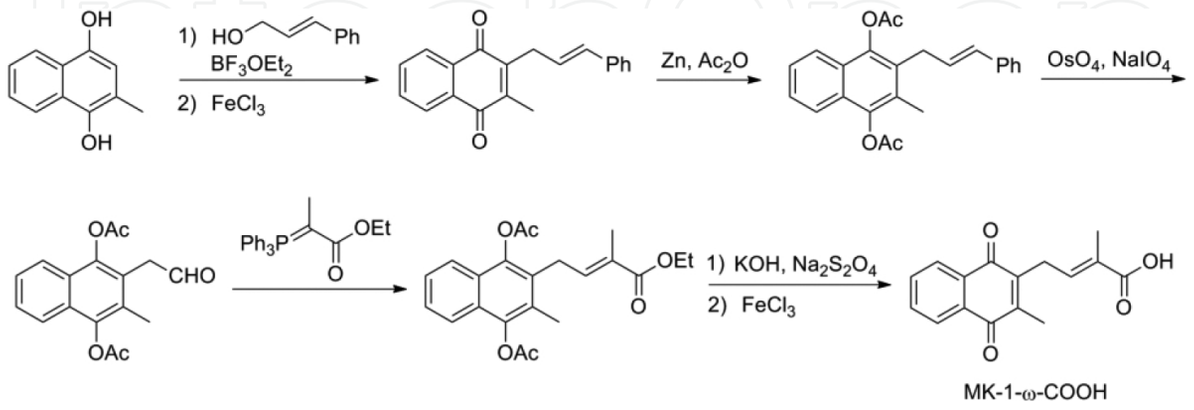

Figure 13. Synthesis of MK-1-ω-COOH (Okamoto et al.).

Terao et al. synthesized MK-3-(ω-2)-COOH and MK-4-(ω-2)-COOH using Claisen rearrangement as a key reaction. Claisen reaction of triethyl orthoacetate and MK-n derivative gave two-carbon-atom-extended carboxylic acid esters, and then hydration afforded MK-n-(ω-2)-COOH derivatives (**Figure 14**) [48].

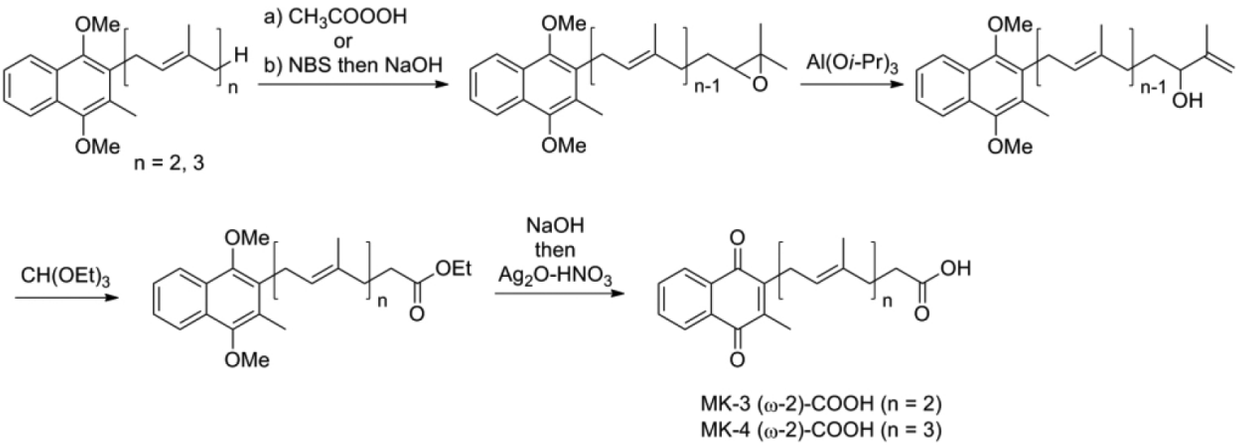

Figure 14. Synthesis of MK-n-(ω-2)-COOH derivatives (Terao et al.).

Masaki et al. employed sulfur-contractive anionic [2,3]-sigmatropic rearrangement for side chain elongation. Treatment of allyl sulfide with base afforded two-carbon-atom-extended carboxylic acid esters in one pot (**Figure 15**). MK-2-(ω-2)-COOH and MK-3-(ω-2)-COOH were obtained in this way [49].

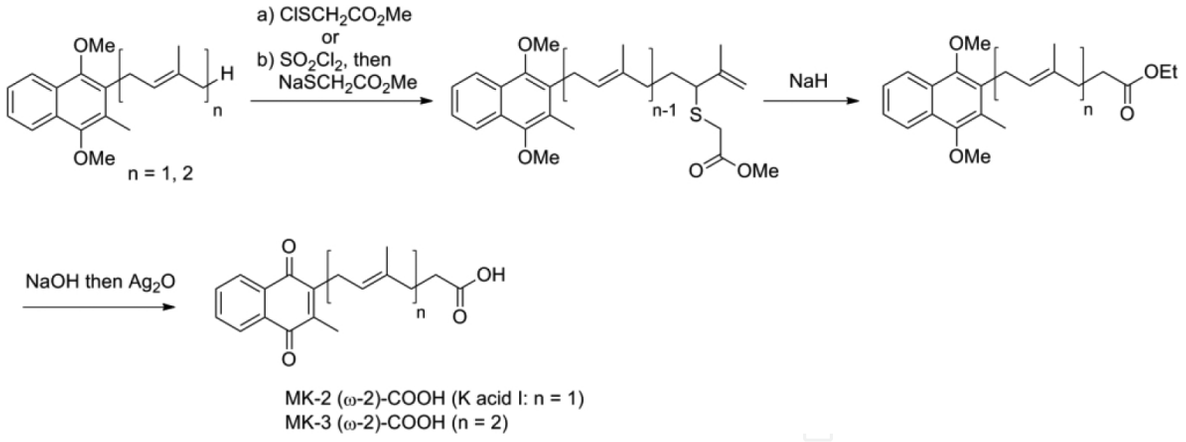

Figure 15. Synthesis of MK-n-(ω-2)-COOH derivatives (Masaki et al.).

Fujii et al. reported systematic synthesis of menaquinone metabolites. MK-n-ω-COOH derivatives were synthesized by oxidation of the terminal carbon of MK-n derivatives. Stereoselective oxidation with selenium oxide, followed by stepwise oxidation, gave MK-n-ω-COOH derivatives. K acid II was synthesized by hydrogenation of MK-1-ω-COOH (**Figure 16**) [50]. MK-n-(ω-2)-COOH derivatives were synthesized by oxidative cleavage of MK-n derivatives. Epoxidation of terminal olefin followed by perchloric acid treatment afforded 1,2-diols. Oxidative cleavage of the diol moiety followed by oxidative reactions gave MK-n-(ω-2)-COOH derivatives (**Figure 17**) [50]. These synthetic schemes correspond to the putative catabolic pathways of menaquinones, that is, ω-oxidation and β-oxidation.

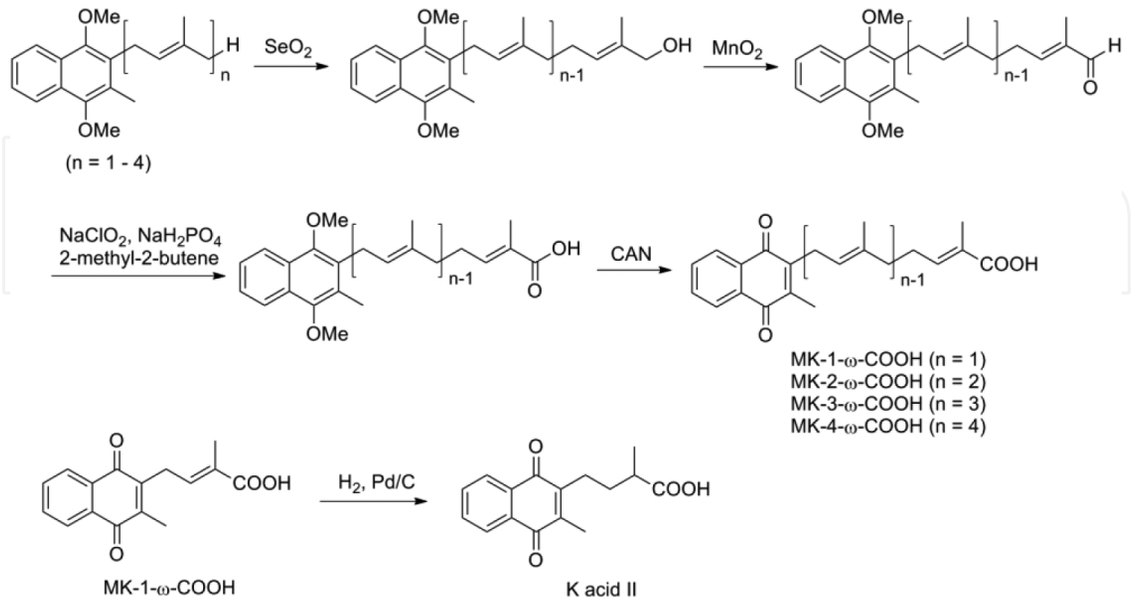

Figure 16. Synthesis of MK-n-ω-COOH derivatives (Fujii et al.).

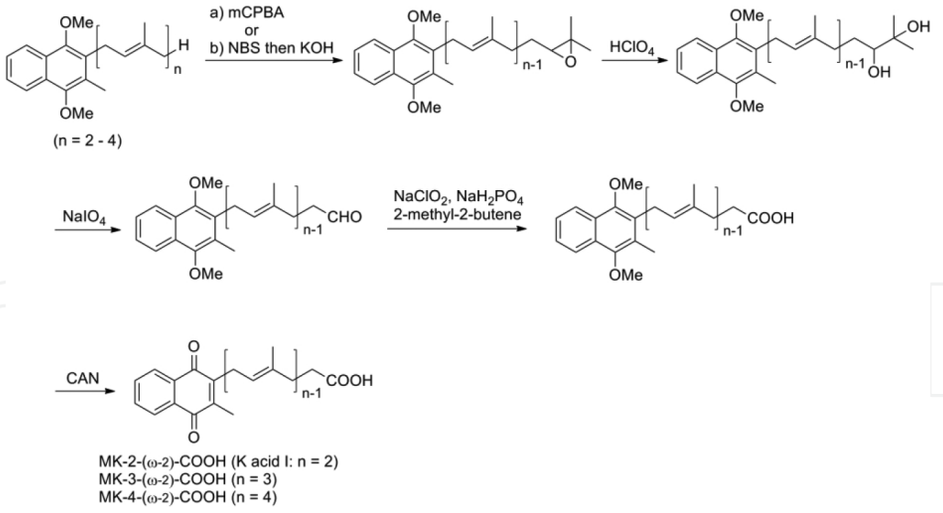

Figure 17. Synthesis of MK-n-(ω-2)-COOH derivatives (Fujii et al.).

Suhara et al. designed and synthesized ω-hydroxy derivatives (ω-alcohols) and ω-formyl derivatives (ω-aldehydes) as menaquinone metabolite analogs. ω-Oxidized side chain moieties were prepared from corresponding isoprene derivatives, and the side chain parts were introduced into the naphthalene core. Oxidation to quinone form afforded ω-alcohols, and then PDC oxidation afforded ω-aldehydes (**Figure 18**) [51, 52].

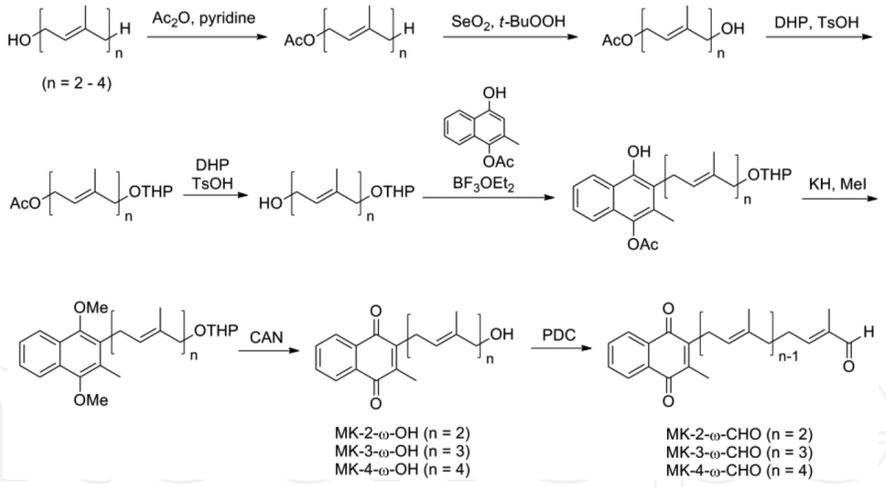

Figure 18. Synthesis of MK-n-ω-alcohols and MK-n-ω-aldehydes (Suhara et al.).

4.2. Biological activities of menaquinone metabolites

These menaquinone carboxylic acid derivatives and related quinone carboxylic acids, including ubiquinone derivatives and tocopheryl derivatives, show lysosomal membrane-stabilizing activity [45, 47]. Appropriate hydrophobicity of the side chain appears to be essential for this activity. Some of these compounds also exert inhibitory effects on the generation of the slow-reacting substance of anaphylaxis [48].

MK-4 has various biological activities, such as anti-inflammatory activity and antitumor activity, and these activities of the menaquinone metabolites were also investigated. All tested menaquinone metabolites inhibited LPS-induced production of proinflammatory cytokines in RAW264.7 cells [50]. It is suggested that naphthoquinone structure is essential for the anti-inflammatory activity of menaquinone derivatives. Regarding antitumor activity, several carboxylic acids, such as MK-2-ω-COOH, significantly inhibited proliferation of JHH7 and HepG2 hepatocellular carcinoma cell lines. On the other hand, MK-2-ω-COOH did not inhibit proliferation of normal hepatic cells. Anti-proliferative activity may be associated with caspase/transglutaminase-related pathways [53].

The ω-alcohols and ω-aldehydes showed apoptosis-inducing activity toward human leukemia cell line HL-60 and human osteosarcoma cell line MG-63. The ω-aldehydes were more potent than the corresponding ω-alcohols [51, 52]. The vitamin K potency of MK-4-ω-OH, that is, its coenzyme activity for GGCX, was also evaluated. MK-4-ω-OH showed a larger V_{max}/K_m value than that of intact MK-4, indicating that MK-4-ω-OH has greater coenzyme activity than MK-4 [52].

5. Future perspective

Vitamin Ks are attractive lead compounds for drug discovery. One of the most promising applications is as candidate antitumor agents, though the mechanism of action of Cpd 5 could be different from that of intact vitamin Ks. In addition, bone homeostasis and neural effects are also possible targets of vitamin K derivatives. Vitamin K may also be used as a food supplement, and therefore, characterization of its metabolites is important. It is noteworthy that some menaquinone metabolites have characteristic activities distinct from those of intact vitamin K_2. Though a clinical study of MK-4 as an agent to prevent recurrence of hepatocellular carcinoma was terminated [54], the metabolites and their analogs still represent potential drug candidates.

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