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The tumor-suppressor cholesterol metabolite, dendrogenin A, is a new class of LXR modulator activating lethal autophagy in cancers

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► To cite this version:

Sandrine Silvente-Poirot, Marc Poirot. The tumor-suppressor cholesterol metabolite, dendrogenin A, is a new class of LXR modulator activating lethal autophagy in cancers. *Biochemical Pharmacology*, 2018, 153, pp.75-81. 10.1016/j.bcp.2018.01.046 . inserm-02380575

HAL Id: inserm-02380575

<https://inserm.hal.science/inserm-02380575v1>

Submitted on 26 Nov 2019

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4 Review, Diamond Jubilee Special Issue
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8 **The tumor-suppressor cholesterol metabolite, dendrogenin A, is a new class of**
9 **LXR modulator activating lethal autophagy in cancers.**
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4 **ABSTRACT**
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7 Dendrogenin A (DDA) is a mammalian cholesterol metabolite recently identified that
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9 displays tumor suppressor properties. The discovery of DDA has revealed the existence in
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11 mammals of a new metabolic branch in the cholesterol pathway centered on 5,6 α -
12
13 epoxycholesterol and bridging cholesterol metabolism with histamine metabolism. Metabolic
14
15 studies showed a drop in DDA levels in cancer cells and tumors compared to normal cells,
16
17 suggesting a link between DDA metabolism deregulation and oncogenesis. Importantly,
18
19 complementation of cancer cells with DDA induced 1) cancer cell re-differentiation , 2) blockade
20
21 of 6-oxo-cholestan-3 β ,5 α -diol (OCDO) production, an endogenous tumor promoter and 3) lethal
22
23 autophagy in tumors. Importantly, by binding the liver X receptor (LXR), DDA activates the
24
25 expression of genes controlling autophagy. These genes include *NR4A1*, *NR4A3*, *LC3* and *TFEB*.
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27 The canonical LXR ligands 22(R)hydroxycholesterol, TO901317 and GW3965 did not induce
28
29 these effects indicating that DDA delineates a new class of selective LXR modulator (SLiM). The
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31 induction of lethal autophagy by DDA was associated with the accumulation in cancer cells of
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33 lysosomes and of the pro-lysosomal cholesterol precursor zymostenol due to the inhibition of the
34
35 3 β -hydroxysteroid- $\Delta^8\Delta^7$ -isomerase enzyme (D8D7I). The anti-cancer efficacy of DDA was
36
37 established on different mouse and human cancers such as breast cancers, melanoma and acute
38
39 myeloid leukemia, including patient derived xenografts, and did not discriminate bulk cancer
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41 cells from cancer cell progenitors. Together these data highlight that the mammalian metabolite
42
43 DDA is a promising anticancer compound with a broad range of anticancer applications. In
44
45 addition, DDA and LXR are new actors in the transcriptional control of autophagy and DDA
46
47 being a “first in line” driver of lethal autophagy in cancers via the LXR.
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60 **Key words:** Dendrogenin A; oxysterol; Nur77; lysosomes; cell death; OCDO
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4 **1. Introduction**
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6 Dendrogenin A (DDA) is the first cationic steroid discovered to date as an endogenous
7 metabolite in mammals. DDA defines a new structural class of mammalian steroidal alkaloids [1-
8 4]. DDA is the product of a stereo-selective condensation of 5,6 α -epoxycholesterol (5,6 α -EC)
9 with histamine. DDA materializes the existence of a new metabolic branch at the crossroad
10 between cholesterol and histamine metabolism. Cholesterol is a neutral semi rigid lipid necessary
11 for mammalian life [5]. Cholesterol is important not only to the constitution of membranes, but
12 also to the formation of various bioactive lipids such as steroid hormones, bile acids (BA) and
13 oxysterols (OS). While the physiological role of steroid hormones is well established, BA and OS
14 were first considered as catabolic products or side products of cholesterol. More recently,
15 researchers discovered that several of these metabolites displayed biological properties [6-11]
16 supporting a physiological function for BA and OS. These metabolites were found to act through
17 nuclear receptors such as LXR, FXR, ER, ROR, GR or through G-protein coupled receptors [6-8,
18 11-15].
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41 **2. The dendrogenin hypothesis**
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43 The hypothesis on the existence of dendrogenins as new metabolites came from
44 biochemical pharmacology studies on tamoxifen (Tam). Tam is an anticancer agent widely used
45 for the treatment and the chemoprevention of estrogen receptor positive breast cancers [16-18].
46 Tam was initially defined as a selective estrogen receptor modulator (SERM), blocking the
47 mitogenic action of 17 β -estradiol by competition on estrogen receptor α (ER α) and displaying
48 tissue selective agonist or antagonist properties [16-18]. Since the seventies, Tam remains the
49 lead compound in the family of SERMs and has not yet been supplanted to date by any other
50 SERM for anticancer applications. Extensive studies on the biochemical pharmacology of Tam,
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4 showed that the mechanism of action mediating its anticancer action was more complex than first
5
6 thought, and involved, in addition to ER, the “microsomal antiestrogen binding site” (AEBS) [19-
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8 31]. The AEBS is not a nuclear receptor, but is an intracellular membranous high affinity binding
9
10 site for Tam[32]. The AEBS is a hetero-oligomeric proteinaceous complex located on the
11
12 membranes of the endoplasmic reticulum from cancer cells and hepatocytes [24, 33-35]. The
13
14 AEBS is made of two subunits: the 3 β -hydroxysteroid- $\Delta^8\Delta^7$ -isomerase (D8D7I) and the 3 β -
15
16 hydroxysteroid- Δ^7 -reductase (DHCR7) [24, 33-35]. Tamoxifen inhibited the D8D7I and induced
17
18 the accumulation of zymostenol in BC cells and in the blood of patients [19, 21, 23, 24, 36-39].
19
20 Importantly, zymostenol accumulation was associated with the induction of a protective
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22 autophagy [7, 19, 21, 22, 32, 36, 40], which impaired Tam efficacy and therefore constitutes a
23
24 mechanism of resistance [19, 32]. It was next showed that the AEBS complex carried out a
25
26 cholesterol-5,6-epoxide hydrolase (ChEH) enzymatic activity [41]. Biochemical studies
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28 established that the D8D7I was the catalytic subunit and the drug-binding site of the
29
30 ChEH/AEBS complex [41, 42]. The AEBS is known as a promiscuous binding site interacting
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32 with different structural families of compounds including SERMs, diphenyl methane compounds
33
34 like tesmilifene, phenothiazines, as well as endogenous metabolites such as ring-B oxysterols,
35
36 unsaturated fatty acids, or histamine [3, 19, 25, 28, 29, 42-44]. The AEBS is present in BC cells
37
38 and other cell lines representative of different cancers [23, 24, 26, 27, 45, 46]. Histamine was the
39
40 only non-lipidic compound ever described as an AEBS ligand, and the AEBS was considered as
41
42 an intracellular binding site for histamine (HIC) for a while [47, 48]. Histamine is involved in
43
44 pleiotropic physiological functions such as neurotransmission, inflammation and gastric acid
45
46 secretion [49] and was proposed to play a role in cell proliferation through the AEBS-HIC [47,
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48 50-53]. Tam and selective AEBS ligands were considered as antagonists of histamine on HIC
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50 [46, 54, 55] before the molecular identification of the AEBS was made. High affinity AEBS
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4 ligands induced breast cancer cell differentiation into lactating cells via binding to the AEBS and
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6 modulation of the cholesterol metabolism in cancer cells [20-23, 44]. Looking at the
7
8 physiological importance of D8D7I and DHCR7, geneticists showed that null mutations on
9
10 DHCR7 and D8D7I were associated with severe alteration of mammalian development, and these
11
12 syndromes were not reversed by cholesterol complementation [56, 57]. Since DHCR7 and D8D7I
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14 carried out the AEBS/ChEH complex, this would suggest that 5,6-EC metabolism could play a
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16 role in developmental processes in mammals and may required the production of compounds that
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18 could activate pluripotent cell differentiation and may induce re-differentiation of de-
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20 differentiated cells like cancer cells. We thus postulated that 5,6-ECs or their putative metabolites
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22 could be involved in the control of cell differentiation. 5,6-EC exist as two diastereoisomers
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24 (5,6 α -EC and 5,6 β -EC) that display different biological properties and are prone to different
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26 metabolic fates [58]. In BC cells expressing the sulfotransferase SULT2B1b, it was found that the
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28 3 β -sulfated form of 5,6 α -EC (but not 5,6 β -EC) was the second messenger of AEBS ligands
29
30 (including Tam) in their induction of BC cell differentiation and LXR-dependent cell death [19,
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32 20]. Other metabolic transformations of 5,6-EC would be possible at the level of the epoxide
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34 group, which can make addition reaction of with nucleophiles (i.e. -SH or -NH₂ groups) in the
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36 presence of a catalyst [58, 59]. A member of the epoxide hydrolase family: the cholesterol-5,6-
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38 epoxide hydrolase (ChEH) is required for the hydration of the epoxide group of both 5,6-EC
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40 isomers in cells and tissues to produce cholestane-3 β ,5 α ,6 β -triol (CT) [42, 60, 61]. CT was not
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42 found to display cell differentiation properties [42], but instead to inhibit osteoblastic
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44 differentiation of rat bone marrow stromal cells [62]. CT is prone to sulfation by SULT2B1b but
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46 not to fatty acid esterification by the AcylCoA-Cholesterol:Acyl Transferase (ACAT) on its 3 β -
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48 hydroxyl group [20, 58]. The biological properties of the 3 β -sulfated form of CT have never been
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50 investigated to date. In BC cells, CT was found extensively metabolized into 6-oxo-cholestan-

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4 3 β ,5 α -diol (OCDO), which was shown to be a tumor promoter [6, 63]. Looking at 5,6-EC
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6 chemical reactivity, 5,6 α -EC (but not 5,6 β -EC) was found prone to conjugation reactions with
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8 nucleophilic groups on its epoxide ring in the presence of a catalyst [3, 58, 59, 64]. Because of
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10 the positioning of the epoxide group at the junction of ring A and B on the steroid backbone and
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12 for thermodynamic reasons, this reaction gave a single product of addition with nucleophiles [58,
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14 59]. The product of this conjugation reaction resulted from a trans-diaxial epoxide ring opening
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16 with the concerted engrafting of the nucleophilic group at C6 in a β orientation, and the formation
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18 of a hydroxyl group on C5 in an α orientation [58, 59]. The facts that: 1) 5,6 α -EC was the only
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20 isomer to react, 2) 5,6 α -EC gave a single product of condensation with nucleophiles, and 3) the
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22 reaction needed a catalyst to occur, suggested a metabolic transformation pathway of 5,6-EC [3].
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24 Because histamine was known as a ligand of the AEBS/ChEH complex [47, 48], it was
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26 postulated that biogenic amines such as histamine or polyamines (spermine, spermidine or
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28 putrescine) could produce compounds with potent cancer cell differentiation properties at low
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30 concentrations. A series of conjugation products were synthesized and screened for their
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32 capacities to induce cell differentiation.
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43 **2. DDA is an inductor of cell differentiation and a mammalian metabolite**

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45 The conjugation of 5,6 α -EC with histamine gave as single product of transformation
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47 identified as 5 α -hydroxy-6 β -[2-(1H-imidazol-4-yl)-ethylamino]-cholestan-3 β -ol also named
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49 dendrogenin A (DDA) (Figure 1A) [64]. DDA induced on cancer cells, *in vitro* and *in vivo*, the
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51 appearance of a “normal-like” phenotype at sub-nM concentrations evidencing a re-
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53 differentiation of cancer cells. 5,6-EC or histamine had no effects in the same conditions [1-4,
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55 64]. As an example, DDA induced the differentiation of melanoma cells into melanocytes, and of
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57 breast cancer cells of ductal origin into lactating cells [4, 64]. In addition, DDA was shown to
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4 induce the differentiation of pluripotent cells and normal neural stem cells into neurons [64, 65].
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6 Dendrogenin A (DDA) was confirmed as a mammalian metabolite in 2013, and was detected in
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8 several mammalian tissues including breast, brain, liver, spleen and blood [4]. Evidences were
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10 obtained that DDA can be produced endogenously by an enzyme [4], and we have recently
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12 succeeded in our quest on the molecular identification of this enzyme confirming the enzymatic
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14 nature of DDA production. (Poirot M & Silvente-Poirot S et al, unpublished observations). The
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16 presence of DDA in serum indicated that DDA circulates in the body and could eventually feed
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18 tissues and organs. Quantification of DDA in tissues were done by reverse phase HPLC
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20 purification and mass fingerprint of fractions of interest to discriminate DDA from its inactive
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22 isomer C17 (Figure 1B) [4]. A new method of dosage is being developed using liquid
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24 chromatography tandem mass spectrometry. This new method is fast, resolving, has a weak
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26 carryover, and efficiently separates DDA from its C17 isomer and other steroidal alkaloids from
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28 the same family [66]. The use of this method will make possible to analyze large cohort of
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30 samples. Despite a high expression of the AEBS/ChEH in cancer cells, DDA was not detected
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32 and DDA levels were found strongly decreased in breast cancers samples from patients compared
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34 to “normal” adjacent tissues, indicating a deregulation of DDA metabolism in cancers [4]. These
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36 observations ruled out the hypothesis that the AEBS/ChEH, even if it could concentrate 5,6 α -EC
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38 and histamine at their ligand binding site, was not sufficient to contribute to DDA biosynthesis
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40 and to catalyze the reaction by a proximity effect in cancer cells[67-69]. The recent molecular
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42 identification of the DDA synthase showed that this enzyme was different from the AEBS/ChEH
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44 and that a loss in DDA synthase expression on breast tumors explained the decrease in the DDA
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46 level (M Poirot Silvente-Poirot et al, unpublished results). Pharmacological studies showed that
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48 DDA induced cancer cell differentiation and death on cells of murine and human origins (Figure
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50 2) [4, 64]. It was shown that DDA was active *in vivo* at low concentrations (0.015 μ g/kg) to
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4 prevent and inhibit the development of BC and melanoma on immunocompetent mice [4]. This
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6 effect was accompanied by cancer cell differentiation and tumor infiltration by T lymphocytes
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8 and dendritic cells, suggesting a possible activation of an immune response by DDA against the
9
10 tumor [4]. DDA was found to be a potent and selective inhibitor of the ChEH, with no impact on
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12 other known epoxide hydrolases, and DDA did not display any ER modulatory activity [4]. DDA
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14 is, to date, the most potent endogenous inhibitor of ChEH compared to other ring-B oxysterols [4,
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16 41, 42]. Importantly, the K_i of DDA for ChEH was 120 nM, which is the range of its endogenous
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18 concentration in healthy tissues [4]. To determine whether DDA might be of clinical interest, the
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20 efficacy of DDA was tested on melanoma and leukemia human cancers and the mechanisms
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22 mediating DDA-induced cell death were studied.
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31 **3. DDA induces lethal autophagy in cancer cells.**

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33 It was shown that DDA was cytotoxic on human and mouse cancer cells of various tissue
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35 origins including melanoma and leukemia cells [7, 64, 70]. DDA induced a dose- and time-
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37 dependent cytotoxicity in both melanoma and acute myeloid leukemia (AML) cell lines
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39 indicating that DDA effects were receptor-mediated, while the C17 compound (Figure 1B), a
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41 geometric isomer of DDA, was inactive. It was shown that DDA induced characteristics of
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43 apoptosis, but caspase inhibitors failed to protect cells against DDA showing that apoptosis was
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45 not the driver of DDA cytotoxicity. DDA cytotoxicity was shown to require transcription and
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47 translation of new genes. The screening on the expression of a panel of transcription factors
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49 stimulated by DDA revealed a huge increase in NR4A1 (Nur77) and NR4A3 (NOR1) mRNAs
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51 expression in melanoma cells. This stimulation was confirmed at the protein level [7]. Knock
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53 down experiments in cancer cells showed that these transcription factors were required in DDA
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55 cytotoxicity [7]. The contribution of Nur77 to cell death was mainly related to caspase
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4 independent cell death [71] and lethal autophagy [72-76] when over expressed. Because DDA
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6 was shown to be a potent inhibitor of ChEH [4], and because the inhibition of ChEH was
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8 associated to the accumulation of pro-autophagic sterol zymostenol [19, 40], the impact of DDA
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10 on cholesterol metabolism in cancer cells was studied. *In vitro* and *in vivo* studies showed that
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12 DDA did not induce 5,6-EC accumulation. As opposed to other known ChEH inhibitors,
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14 cholesterol epoxidation was not stimulated by DDA, even if DDA induced ROS production. The
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16 explanation was that DDA induced catalase expression, the enzyme that destroys H₂O₂. This
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18 mechanism impairs the cholesterol epoxidation process. By comparison the ChEH inhibitors Tam
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20 and PBPE stimulated H₂O₂ production but had no impact on catalase expression [7], and they
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22 induced 5,6-EC formation and accumulation [7, 19]. DDA induced the accumulation of the
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24 cholesterol precursor zymostenol in cancer cells as observed with other high affinity ChEH
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26 inhibitors [7, 19]. Because zymostenol accumulation [19, 21, 22, 36, 44] and NR4A1 [73, 75, 76]
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28 have been linked to autophagy, the impact of DDA on autophagy was studied. It was found that
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30 DDA induced various characteristics of autophagy such as the formation and the accumulation of
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32 autophagosomes, lysosomes, and autolysosomes in melanoma and acute myeloid leukemia cells
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34 [7]. DDA did not induce a blockage of autophagy as observed for several compounds [77, 78] but
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36 on the contrary stimulated the autophagic flux [7]. Pharmacologic and genetic inhibitions of
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38 autophagy and NR4A protein expression inhibited DDA-induced tumor cell death, evidencing
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40 that DDA induced a lethal autophagy (Figure 2). This is the opposite to what was found with
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42 ChEH inhibitors such as Tam or PBPE which induced a protective autophagy in cancer cells [7,
43
44 19, 21, 22, 70]. Because DDA is not a SERM like Tam, but is an AEBS ligand and a ChEH
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46 inhibitor like PBPE, and because DDA induces a lethal autophagy and not a survival autophagy
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48 like Tam and PBPE, the existence of another molecular target for DDA that could explain this
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50 effect was investigated.
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7 **4. DDA is a ligand and modulator of the nuclear receptors LXR.**
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9 Microscopic autoradiography of cancer cells treated with ¹⁴C-labelled DDA showed that
10 DDA was mainly present into the nucleus of cells [7], suggesting that DDA could activate a
11 ligand-dependent transcription factor. DDA being an OS and NOR1 which expression is
12 stimulated by DDA being under the transcriptional control of the OS receptor [20, 79-82] liver-
13 X-receptor (LXR) [83], it was investigated whether the LXR could be a DDA target. LXR belong
14 to the nuclear receptor superfamily and exist as two isoforms, LXR α (NR1H3) and LXR β
15 (NR1H2) [84]. OS are oxygenation products of cholesterol [85], and while side chain OS were
16 found to be agonists on LXR, ring B-OS were reported to exert cell and gene context-dependent
17 antagonist, agonist, or inverse agonist activities on the LXR [20, 79, 80]. Tests using LXR-
18 dependent gene reporter assays showed that DDA inhibited dose-dependently the stimulation of
19 the reporter gene by the agonist 22(R)hydroxycholesterol with an IC₅₀ of 76 \pm 12 nM for LXR β
20 and 362 \pm 52 nM for LXR α [7]. This established a potent regulatory activity on the LXR different
21 from side chain-OS that displayed only agonist activity on such assays [8]. A similar approach
22 was used to established that DDA did not modulate other ligand-dependent nuclear receptors
23 such as steroid hormone receptors or SXR, AHR, VDR, RAR and PPAR[7]. The direct targeting
24 of LXR by DDA was supported by DDA binding experiments performed on purified ligand
25 binding domain LXR isoforms through both a ligand competition assay and surface plasmon
26 resonance assays. Molecular modeling and docking experiments of DDA-ligand-binding domain
27 of LXR isoforms complexes revealed the importance of specific chemical groups of DDA in their
28 interaction with specific amino acids of LXRs. Structure-activity studies with DDA analogues
29 modified on specific chemical groups of DDA such as the imidazol ring (C41, Fig 1B), the
30 hydroxyl in C5 (C31, Fig 1B) or the sterol side chain (C51, Fig 1B), as well as the DDA isomer
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4 in which histamine was grafted on 5,6 α -EC by the imidazol ring (C17, Fig 1B), induced a loss or
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6 an inversion in the LXR modulatory activities of DDA. Although it was shown on the gene
7
8 reporter assay that DDA was an antagonist. DDA treatment of cancer cells increased in an LXR β -
9
10 dependent manner the levels of mRNAs encoding NR4A1, NR4A3, LC3A and LC3B, while the
11
12 prototypical LXR ligands 22(R)HC, GW3965 and T0901317 had little or no effects [7] (Table 1).
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14 Looking at the LXR-dependent gene expression at the mRNA level. It was found that DDA
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16 repressed ABCA1 mRNA expression while it stimulated the expression of SCD1, two LXR-
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18 dependent genes. DDA stimulated the expression of the LDLR at the mRNA level. LDLR is
19
20 known as indirectly regulated through LXR-Idol pathway at the protein level [86], but no
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22 regulation of Idol mRNA expression by DDA was found at least on mouse embryonic fibroblast
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24 even if 22(R)HC increased Idol expression in an LXR β -dependent manner [7]. *LDLR* is known to
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26 be primarily under the transcriptional control of the transcription factor SREBP2, which is
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28 activated when the intracellular cholesterol decreases [87]. However, chromatin
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30 immunoprecipitation assays showed that DDA repressed the binding of LXR β on an enhancer
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32 region close to the *LDLR* gene suggesting a direct regulation of LDLR by LXR β , while it was
33
34 found on the same study that 22(R)HC increased LXR β binding [7]. Thus, it is probable that
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36 DDA cholesterol efflux and influx in cancer cells and a detailed analysis will required further
37
38 investigations. Altogether, these data showed that DDA was an LXR modulator rather than an
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40 antagonist. The use of a gene ontology (GO) that could be regulated by LXR led to the
41
42 identification of several genes regulating autophagy and lysosome biogenesis, in particular the
43
44 transcription factor EB (TFEB), known as a master regulator of both pathways [88-90]. DDA
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46 decreased LXR β -binding to a TFEB enhancer and stimulates TFEB expression in a
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48 concentration-dependent manner, while 22(R)HC did the opposite, evidencing that the LXR β and
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50 LXR agonists act as repressors of TFEB, while DDA de-repressed this gene. In accordance with
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4 this, DDA increased the activity of a TFEB-dependent gene reporter assay dose-dependently
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6 showing that DDA stimulated the transcriptional activity of TFEB [7]. The targeting of LXR by
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8 DDA was further confirmed through knockdown experiments showing that LXR β was necessary
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10 for DDA-induced NR4A1, NR4A3, LC3 expression and lethal autophagy (Figure 3). Moreover,
11
12 it was shown that LXR agonists partially reversed DDA cytotoxicity. Altogether, these data
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14 indicated that DDA triggered an LXR-dependent tumor cell death. This effect was specific of
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16 DDA and was not observed with other LXR ligands such as 22(R)HC, GW3965 and T091317
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18 and thus DDA appears as “first in line” on this effect (Table 1). These data revealed that DDA
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20 and LXR β are new players in the control of autophagy and lysosomes biogenesis [70].
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28 **5. DDA triggers anticancer action *in vivo* on human cancer cells, including patient-derived** 29 30 **AML.** 31

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33 It was shown that DDA displayed chemopreventive and anticancer effects at low doses on
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35 syngeneic tumors implanted on immunocompetent mice. These affects were associated with
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37 cancer cell re-differentiation and T lymphocyte and dendritic cell infiltration suggesting the a
38
39 contribution of the immune system on the anticancer action of DDA [4]. DDA also killed human
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41 cancer cells *in vitro* at micromolar concentrations [64] suggesting that DDA could be active
42
43 against human tumors *in vivo*. To investigate the efficacy of DDA on human cancers, DDA was
44
45 tested on human cell lines or patient tumors implanted on immunodeficient mice. A new
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47 formulation of DDA was required to achieve higher concentration, and a lactate salt form of
48
49 DDA with improve water solubility was produced [91]. Experiments were conducted by
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51 implanting melanoma cells lines B16F10 and SKMEL-28 on nude mice, acute myeloid leukemia
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53 cell lines HL-60 and KG1 on NOD/SCID mice. Administration of DDA to mice bearing
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55 established tumors showed a blockade in the tumor growth. Tumor analyses showed that DDA
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4 treatment induced an over-expression of Nur77 and NOR1 and a stimulation of LC3-II
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6 expression and a punctation of LC3 was observed by immunohistochemistry. All these
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8 characteristics are those that were measured *in vitro*. The LXR-dependence of DDA effects *in*
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10 *vivo* was demonstrated both by genetic and pharmacologic approaches. The knock down of
11
12 LXR β in cancer cells using small hairpin RNA targeting LXR β , induced a loss of sensitivity to
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14 DDA in these cells on *in vitro* and *in vivo* assays and the synthetic LXR agonist T0901317
15
16 partially reversed DDA anticancer action [7]. Because DDA is not a modulator of most other
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18 nuclear receptor, DDA could be consider at the moment as a selective liver X receptor modulator
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20 (SLiM) [92], confirming that developing modulator of such compounds is of interest for
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22 therapeutic application as earlier suggested [93].
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29 To further confirm the clinical interest of DDA, tests were conducted on primary tumors
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31 from patients with AML. Theses cancer cells were found sensitive to DDA independently to
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33 their molecular and cytogenetic classification and thus AML cells with intrinsic resistance to
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35 cytarabin (AraC) or anthracyclins were found sensitive to DDA as well as cancer stem cells [7].
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37 DDA induced *in vitro* and *in vivo* an anticancer action of these cells blocking bone colonization
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39 by cancer cells. No toxicity was observed at active doses of 20 to 40 mg/kg and DDA met the
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41 important expectation for an LXR ligand that is candidate for a clinical evaluation [94]; DDA did
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43 not induced steatosis and hypertriglyceridemia in mice[7]. Importantly, DDA treatment led to the
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45 accumulation of DDA in tumors to reach an active anticancer concentration. Together these data
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47 established the strong anticancer potency of DDA *in vivo* on melanoma and AML.
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56 **Conclusion**

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4 If genomic and proteomic approaches led to an extensive characterization of the existing genes
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6 and proteins, the metabolome is still an underexplored universe [95] in which the immersed and
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8 hidden part of this iceberg remains to be characterized [96]. Lipids account for more than 30,000
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10 different species and specialists estimated that this number could grow up to 200,000 different
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12 species [97]. Among them, sterol lipids constitute an emerging class defining the sterolomics [98,
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14 99]. Cholesterol-5,6-epoxides (5,6-EC) was found at the center of a new branch [58] in the
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16 cholesterol pathway thanks to the recent identification of DDA [4]. The identification of DDA as
17
18 a metabolite was possible because DDA was first chemically synthesized, chemical tools were
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20 produced (labeled precursors and DDA), specific analytical methods were set up, and because
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22 synthetic DDA displayed cancer cell re-differentiation properties at low concentrations *in vitro*.
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24 Studies on DDA metabolism led to the discovery that DDA was present in various mammalian
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26 tissues. The analyses of cancer cells and tumors revealed a deficiency in DDA presence
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28 highlighting a deregulation in DDA metabolism during carcinogenesis. This suggested that a
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30 DDA complementation therapy may constitute a possible therapeutic approach against cancer.
31
32 This hypothesis was validated on tumor implanted in mice showing that DDA displayed
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34 anticancer properties against various cancers. This was exemplified for breast cancer, melanoma
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36 and acute myeloid leukemia [4, 7]. The analysis of the cellular effects of DDA showed that it
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38 activated cancer cell differentiation and death. The nature of cell death was lethal autophagy as
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40 opposed to most chemotherapeutic drugs that induced apoptosis and protective autophagy [40,
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42 100, 101]. DDA does not affect normal cell fate in mice, and thus DDA targets specifically
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44 cancer cells *in vivo*, deserving further clinical evaluations. Analyses of the molecular mechanism
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46 involved in the effect of DDA revealed that autophagic genes stimulated by DDA were under the
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48 transcriptional control of LXR β showing for the first time that this nuclear receptor controlled the
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50 expression of genes involved in autophagy and lysosome biogenesis. LXR β was found necessary
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4 to mediate DDA anticancer effects and the presence of LXR β in cancer cells will condition a
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6 response to DDA. LXR β is widely expressed in cancer cells of different origins and is up
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8 regulated in cancer cells compared to normal tissues [7, 102], strongly suggesting a possible
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10 efficacy on other cancers in addition to breast cancers, melanoma and AML as already shown in
11
12 vitro on cancer cell lines [64]. Both LXR and autophagy have been shown to be involved in the
13
14 control of immunity [93, 103-105], thus it would be of interest to determine if DDA have a
15
16 positive impact on antitumor immunity which could strengthen its anticancer potency. In
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18 conclusion, DDA is a molecule from the self, with tumor suppressor and anticancer properties
19
20 that induces lethal autophagy through an original mechanism making of DDA a "first in line"
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22 anticancer drug candidate. DDA is well tolerated in mice at therapeutic concentrations and
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24 exhibits the expected properties of a drug candidate for further application in LXR-targeted
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26 anticancer therapy.
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40 **List of abbreviations**

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42 AEBS, antiestrogen binding site; ChEH, cholesterol-5,6-epoxide hydrolase; dendrogenin
43 A/DDA, 5 α -hydroxy-6 β -[2-(1H-imidazol-4-yl)-ethylamino]-cholestan-3 β -ol; DHCR24, 3 β -
44 hydroxysteroid- Δ^{24} -reductase; DHCR7, 3 β -hydroxysteroid- Δ^7 -reductase; D8D7I/EBP, 3 β -
45 hydroxysteroid- Δ^8, Δ^7 -isomerase; cholesterol, cholest-5-en-3 β -ol; desmosterol, cholest-5,24-dien-
46 3 β -ol; zymostenol, 5 α -cholest-8-ene-3 β -ol; zymosterol, 5 α -cholesta-8,24-dien-3 β -ol; 7-
47 dehydrocholesterol, cholest-5,7-dien-3 β -ol; lanosterol, lanosta-8,24-dien-3 β -ol; 5,6 α -EC, 5,6 α -
48 epoxycholesterol; 5,6 β -EC, 5,6 β -epoxycholesterol; 5,6 α -ECS, HA, histamine; ER, estrogen
49 receptor; BC, breast cancer.
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55 **Chemical compounds:**

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4 dendrogenin A (PubChem CID: 9806490); tamoxifen (PubChem CID: 2733526); zymostenol
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6 (PubChem CID: 101770); 5,6 α -epoxycholesterol (PubChem CID: 227037); histamine (PubChem
7
8 CID: 774).
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10 11 12 13 14 **Conflict of interest**

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17 The authors declare no conflicts of interest.
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22 23 **Acknowledgements**

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25
26 Both authors have contributed to the writing of this manuscript. This work was funded by the
27
28 Institut National de la Santé et de la Recherche Médicale, the university of Toulouse III, the
29
30 Fondation de France (R11166BB), the INCA (PRTK-K15-118), the association « pour Céline »
31
32 and the association « Flo ».
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4 **Figure legends**
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7 **Figure 1. A) scheme presenting the biosynthesis of dendrogenin A from 5,6 α -epoxy-**
8 **cholesterol and histamine. B) chemical structure of DDA inactive analogues.**
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12 **Figure 2: Anti-cancer properties of DDA.** DDA induces cancer cell differentiation at nM
13 concentration and lethal autophagy at μ M concentration.
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18 **Figure 3: Scheme describing the mechanism of lethal autophagy induced by DDA.** The
19 binding of DDA to the LXR β and the transcriptional activation of LC3, TFEB, Nur77 and NOR1
20 genes are essential for DDA to mediate lethal autophagy in cancers *in vitro* and *in vivo*. The
21 inhibition of the cholesterol-5,6-epoxide hydrolase (ChEH) and of its D8D7 subunit by DDA
22 leading to sterol accumulation participates to DDA-induced increase lysosome formation, an
23 essential component of the autophagy machinery. This dual targeting may explain the sustained
24 lethal autophagy induced by DDA. LY: lysosome; AP: autophagosome; AM: amphisome; AL:
25 autolysosome.
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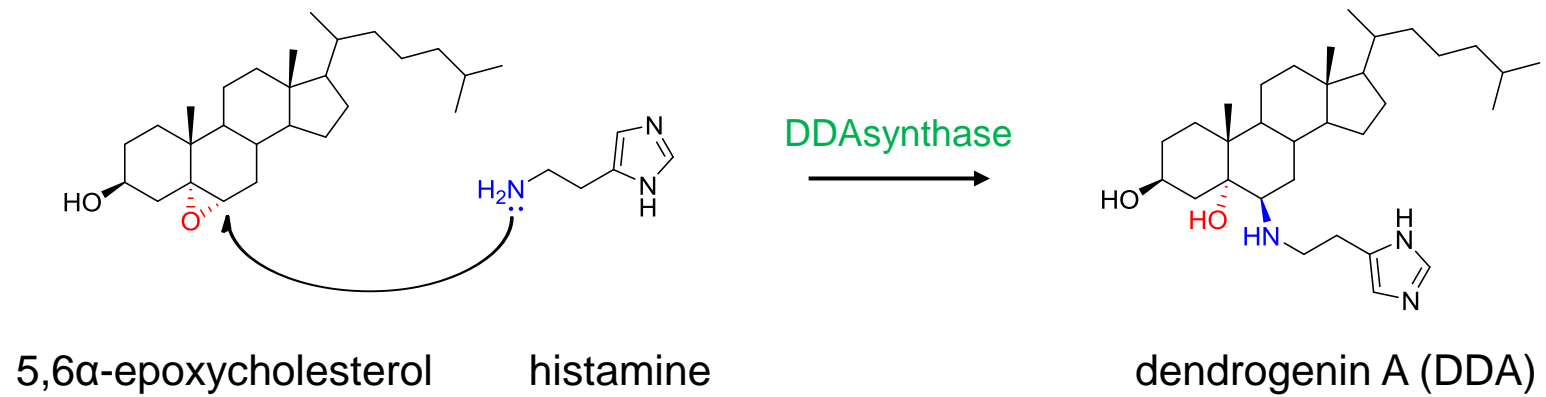
Table 1: Comparison between DDA and canonical LXR ligands on LXR-dependent genes expression and cancer cell fate.

	LXR-dependent gene expression						D8D7I inhibition	Cell death	Autophagy	
	LXR α/β	ABCA1	SCD1	LDLR	NR4A1	LC3A	TFEB			
DDA	yes	-	+	+	++	+	+	+	+	+
22(R)HC	yes	+	0	0	+	0	0	0	0	0
TO901317	yes	+	+	0	0	0	n.d.	0	0	0
GW3965	yes	+	+	0	0	0	n.d.	0	0	0

yes: LXR α/β ligand; -: down regulation; +: up regulation; 0: no effect; n.d. not determined.

Figure 1

A



B

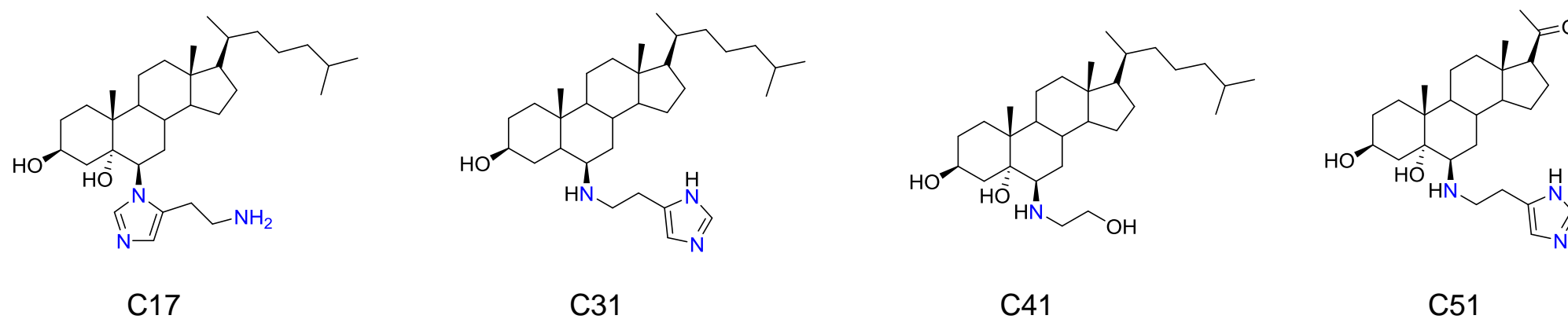


Figure 2

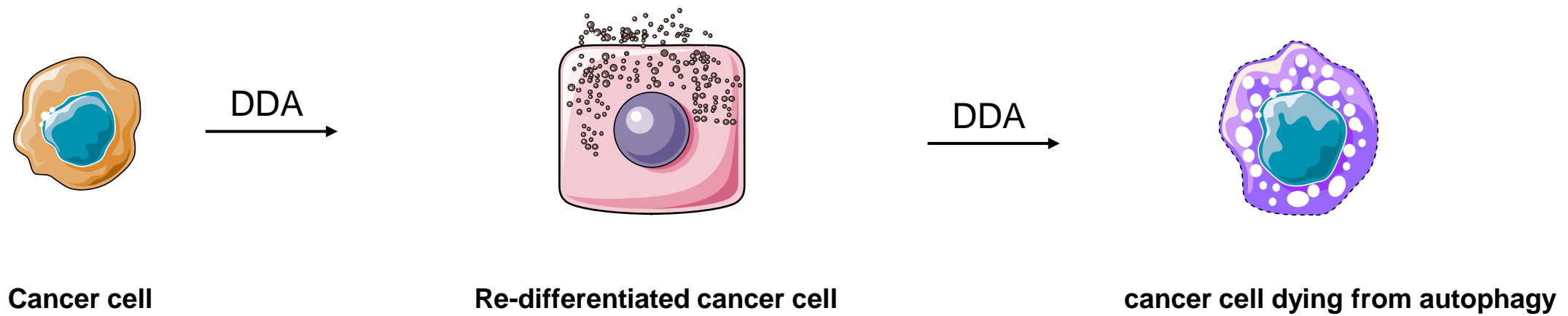


Fig 2 Poirot

Figure 3

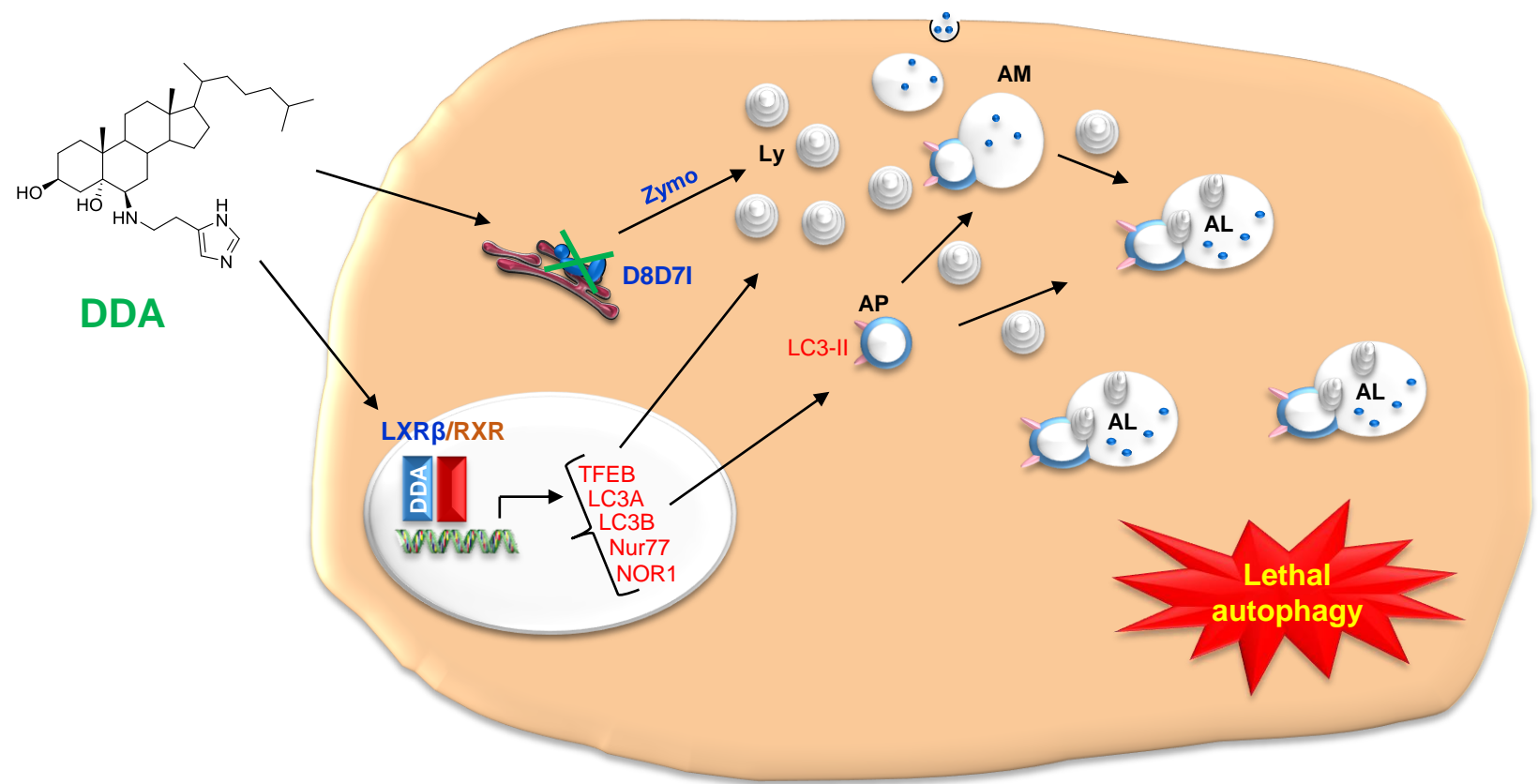


Fig 3 Poirot M

