Synthesis and cytotoxicity evaluation of functionalized betulin derivatives

Amardeep Patel
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SYNTHESIS AND CYTOTOXICITY EVALUATION OF FUNCTIONALIZED BETULIN DERIVATIVES

by

Amardeep Patel

A Thesis

Submitted to the
Department of Chemistry & Biochemistry
College of Science & Mathematics
In partial fulfillment of the requirement
For the degree of
Master of Science in Pharmaceutical Sciences
at
Rowan University
December 11, 2017

Thesis Chair: Subash Jonnalagadda, Ph.D.
Dedications

I dedicate my monograph work to my parents Ghanshyam Patel and Mina Patel, and my spouse Shruti Patel, who has been a consistent source of support and inspiration during the challenges of graduate school and the life. I am truly thankful for having you in my life and for having always loved me unconditionally. I also dedicate this monograph to my brother Varshil Patel and my son Prince Patel. I will always welcome all they have done for me.
Acknowledgments

I would like to express my appreciation to Prof. Subash Jonnalagadda for his guidance and help throughout this research. The skills and knowledge that I have gained are things that I will take with me into my next professional endeavour. I look forward to whatever challenges that come my way knowing that I am prepared to take them on. I would also like to thank Dr. Suman Pathi for his kind support through this journey.
Abstract
Amardeep Patel
SYNTHESIS AND CYTOTOXICITY EVALUATION OF FUNCTIONALIZED BETULIN DERIVATIVES
2017-2018
Subash Jonnalagadda, Ph.D.
Master of Science in Pharmaceutical Sciences

Betulin and betulinic acid are complex natural compounds that can be readily extracted in high quantities from external bark of yellow and white birch trees. Birch tree is native to northern New Jersey and is also commonly available for purchase as firewood. Betulinic acid is found to exhibit very good activity against few cancer cell lines, and is relatively non-toxic to normal cells. The ready availability and selective cytotoxicity coupled with the favorable therapeutic index have made betulinic acid an attractive and promising anticancer agent. However, this molecule is almost insoluble in water and shows anti-cancer activity only on very few cell lines.

This thesis details our efforts on the development of novel synthetic methodologies for the synthesis of functionalized betulin derivatives as potential anti-cancer agents. We initiated the synthesis of betulin conjugates starting from betulinic acid employing reactions such as Baylis-Hillman reaction and click reaction. Further functionalization of these conjugates was achieved via reduction and succinylation. The cytotoxicity evaluation of these compounds showed good potential as anti-cancer agents.
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Chapter 1
Introduction

Betulin/Betulinic Acid

Betulin 1 and betulinic acid (B/BA) are pentacyclic lupane–type triterpenoids that are found as secondary metabolites in various types of plants distributed across of plant kingdom (Figure 1).\textsuperscript{1,2} Betulin is abundantly available in the outer part of the birch bark and these trees are native to northern America and various parts of Europe. Betulonic acid 2 and betulinic acid 3 can be easily synthesized from betulin via simple redox chemistry. Betulinic acid exhibits significant cytotoxicity against various cancer such as melanoma, glioblastoma pancreatic cancer, breast, and prostate cancer, etc.\textsuperscript{3} Further their derivatives also exhibit diverse range of pharmacological properties ranging from anti-HIV, anti-micotic, anti-inflammatory, anti-parasitic, and antioxidants.\textsuperscript{4-13} There have been several reports on the synthesis and development of the betulin derivatives as potential medicinal agents.\textsuperscript{4-13} One of the recognized analogs of betulinic acid is bevirimat 4, which shows excellent anti-HIV activity with a new mechanism of action known as virus maturation inhibition. This molecule was developed by Panacos Pharmaceuticals and it reached Phase IIb clinical trials for the treatment of HIV. While the mechanism of action is unclear, several reports indicate that betulinic acid triggers apoptosis via direct regulation of mitochondrial pathways and increased production of caspase-3.\textsuperscript{4-14} Betulinic acid is also known to produce an anti-angiogenic response as well as affect the immuno-regulation \textit{in-vivo} and arrest the cell cycle in the G2/M phase.\textsuperscript{4-13}
Further, betulinic acid has been evaluated for the *in vivo* protective effect on dexamethasone-induced thymocyte apoptosis via reduction of oxidative stress.\textsuperscript{15} Betulin also inhibits TLR4/NF-kB pathway which results in reduction of kidney,\textsuperscript{16} liver, and lung\textsuperscript{17} injuries in rats. It also exhibits protective effects against colitis in mice.\textsuperscript{18}

![Figure 1. Betulinic acid analogs.](image)

**Multicomponent Reactions**

Multi-component coupling reactions involve the combination of three or more precursors to form complex products. These reactions are highly atom, economical and exhibit excellent chemo selectivity. These reactions offer wide range of benefits in drug development as these are usually highly convergent one pot reactions which offer
high diversity in the product formation. There have been several examples of the use of MCRs for the development of medicinal compounds such as kinase inhibitors, tubulin inhibitors, aspartyl protease inhibitors, serine protease inhibitors, metaloprotease inhibitors, GPCR inhibitors and so on.\textsuperscript{19}

Some of the famous examples of MCRs include alkyne trimerization, Biginelli reaction, Bucherer-Bergs reaction, Gewald reaction, Greico three component coupling, Hantzsch pyridine synthesis, Mannich reaction, Passerini reaction, Pauson-Khand reaction, Petasis reaction, Ugi reaction, Strecker synthesis, etc.\textsuperscript{20}

Passerini reaction involves the coupling of an isocyanide 7 with an aldehyde 5 or ketone and a carboxylic acid 6 to yield an $\alpha$-acyloxy amide product 8;\textsuperscript{21} similarly the Ugi reaction involves four components coupling between an isocyanide 7, and aldehyde/ketone 5, an amine 9, and a carboxylic acid 6 to furnish $\alpha$-carboamido amides 10 (Figure 2).\textsuperscript{22}
Prior to the current work, our group has synthesized several betulinic acid analogs via multicomponent coupling reactions such as reductive amination, aldol condensation, and Passerini reaction.

**Synthesis of Betulin-Chalcone Conjugates**

The betulin-chalcone analog 15 was synthesized starting from betulin in five steps. Initially, betulin 1 was esterified as C$_3$-C$_{28}$ diester, which was then selectively hydrolyzed with aluminum isopropoxide to furnish the primary alcohol and subsequently oxidized with PCC to generate the aldehyde 11. Reaction of 11 with acetophenone 12 in the presence of potassium tert-butoxide in THF yielded the chalcone 13 with the concomitant hydrolysis of C$_3$ ester. This compound was further converted to the target compound succinic acid hemi ester 14 upon heating with succinic anhydride 14 in the presence of DMAP (Figure 3).
Figure 3. Preparation of betulin-chalcone conjugates.

Synthesis of Betulin Conjugates via Passerini Reaction

The betulin aldehyde 11 was reacted with variety of carboxylic acids and isocyanides to furnish the C_{28} acetoxyamide derivatives 16 and 17. We were also able to synthesize a fluorescent BODIPY- betulin conjugate 19 via this protocol (Figure 4).
Figure 4. Preparation of betulin conjugates via Passerini reaction.

Synthesis of Betulin Conjugates via Reductive Amination

The betulin aldehyde 20 was subjected to reductive amination with benzyl amine and sodium borohydride to yield secondary amine, which was then treated with benzyl
bromide to furnish the tertiary amine 21 (Figure 5).

![Figure 5. Preparation of betulin conjugates via reductive amination.](image)

**Synthesis of Betulin Conjugates via Click Reaction**

The click reaction is a 1,3-dipolar cycloaddition reaction involving the coupling of azides 22 and alkynes 23 in the presence of copper catalyst which results in the formation of 1,4 disubstituted 1,2,3 triazoles 24 (Figure 6).24 The product triazoles have a wide range of medicinal application and are heavily used in natural product drug discovery,25 biopolymers,26 nano-technology,27-28 and other biomaterials.29 Click chemistry has been used extensively in high throughput synthesis and assembly of the chemical libraries.

![Figure 6. Click reaction.](image)

Several betulin conjugates have been developed via click chemistry *albeit*
with limited biological success. Bori et al. described an efficient strategy to link azidothymidine with betulin/betulinic acid via click chemistry. Selective monoprotection of C$_{28}$ primary alcohol in 1 with TBS chloride was achieved followed by the propargylation of C$_3$ secondary alcohol to provide the ether 25a. Alternatively, betulin propargyl carbonate 25b was also obtained via the reaction of C$_{28}$ silyl betulin ether with triphosgene followed by the addition of propargyl alcohol. Theses alkynes 25a-b were subjected to click coupling with azidothymidine to yield the triazoles 26a-b (Figure 7).}

\[
\text{HO} \quad \text{AZT}, \text{Cu}, \text{CuSO}_4.5\text{H}_2\text{O} \\
\text{R} \quad \text{OTBS} \\
\text{(a) TBSCI, DMAP, DIPEA, 0}^0\text{C} \\
\text{(b) Propargyl bromide, NaH} \\
\text{(c) (i) triphosgene, (ii) propargyl alcohol} \\
\]

\[
\text{HO} \quad \text{N} \quad \text{N} \quad \text{N} \quad \text{O} \quad \text{N} \quad \text{N} \quad \text{H} \quad \text{O} \quad \text{HO} \\
\text{26a, R = O, 26b, R = OCO}_2 \\
\]

\[
\text{AZT, Cu, CuSO}_4.5\text{H}_2\text{O} \\
\text{R} \quad \text{OTBS} \\
\text{25a, R = O, 25b, R = OCO}_2 \\
\]

\[
\text{HO} \quad \text{N} \quad \text{N} \quad \text{N} \quad \text{O} \quad \text{N} \quad \text{N} \quad \text{H} \quad \text{O} \quad \text{HO} \\
\text{26a, R = O, 26b, R = OCO}_2 \\
\]

**Figure 7.** Betulin-AZT conjugates via click chemistry.

Bori and co-workers were also able to synthesize Betulinic acid-AZT conjugate 29 via the succinylation of betulinic acid 3 with dimethylsuccinic anhydride 27 to yield the diacid 28. Esterification of C$_{28}$ acid in 28 with propargyl bromide followed by click coupling with AZT resulted in the formation of the target compound 29.
Some of these compounds showed efficacy as anti-AIDS agents with EC50 values ~0.1 μM.

Figure 8. Betulinic acid-AZT conjugates via click chemistry.

Similarly, Khan and co-workers synthesized N-aryl triazole conjugates 30 of betulinic acid 3 under identical conditions (Figure 9). Some of these analogs showed better potency against four human cancer cell lines (HL-60, MiaPaCa-2, PC-3, and A549) when compared to the parent natural products of betulinic acid. 31

Dang Thi et al reported betulinic acid AZT conjugates 32, which showed moderate cytotoxicity on KB and Hep-G2 cancer cells (Figure 10). 32
Figure 9. Betulinic acid-triazole conjugates via click chemistry.

Csuk et al reacted the aldehyde 33 with lithium acetylide followed by the oxidation of the resulting alcohol to furnish the diketone 34, which was then coupled with \( p \)-azidobenzoic acid or ethyl azidoacetate to yield the triazoles 35. Some of these molecules showed moderate cytotoxicity as established via fifteen human cancer cell line assay (Figure 11)\textsuperscript{33}.

Figure 10. Betulinic acid-AZT conjugates as anti-cancer agents.
Figure 11. Betulonic acid-triazole conjugates via click chemistry.

Shi et al synthesized the triazoles 37 via modification at the C30 position of betulin 1. Initial diesterification of betulin 1 followed by the selective monodeprotection of the primary alcohol and allylic bromination with NBS yielded the bromide 36. The bromide 36 was converted to azide and further subjected to click coupling with variety of terminal alkynes in a one-pot transformation to yield the target compounds 37. These compounds showed anticancer activity against Leukemia cell lines HL60 (Figure 12). Under similar condition the C30 triazoles 39 of betulinic acid 3 were also synthesized (Figure 13).
Figure 12. Betulin-C30 triazole conjugates via click chemistry.
Chakrabarty et al. converted the C₃ alcohol of betulinic acid 3 as the chloroacetyl ester followed by the treatment with sodium azide to yield the azido acid 40 which was then subjected to click coupling with different alkynes to furnish the target compounds 41 (Figure 14). The biological evaluation of these molecules showed anticancer activity in HT29 cell lines via induction of apoptosis and activation of caspase-3.35
Majeed and co-workers synthesized O-propargyl betulinic acid and coupled it with various azides using click chemistry resulting in the formation of triazolylbetulinic acid conjugates 42 (Figure 15). Some of these compounds showed potential as apoptotic agents.\textsuperscript{36}

**Figure 14.** Betulinic acid-C3 triazole ester conjugates via click chemistry.

**Figure 15.** Betulinic acid-C3 triazole ether conjugates via click chemistry.
Baylis-Hillman Reaction

Baylis-Hillman reaction was first reported in 1972 by German scientist A.B. Baylis and M.E.D. Hillman. This reaction is highly robust and involves in the coupling of activated alkenes with carbonyl or imine moieties resulting in the formation of densely functionalized allylic alcohols and amines. BH reaction involves the Michael addition of DABCO on an activated alkene followed by an aldol addition of the resulting enolate to the carbonyl compound. This reaction is quite versatile and has attracted the attention of several synthetic chemists worldwide. One of the minor drawbacks of this reaction deals with the slow rate of reaction. Accordingly, several approaches have been reported for the acceleration of the rate including the use of reactive activated olefins/electrophiles, microwave irradiation, enhanced hydrogen bonding capabilities, use of aqueous medium, and high pressures. Variety of activated olefins such as alkyl vinyl ketone, acrylates, acrylamides, acrylonitriles, acrolein, vinyl sulfones, vinyl sulfoxides, vinyl phosphonates, and allenyl esters etc. have been used for the effective coupling with an array of aliphatic, alicyclic, aromatic, and heteroaromatic aldehydes and the corresponding allylic alcohols have been obtained in high selectivity and yields (Figure 16). Baylis-Hillman template offers another significant advantage because of the presence of multiple sites for further functionalization, which gains importance especially in medicinal chemistry in terms of the determination of structure activity relationship (SAR) profile.
Figure 16. Baylis-Hillman reaction.
Chapter 2
Preparation of Betulin-Triazole Conjugates

In this project, we envisioned the preparation of betulinic acid-triazole conjugates using Baylis-Hillman reaction and click chemistry so as to improve the biological efficacy. Herein, we provide an account of our synthetic and biological evaluation results. We started our synthesis with the preparation of the two precursors for click chemistry namely the azides and alkynes. We contemplated the synthesis of azides utilizing Baylis-Hillman reaction and the alkynes starting from betulinic acid.

Synthesis of Azides via Baylis-Hillman Reaction

Under Baylis-Hillman reaction conditions, benzaldehyde 47 reacted with methyl acrylate 48 in the presence of DABCO at room temperature to afford the corresponding allylic alcohol 49 (Figure 17) as the colorless liquid in 78% yield. The three Baylis-Hillman motif derived allylic azides 51a-c were then prepared from the alcohol 49. Nucleophilic substitution of allylic alcohol 49 with HBr in the presence of H₂SO₄ at 0°C yielded the corresponding allylic bromide 50 in 74% yield. Conversion of the allylic bromide to allylic azide 51a was achieved using sodium azide in acetone: H₂O solvent medium at room temperature. The corresponding carboxylic acid derivative 52 was easily obtained upon hydrolysis in the presence of aq. NaOH in a mixture of THF/methanol solvent. Two other allylic azides 51b-c were synthesized by employing conventional amide coupling of the carboxylic acid 52 with N,N,N-trimethyl ethylenediamine 53 or N-methyl piperazine 54 in the presence of 2-(1H-benzo[d][1,2,3]triazol-1-yl)-1,1,3,3-tetramethyluronium tetrafluoroborate (TBTU) as coupling agent and
diisopropylethylamine (DIPEA) as the base in dimethylformamide (DMF) as solvent (Figure 17).

Figure 17. Preparation of α-azidomethylcinnamamides.

After succeeding in the synthesis of three Baylis-Hillman derived allylic azides 51a-c, we ventured into the synthesis of three β-azidoethylamides 51d-f. The two β-azidoethylamides 51d-e were prepared from BH allylic alcohol 49 (Figure 18). Reaction of 49 with acetic anhydride in the presence of triethylamine in dichloromethane (CH2Cl2) yielded corresponding acetate 55 in very good yield. The nucleophilic substitution (S_N2') of acetate 55 with N,N,N'-trimethylethylenediamine 53 in the presence of potassium carbonate (K2CO3) in DMF furnished the allylic amine 56 in 77% yield. Alkaline hydrolysis of 56 and the coupling of the resulting acid 57 with 2-azido ethylamine
in the presence of 1-ethyl-3-(-3-dimethylamino propyl) carbodiimide hydrochloride (EDCI), 1-hydroxybenzotriazole (HOBr) and Hünig’s base yielded β-azidoethylamide 51d in 74% yield. The β-azidoethylamide 51e was obtained following a similar procedure by replacing N,N,N-trimethylethylendiamine 53 with N-methyl piperazine 54 for coupling with acetate 55 followed by hydrolysis and amide coupling with 2-azidoethylamine (Figure 18).

The coupling of cinnamic acid 60 with 2-azidoethylamine under HOBr conditions furnished β-azidoethyl-cinnamamide 51f as a white solid in 73% yield (Figure 19). All of these compounds were characterized using proton, carbon, and mass spectral analysis.
Figure 18. Preparation of α-aminomethyl N-azidoethylcinnamamides.
Figure 19. Preparation of N-azidoethylcinnamamide.

**Synthesis of N-Propargyl Betulonamide**

Having prepared the azides from BH template, we focused our efforts on the functionalization of betulin for the preparation of click reaction counterpart. We initiated the synthesis of N-propargyl betulonamide 61 using Jones oxidation (CrO₃ in acetone, conc. H₂SO₄) of betulin 1, resulting in the formation of betulonic acid 2 as a white solid. The coupling of betulonic acid 2 with propargyl amine using TBTU and Hünigs base furnished N-propargyl betulonamide 16 in 73% yield upon recrystallization from hexane (Figure 20).
Figure 20. Preparation of N-propargyl betulonamide.

**Synthesis of Betulinic Acid-Triazole Conjugates**

After preparing the key intermediates N-propargyl betulonamide 61 and Baylis-Hillman motif-derived azides 51a-f, we undertook the click coupling of these precursors for the synthesis of 1,2,3-triazoles (Figure 21).
Figure 21. Target betulinic acid-triazole conjugates.

Click Coupling of N-Propargylbetulonamide with Azides

Initially, we attempted click coupling of methyl α-azidomethylcinnamate 51a with N-propargyl-betulonamide 61 using copper iodide. Under these conditions, we were unable to obtain the product triazole 62a in decent yield even after performing the reaction in different solvents at room temperature or reflux conditions. Switching from copper iodide to copper sulfate and sodium ascorbate mediated cycloaddition in t-butyl alcohol/water resulted in the formation corresponding 1,2,3-triazole derivative 62a as a cream solid in 89% yield (Figure 22). The compound 62a was confirmed by the characteristic triazole proton signal δ 7.74 (1H, s) in 1H NMR spectrum as well as by
ESI-MS spectral peak at 709.55 (M+H)^+.

Figure 22. Coupling of N-propargylbetulonamide with azides.

After synthesizing the betulinic acid-triazole conjugate 62a, under identical conditions, the reaction of the remaining Baylis-Hillman motif derived azides 51b-f with N-propargyl betulonamide 61 furnished the corresponding triazoles 62b-f in high yield (Figures 22 and 23). All the compounds were well characterized using NMR and mass spectrometric analyses.
Figure 23. Triazoles obtained from N-propargylbetulonamide.
Reduction of Betulonamide-Triazole Conjugates

We then reduced the C₃ ketone of 62a-f to the corresponding alcohol 63a-f using NaBH₄ in methanol. Under these conditions, the betulinic acid-triazoles 63a-f were obtained in good yield (Figures 24 and 25). All the compounds were well characterized using NMR and mass spectrometric analyses.

*Figure 24. Reduction of betulonamide-triazole conjugates.*
Figure 25. Triazoles obtained via reduction of betulonamide conjugates.
Succinylation of Betulinamide-Triazole Conjugates

Having prepared a series of C₃ alcohol betulinic acid-triazoles 63a-f, in an effort towards increasing the hydrophilicity of these compounds, these alcohols were heated with succinic anhydride in toluene to yield the corresponding succinic acid hemiesters 64a-f in 80-87% yield (Figures 26 and 27). All the compounds were well characterized using NMR and mass spectrometric analyses.

![Figure 26](image.png)

*Figure 26. Succinylation of betulinamide-triazole conjugates.*
Figure 27. Triazoles obtained via succinylation of betulinamide conjugates.
Biological Evaluation

All the synthetic analogs, as well as some of the intermediates, were evaluated for their cytotoxicity against murine breast cancer (4T1) and pancreatic cancer (MIA PaCa-2) cell lines. The cells were purchased from ATCC, and the assays were performed using standard conditions by seeding the cells in 96 well plates, and the cell viability was determined using MTT assay. Primary screening was carried out at concentrations of 50 \( \mu \text{M} \), 12.5 \( \mu \text{M} \) and 1.5 \( \mu \text{M} \) on two tumor cell lines as the parent natural product betulinic acid showed moderate activity (~60% inhibition of 4T1 and ~40% of MIA PaCa-2 cells) at 12.5 \( \mu \text{M} \), and majority of betulinic acid-triazole conjugates that were assayed, also displayed promising activity at this concentration (>90% inhibition of 4T1 and ~80-90% MIA PaCa-2 cells). The IC\(_{50}\) values were determined for the compounds that displayed moderate to good cytotoxicity. As shown in Table 1, the cytotoxicity profile of C3-alcohol containing betulinic acid-triazoles 63a-f proved to be better relative to the C3-ketone based analogs 62a-f. Interestingly, conversion of C3-alcohol to succinic acid hemiester, i.e., compounds 64a-f, resulted in a slight reduction in anticancer activity. Two compounds (63d-e) in the C3-alcohol series displayed good anti-cancer activity against 4T1 (2-3 \( \mu \text{M} \)) and MIA PaCa-2 (1-3 \( \mu \text{M} \)) cell lines when compared to their analogous C3-ketones 62d-e (4T1, 5-6 \( \mu \text{M} \); MIA PaCa-2, 5-9 \( \mu \text{M} \)) and C3-hemi esters 64d-e (4T1, 4-8 \( \mu \text{M} \); MIA PaCa-2, 10-27 \( \mu \text{M} \)).

Based on these results, we perceive the significance of C3-alcohol unit and \( N,N,N' \)-trimethylethlyenediamine/\( N \)-methylpiperazine motif at \( \alpha \)-position of cinnamamides for improving the biological action of these molecules. It should also be
noted that none of the intermediates tested showed any toxicity, which leads us to believe that the BH motif is also required for the activity. Efforts are currently underway to identify the mechanism of action for the lead derivatives as well as for the identification of potent candidate for further development.
Table 1

*In vitro cytotoxicity of betulinic acid-triazole conjugates.*

<table>
<thead>
<tr>
<th>#</th>
<th>Compound</th>
<th>4T1 [IC₅₀ (µM)]</th>
<th>MIA PaCa-2 [IC₅₀ (µM)]</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>62a</td>
<td>NT</td>
<td>NT</td>
</tr>
<tr>
<td>2</td>
<td>62b</td>
<td>6.93 ± 1.09</td>
<td>9.87 ± 0.79</td>
</tr>
<tr>
<td>3</td>
<td>62c</td>
<td>7.15 ± 0.18</td>
<td>14.99 ± 2.12</td>
</tr>
<tr>
<td>4</td>
<td>62d</td>
<td>5.67 ± 0.10</td>
<td>8.11 ± 1.54</td>
</tr>
<tr>
<td>5</td>
<td>62e</td>
<td>5.17 ± 0.60</td>
<td>5.98 ± 0.99</td>
</tr>
<tr>
<td>6</td>
<td>62f</td>
<td>NT</td>
<td>NT</td>
</tr>
<tr>
<td>7</td>
<td>63a</td>
<td>39.75 ± 9.45</td>
<td>NT</td>
</tr>
<tr>
<td>8</td>
<td>63b</td>
<td>3.97 ± 0.73</td>
<td>2.44 ± 0.36</td>
</tr>
<tr>
<td>9</td>
<td>63c</td>
<td>4.37 ± 0.43</td>
<td>8.69 ± 0.33</td>
</tr>
<tr>
<td>10</td>
<td>63d</td>
<td><strong>2.38 ± 0.45</strong></td>
<td><strong>1.36 ± 0.21</strong></td>
</tr>
<tr>
<td>11</td>
<td>63e</td>
<td><strong>2.62 ± 0.24</strong></td>
<td><strong>1.64 ± 0.20</strong></td>
</tr>
<tr>
<td>12</td>
<td>63f</td>
<td>27.26 ± 12.2</td>
<td>32.50 ± 7.92</td>
</tr>
<tr>
<td>13</td>
<td>64a</td>
<td>5.26 ± 0.65</td>
<td>47.58 ± 5.51</td>
</tr>
<tr>
<td>14</td>
<td>64b</td>
<td>7.48 ± 0.59</td>
<td>21.73 ± 5.12</td>
</tr>
<tr>
<td>15</td>
<td>64c</td>
<td>6.13 ± 0.81</td>
<td>14.44 ± 3.44</td>
</tr>
<tr>
<td>16</td>
<td>64d</td>
<td>4.13 ± 0.22</td>
<td>9.66 ± 0.51</td>
</tr>
<tr>
<td>17</td>
<td>64e</td>
<td>7.05 ± 0.53</td>
<td>24.28 ± 3.24</td>
</tr>
<tr>
<td>18</td>
<td>64f</td>
<td>8.61 ± 2.27</td>
<td>NT</td>
</tr>
</tbody>
</table>
Table 1 (Continued)

<table>
<thead>
<tr>
<th>#</th>
<th>Compound</th>
<th>4T1 $\text{IC}_{50}$ (µM)</th>
<th>MIA PaCa-2 $\text{IC}_{50}$ (µM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td><strong>3</strong> (betulinic acid)</td>
<td>$6.29 \pm 0.96$</td>
<td>$25.63 \pm 3.79$</td>
</tr>
</tbody>
</table>

NT = Not toxic
Conclusions

In conclusion, we have prepared betulinic acid-triazole derivatives utilizing Baylis-Hillman reaction and click chemistry as the key protocols in our synthesis. These compounds were tested for their biological efficacy against murine breast cancer cell line (4T1) and human pancreatic cancer cell line (MIA PaCa-2). Based on these *in vitro* assays, we have been able to identify two series of betulin derivatives for further SAR and pre-clinical studies. The ready availability of betulin from natural resources as well as the great chemical diversity afforded by the Baylis-Hillman template imparts significance to this class of compounds for potential development as *anti*-cancer agents.
Chapter 3
Experimental Procedures

Materials and Methods

All the reactants were of reagent grade, purchased from Acros Organics, Alfa Aesar or Sigma Aldrich, and used without further purification. All solvents were used without further drying or purification and were of ACS grade purchased from Fisher Scientific. All operations were carried out under an inert atmosphere of nitrogen. Glassware for all reactions was oven dried at 125 °C and cooled under nitrogen prior to use. Liquid reagents and solvents were introduced by oven-dried syringes or cannulas through septa sealed flasks under a nitrogen atmosphere.

Instrumentation

Nuclear Magnetic Spectroscopy (NMR) spectra were produced using a Varian 400 MHz spectrophotometer. The instrument was maintained at 25° C operating at 400 MHz for ¹H NMR, and 101 MHz for ¹³C NMR. The deuterated solvent (CDCl₃, DMSO-d₆) used for each respective spectrum is referenced to the appropriate literature peak shift.

Procedures

General amide-coupling procedure A. To a stirred solution of the appropriate acid (1.0 mmol) in dimethylformamide (10.0 mL), was added N,N-diisopropylethylamine (2.0 mmol) followed by TBTU (1.1 mmol) at 0 °C and stirred for 30 min. The appropriate amine (1.0 mmol) was then added in one portion and stirred overnight at room temperature. Upon completion (as indicated by TLC), the reaction mixture was quenched by the addition of saturated NaHCO₃ and extracted with dichloromethane (2 x 10.0 mL). The combined extracts were washed with cold water (10.0 mL) and brine (10.0 mL).
mL). The organic layer was dried over anhydrous Na₂SO₄, concentrated in vacuo, and purified by column chromatography (silica gel, hexanes:ethyl acetate) to obtain pure amides.

**General amide-coupling procedure B.** N,N-diisopropylethylamine (2.0 mmol), HOBt (1.1 mmol), and EDCI (1.1 mmol) were added at 0 °C to a stirred solution of the appropriate acid (1.0 mmol) in dichloromethane (10.0 mL) and the reaction was stirred for 30 min. The appropriate amine (1.0 mmol) was added in one portion and the reaction was stirred overnight at room temperature. After completion of the reaction as indicated by TLC, the reaction mixture was quenched by the addition of saturated NaHCO₃ solution and worked up with dichloromethane (2 x 10.0 mL). The combined extracts were washed with brine (10.0 mL), dried over anhydrous Na₂SO₄, concentrated in vacuo, and purified by column chromatography (silica gel, hexanes:ethyl acetate) to obtain pure amides in good yields.

(E)-2-(azidomethyl)-N-(2-(dimethylamino)ethyl)-N-methyl-3-phenylacrylamide: The reaction of (E)-2-(azidomethyl)-3-phenylacrylic acid (1.0 g, 4.9 mmol) with N,N,N’-trimethylethylene diamine (602 mg, 5.9 mmol) as per the general amide coupling procedure A yielded 1.02 g (72%) of 51b as a pale brown liquid. \(^1\)H NMR (400 MHz, CDCl₃): \(\delta\) (ppm) 7.31 – 7.44 (m, 3H), 7.26 – 7.31 (m, 2H), 6.78 (s, 1H), 4.30 (s, 2H), 3.61 (t, \(J = 7.1\) Hz, 2H), 3.15 (s, 3H), 2.55 (t, \(J = 7.1\) Hz, 2H), 2.28 (s, 6H); \(^13\)C NMR
(101 MHz, CDCl₃): $\delta$ (ppm) 169.5, 134.4, 133.5, 131.6, 128.8, 128.6, 128.4, 49.4, 45.7.

ESIMS: m/z calculated for C₁₅H₂₁N₅O (M+H)⁺ 288.18, found 288.38.

(E)-2-(azidomethyl)-1-(4-methylpiperazin-1-yl)-3-phenylprop-2-en-1-one: The reaction of (E)-2-(azidomethyl)-3-phenylacrylic acid (1.0 g, 4.92 mmol) with N-methylpiperazine (590 mg, 5.90 mmol) as per the general amide coupling procedure A furnished 1.04 g (74%) of 51c as a pale brown liquid. $^1$H NMR (400 MHz, CDCl₃): $\delta$ (ppm) 7.24 – 7.41 (m, 5H), 6.69 (s, 1H), 4.26 (s, 2H), 3.61 – 3.80 (m, 4H), 2.37 – 2.50 (m, 4H), 2.29 (s, 3H); $^{13}$C NMR (101 MHz, CDCl₃): $\delta$ (ppm) 169.9, 134.3, 134.0, 131.2, 129.0, 128.9, 128.8, 55.0, 49.5, 46.2. ESIMS: m/z calculated for C₁₅H₁₉N₅O (M+H)⁺ 286.16, found 286.30.

Methyl (E)-2-(((2-(dimethylamino)ethyl)(methyl)amino)methyl)-3-phenylacrylate: $N,N,N'$-Trimethylethlenenediamine (521 mg, 5.1 mmol) and K₂CO₃ (883 mg, 6.40 mmol) were added to a stirred solution of 55 (1.0 g, 4.27 mmol ) in N,N-dimethylformamide (10.0 mL) at room temperature and the reaction mixture was stirred overnight. Upon completion (TLC), the reaction was quenched with cold water and extracted with ethyl acetate (2 x 20.0 mL). The combined organic layers were washed thoroughly
with cold water (2 x 10.0 mL), brine (2 x 10.0 mL) and dried over anhydrous Na$_2$SO$_4$. The ethyl acetate was concentrated \textit{in vacuo} and purified by column chromatography (silica gel, hexanes: ethyl acetate, 1:4) to obtain 56 as brown liquid (912 mg, 77\%). $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ (ppm) 7.80 (s, 1H), 7.57 – 7.61 (m, 2H), 7.29 – 7.41 (m, 3H), 3.82 (s, 3H), 3.39 (s, 2H), 2.48 – 2.54 (m, 2H), 2.37 – 2.44 (m, 2H), 2.21 (s, 6H), 2.18 (s, 3H); $^{13}$C NMR (101 MHz, CDCl$_3$): $\delta$ (ppm) 168.9, 142.6, 135.3, 130.4, 130.2, 128.7, 128.3, 57.2, 55.5, 53.1, 51.9, 45.8, 41.9. ESIMS: m/z calculated for C$_{16}$H$_{24}$N$_2$O$_2$ (M+H)$^+$ 277.19, found 277.38.

\chem{\begin{array}{c}
\text{O} \\
\text{N}
\end{array}}\text{N} \text{N} \\
\text{OH}
(E)-2-(((2-(dimethylamino)ethyl)(methyl)amino)methyl)-3-phenylacrylic acid: \textit{aq.} NaOH (2.9 mL, 2.5 M, 7.3 mmol) was added to a solution of 56 (1.0 g, 3.6 mmol) in THF:MeOH (9:1, 20.0 mL) at 0 °C and the reaction was stirred overnight at room temperature. Upon completion (TLC), the solution was acidified to pH 6 with 1N HCl. The solution was concentrated \textit{in vacuo} and the resulting slurry was dissolved in isopropyl alcohol to effect the precipitation of sodium chloride. The reaction was then filtered and the filtrate was concentrated \textit{in vacuo} to yield 671 mg (71\%) of 57 as pale cream-colored semi-solid. $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ (ppm) 7.96 (s, 1H), 7.33 – 7.42 (m, 3H), 7.26 – 7.31 (m, 2H), 3.81 (s, 2H), 3.45 (m, 2H), 3.19 (m, 2H), 2.89 (s, 6H), 2.43 (s, 3H); $^{13}$C NMR (101 MHz, DMSO-d$_6$): $\delta$ (ppm) 169.5, 142.9, 134.9, 130.4, 129.5, 129.1, 52.9, 52.7, 51.3, 42.6, 41.4. ESIMS: m/z calculated for C$_{15}$H$_{22}$N$_2$O$_2$ (M+H)$^+$ 277.19, found 277.38.
263.17, found 263.37.

(E)-N-(2-azidoethyl)-2-(((2-(dimethylamino)ethyl)(methyl)amino)methyl)-3-phenylacrylamide 7c: The reaction of 57 (500 mg, 1.90 mmol) with 2-azidoethylamine (180 mg, 2.09 mmol) as per the general amide-coupling procedure B yielded 460 mg (74%) of 51d as a pale orange liquid. $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ (ppm) 10.10 (s, 1H), 7.96 (s, 1H), 7.21 – 7.41 (m, 5H), 3.49 – 3.53 (m, 4H), 3.39 (s, 2H), 2.43 – 2.51 (m, 2H), 2.34 – 2.42 (m, 2H), 2.24 (s, 6H), 2.14 (s, 3H); $^{13}$C NMR (101 MHz, CDCl$_3$): $\delta$ (ppm) 168.6, 140.1, 136.1, 131.0, 129.2, 128.4, 128.0, 56.8, 54.6, 53.1, 50.8, 45.6, 42.0, 39.7. ESIMS: m/z calculated for C$_{17}$H$_{26}$N$_6$O (M+H)$^+$ 331.22, found 331.35.

Methyl (E)-2-(((4-methylpiperazin-1-yl)methyl)-3-phenylacrylate: The reaction of 55 (1.0 g, 4.3 mmol) with N-methylpiperazine (512 mg, 5.1 mmol) and K$_2$CO$_3$ (883 mg, 6.4 mmol) provided 943 mg (81%) of 58 as a pale cream liquid. $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ (ppm) 7.84 (s, 1H), 7.63 – 7.68 (m, 2H), 7.32 – 7.41 (m, 3H), 3.81 (s, 3H), 3.35 (s, 2H), 2.31 – 2.63 (m, 8H), 2.26 (s, 3H); $^{13}$C NMR (101 MHz, CDCl$_3$): $\delta$ (ppm) 169.3, 143.6, 135.6, 130.7, 129.9, 129.1, 128.6, 55.5, 53.4, 52.8, 52.3, 46.3. ESIMS: m/z
calculated for C\textsubscript{16}H\textsubscript{22}N\textsubscript{2}O\textsubscript{2} (M+H)\textsuperscript{+} 275.17, found 275.10.

(E)-2-((4-methylpiperazin-1-yl)methyl)-3-phenylacrylic acid: The reaction of 58 (1.0 g, 3.6 mmol) and aq. NaOH (2.9 mL, 2.5 M, 7.3 mmol) yielded 710 mg (74%) of 59 as a pale cream-colored solid. \textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}): δ (ppm) 8.02 (s, 1H), 7.38 – 7.42 (m, 3H), 7.30 – 7.32 (m, 2H), 3.66 (s, 2H), 2.95 – 3.10 (m, 8H), 2.69 (s, 3H). \textsuperscript{13}C NMR (101 MHz, CDCl\textsubscript{3}): δ (ppm) 169.5, 142.9, 134.6, 129.5, 128.8, 128.3, 127.9, 53.2, 52.9, 49.4, 43.4. ESIMS: m/z calculated for C\textsubscript{15}H\textsubscript{20}N\textsubscript{2}O\textsubscript{2} (M+H)\textsuperscript{+} 260.15, found 260.80.

(E)-N-(2-azidoethyl)-2-((4-methylpiperazin-1-yl)methyl)-3-phenylacrylamide: The reaction of 59 (250 mg, 0.96 mmol) with 2-azidoethylamine (90 mg, 1.05 mmol) as per the general amide-coupling \textbf{procedure B} yielded 226 mg, (72%) of 51e as a pale orange liquid. \textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}): δ (ppm) 10.04 (s, 1H), 7.92 (s, 1H), 7.18 – 7.36 (m, 5H), 3.50 – 3.56 (m, 2H), 3.45 – 3.49 (m, 2H), 3.39 (s, 2H), 2.33 – 2.68 (m, 8H), 2.25 (s, 3H); \textsuperscript{13}C NMR (101 MHz, CDCl\textsubscript{3}): δ (ppm) 168.6, 140.7, 135.7, 129.8, 129.2, 128.5, 128.2, 55.3, 54.9, 52.5, 51.2, 46.2, 38.9. ESIMS: m/z calculated for C\textsubscript{17}H\textsubscript{24}N\textsubscript{6}O (M+H)\textsuperscript{+}
Preparation of triazole 62a. To a stirred solution of alkyne 61 (450 mg, 0.9 mmol) and azide 51a (198 mg, 0.9 mmol) in a mixture of t-butanol/water (1:1, 8.0 mL), was added CuSO₄ (23 mg, 0.1 mmol) and sodium ascorbate (36 mg, 0.2 mmol). The reaction mixture was stirred overnight at room temperature. Upon completion (TLC), the reaction was concentrated in vacuo and diluted with water to effect precipitation. The resulting solid was filtered, washed with water, and further purified via column chromatography (silica gel, methanol:dichloromethane, 2:3) to obtain 528 mg (89%) of 1,2,3-triazole 62a as a white solid. Mp 124 – 126 °C, ¹H NMR (400 MHz, CDCl₃): δ (ppm) 8.07 (s, 1H), 7.74 (s, 1H), 7.62 (d, J = 7.4 Hz, 2H), 7.39 – 7.46 (m, 3H), 6.36 (t, J = 5.2 Hz, 1H), 5.35 (s, 2H), 4.72 (s, 1H), 4.58 (s, 1H), 4.40 – 4.56 (m, 2H), 3.84 (s, 3H), 3.11 (dt, J = 4.2, 11.0 Hz, 1H), 2.33 – 2.49 (m, 3H), 0.70 – 2.04 (m, 21H), 1.66 (s, 3H), 1.03 (s, 3H), 0.95 (s, 3H), 0.93 (s, 3H), 0.83 (s, 3H), 0.75 (s, 3H); ¹³C NMR (101 MHz, CDCl₃): δ (ppm) 218.4, 176.5, 167.2, 151.1, 146.2, 145.2, 133.7, 130.2, 129.9, 129.2, 125.1, 123.4, 109.6, 55.8, 55.1, 52.8, 50.2, 50.1, 47.5, 47.1, 46.9, 42.6, 40.8, 39.8, 38.4, 37.9, 37.0, 34.8, 34.3, 33.7, 33.6, 31.0, 29.5, 26.8, 25.8, 21.6, 21.2, 19.8, 19.7, 16.1, 15.8, 14.7; ESIMS: m/z calculated for C₄₄H₆₀N₄O₄ (M+H)+ 709.47, found 709.55.
Preparation of triazole 62b: Procedure similar to that of 62a. This compound was prepared by the reaction of alkyne 61 with azide 51b. Yield: 88%; cream color solid; mp 98 – 101 °C; \(^1\)H NMR (400 MHz, CDCl\(_3\)): δ (ppm) 7.62 (s, 1H), 7.33 – 7.46 (m, 5H), 6.92 (s, 1H), 6.25 (t, \(J = 5.3\) Hz, 1H), 5.31 – 5.42 (m, 2H), 4.73 (s, 1H), 4.55 – 4.61 (m, 1H), 4.50 (dd, \(J = 5.5, 15.0\) Hz, 1H), 4.44 (dd, \(J = 5.5, 15.2\) Hz, 1H), 3.42 – 3.50 (m, 2H), 3.12 (dt, \(J = 4.3, 11.2\) Hz, 1H), 3.00 (brs, 3H), 2.33 – 2.52 (m, 5H), 2.24 (brs, 6H), 0.78 – 2.01 (m, 21H), 1.67 (s, 3H), 1.05 (s, 3H), 0.99 (s, 3H), 0.94 (s, 3H), 0.87 (s, 3H), 0.82 (s, 3H); \(^{13}\)C NMR (101 MHz, CDCl\(_3\)): δ (ppm) 218.0, 176.2, 150.8, 145.0, 134.8, 134.0, 130.2, 128.8 (2C), 128.7, 123.2, 109.4, 55.5, 54.9, 50.0, 49.9, 48.5, 47.2, 46.6, 45.6, 42.4, 40.6, 39.6, 38.2, 37.7, 36.8, 34.7, 34.1, 33.6, 33.4, 30.8, 29.6, 29.3, 26.6, 25.6, 21.4, 20.9, 19.6, 19.4, 15.9, 15.6, 14.5; ESIMS: m/z 779.70 [100%, (M+H)+]. HRMS-ESI: calculated for C\(_{48}\)H\(_{70}\)N\(_6\)O\(_3\) [M+H]+ 779.5582, found 779.5578.
Preparation of triazole 62c: Procedure similar to that of 62a. This compound was prepared by the reaction of alkyne 61 with azide 51c. Yield: 90%; cream color solid; mp 134 – 137 °C; 1H NMR (400 MHz, CDCl3): δ (ppm) 7.61 (s, 1H), 7.34 – 7.43 (m, 5H), 6.87 (s, 1H), 6.25 (m, 1H), 5.35 (s, 2H), 4.73 (s, 1H), 4.59 (s, 1H), 4.52 (dd, J = 4.0, 16.0 Hz, 1H), 4.42 (dd, J = 4.0, 16.0 Hz, 1H), 3.63 (m, 4H), 3.12 (dt, J = 4.3, 11.2 Hz, 1H), 2.34 – 2.52 (m, 3H), 2.17 – 2.30 (m, 4H), 2.25 (s, 3H), 0.77 – 1.94 (m, 21H), 1.67 (s, 3H), 1.05 (s, 3H), 1.01 (s, 3H), 0.94 (s, 3H), 0.87 (s, 3H), 0.81 (s, 3H); 13C NMR (101 MHz, CDCl3): δ (ppm) 218.4, 176.5, 169.0, 150.9, 145.3, 134.8, 134.1, 129.9, 129.1, 129.0, 128.9, 123.7, 109.6, 55.8, 55.2, 54.9, 50.3, 50.1, 48.8, 47.5, 46.9, 46.2, 42.7, 40.9, 39.8, 38.4, 37.9, 37.1, 34.9, 34.3, 33.8, 33.7, 31.0, 29.6, 26.8, 25.8, 21.6, 21.2, 19.8, 19.7, 16.2, 15.8, 14.8; ESIMS: m/z 777.65 [100%, (M+H)+], HRMS-ESI: calculated for C48H68N6O3 [M+Na]+ 799.5245, found 799.5239.

Preparation of triazole 62d: Procedure similar to that of 62a. This compound was
prepared by the reaction of alkyne 61 with azide 51d. Yield: 85%; cream color solid; mp
108 – 110 °C; $^1$H NMR (400 MHz, CDCl$_3$): δ (ppm) 9.89 (brs, 1H), 7.94 (s, 1H), 7.59 (s, 1H), 7.22 – 7.40 (m, 5H), 6.37 (brs, 1H), 4.73 (s, 1H), 4.56 – 4.60 (m, 3H), 4.51 (dd, $J = 5.4$, 15.0 Hz, 1H), 4.44 (dd, $J = 5.5$, 15.0 Hz, 1H), 3.65 – 3.82 (m, 2H), 3.34 (s, 2H), 3.12 (dt, $J = 4.2$, 11.1 Hz, 1H), 2.34 – 2.52 (m, 7H), 2.19 (brs, 3H), 2.07 (s, 6H), 0.82 – 1.97 (m, 21H), 1.67 (s, 3H), 1.05 (s, 3H), 1.01 (s, 3H), 0.94 (s, 3H), 0.90 (s, 3H), 0.84 (s, 3H); $^{13}$C NMR (101 MHz, CDCl$_3$): δ (ppm) 218.1, 176.4, 168.5, 150.8, 145.0, 140.1, 135.6, 130.5, 128.9, 128.3, 127.9, 122.9, 109.4, 55.9, 55.5, 54.9, 53.8, 52.7, 50.0, 49.9, 49.2, 47.3, 46.7, 44.9, 42.4, 41.6, 40.6, 39.9, 39.6, 38.2, 37.7, 36.9, 34.7, 34.1, 33.6, 33.4, 30.8, 29.6, 29.3, 26.6, 25.6, 21.4, 21.0, 19.7, 19.4, 15.9, 15.6, 14.5; ESIMS: m/z 822.65 [100%, (M+H)$^+$], HRMS-ESI: calculated for C$_{50}$H$_{75}$N$_7$O$_3$ [M+Na]$^+$ 844.5824, found 844.5831.

Preparation of triazole 62e: Procedure similar to that of 62a. This compound was
prepared by the reaction of alkyne 61 with azide 51e. Yield: 87%; cream color solid; mp
118 – 120 °C; $^1$H NMR (400 MHz, CDCl$_3$): δ (ppm) 9.87 (s, 1H), 7.92 (s, 1H), 7.61 (s, 1H), 7.22 – 7.37 (m, 3H), 7.20 – 7.25 (m, 2H), 6.23 – 6.29 (m, 1H), 4.73 (s, 1H), 4.59 (s, 1H), 4.38 – 4.55 (m, 4H), 3.79 – 3.92 (m, 2H), 3.34 (s, 2H), 3.08 – 3.15 (m, 1H), 2.29 – 2.52 (m, 11H), 2.25 (s, 3H), 0.76 – 1.92 (m, 21H), 1.75 (s, 3H), 1.04 (s, 3H), 1.00 (s, 3H), 44
0.94 (s, 3H), 0.90 (s, 3H), 0.81 (s, 3H); $^{13}$C NMR (101 MHz, CDCl$_3$): $\delta$ (ppm) 218.3, 176.7, 168.9, 150.9, 145.5, 140.9, 135.4, 129.5, 129.2, 128.5, 128.3, 123.2, 109.7, 55.7, 55.2, 54.9, 54.9, 52.3, 50.2, 50.1, 49.9, 47.5, 46.9, 45.9, 42.7, 40.9, 39.8, 39.4, 38.4, 38.0, 37.1, 35.0, 34.3, 33.8, 33.7, 31.0, 29.6, 26.8, 25.8, 21.6, 21.2, 19.8, 19.7, 16.2, 15.8, 14.8; ESIMS: m/z 820.70 [100%, (M+H)$^+$], HRMS-ESI: calculated for C$_{50}$H$_{73}$N$_7$O$_3$ [M+H]$^+$ 820.5848, found 820.5877.

Preparation of triazole 62f: Procedure similar to that of 62a. This compound was prepared by the reaction of alkyne 61 with azide 51f. Yield: 91%; white solid; mp 139 – 141 °C; $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ (ppm) 7.62 (d, $J$ = 15.6 Hz, 1H), 7.60 (s, 1H), 7.46 – 7.51 (m, 2H), 7.32 – 7.36 (m, 3H), 6.26 – 6.42 (m, 3H), 4.70 (s, 1H), 4.57 (s, 1H), 4.46 – 4.54 (m, 3H), 4.40 (dd, $J$ = 5.7, 15.0 Hz, 1H), 3.85 – 3.94 (m, 2H), 3.12 (dt, $J$ = 4.4, 11.1 Hz, 1H), 2.32 – 2.51 (m, 3H), 0.75 – 1.95 (m, 21H), 1.64 (s, 3H), 1.02 (s, 3H), 0.98 (s, 3H), 0.92 (s, 3H), 0.88 (s, 3H), 0.80 (s, 3H); $^{13}$C NMR (101 MHz, CDCl$_3$): $\delta$ (ppm) 218.5, 176.9, 166.7, 150.8, 145.7, 141.7, 134.8, 130.1, 129.0, 128.0, 123.6, 120.3, 109.8, 55.8, 55.1, 50.2, 50.1, 49.9, 47.5, 46.9, 42.7, 40.8, 39.8, 38.4, 37.9, 37.1, 35.0, 34.4, 33.8, 33.6, 31.0, 29.6, 26.8, 25.8, 21.6, 21.2, 19.8, 19.6, 16.2, 15.9, 14.7; ESIMS: m/z 708.55 [100%, (M+H)$^+$], HRMS-ESI: calculated for C$_{44}$H$_{61}$N$_5$O$_3$ [M+H]$^+$ 708.4847, found 708.4833.
**Preparation of alcohol 63a.** To a stirred solution of the appropriate ketone 62a (180 mg, 0.2 mmol) in methanol at 0 °C, was added NaBH₄ (14 g, 0.4 mmol), and stirred for 2 h at room temperature. Upon completion of reaction (as monitored by TLC), the reaction mixture was concentrated *in vacuo*, diluted with water and extracted with ethyl acetate (2 x 10.0 mL). The combined organic extracts were washed with brine (10.0 mL), dried over anhydrous Na₂SO₄, concentrated under vacuum and purified via column chromatography (silica gel, hexane:ethyl acetate, 1:2) to obtain 155 mg (86%) of pure alcohol 63a as a white solid. Mp 123 – 125 °C; ¹H NMR (400 MHz, CDCl₃): δ (ppm) 8.06 (s, 1H), 7.72 (s, 1H), 7.57 – 7.64 (m, 2H), 7.39 – 7.46 (m, 3H), 6.49 (m, 1H), 5.33 (s, 2H), 4.70 (s, 1H), 4.56 (s, 1H), 4.50 (dd, J = 5.7, 15.0 Hz, 1H), 4.41 (dd, J = 5.5, 15.0 Hz, 1H), 3.82 (s, 3H), 3.03 – 3.22 (m, 2H), 2.34 (dt, J = 3.5, 12.7 Hz, 1H), 0.59 – 2.02 (m, 24H), 1.64 (s, 3H), 0.91 (s, 3H), 0.90 (s, 3H), 0.72 (s, 3H), 0.70 (s, 3H), 0.69 (s, 3H); ¹³C NMR (101 MHz, CDCl₃): δ (ppm) 176.5, 167.2, 151.2, 146.2, 145.2, 133.8, 130.2, 129.9, 129.2, 125.1, 123.3, 109.6, 79.1, 55.8, 55.5, 52.8, 50.8, 50.3, 47.1, 47.0, 42.6, 40.9, 39.0, 38.9, 38.4, 37.9, 37.4, 34.8, 34.5, 33.7, 31.1, 29.6, 28.2, 27.6, 25.8, 21.1, 19.7, 18.5, 16.3, 16.0, 15.6, 14.8; ESIMS: m/z calculated for C₄₄H₆₂N₄O₄ (M+H)⁺ 711.48, found 711.70.
Preparation of 63b: Procedure similar to that of 63a. Yield: 85%; cream color solid; mp 118 – 121 °C; $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ (ppm) 7.60 (s, 1H), 7.33 – 7.43 (m, 5H), 6.99 (s, 1H), 6.25 – 6.34 (m, 1H), 5.35 (s, 2H), 4.72 (s, 1H), 4.58 (s, 1H), 4.49 (dd, $J = 5.6$, 15.1 Hz, 1H), 4.42 (dd, $J = 5.6$, 15.1 Hz, 1H), 3.61 (brs, 2H), 3.05 – 3.18 (m, 5H), 2.29 – 2.77 (m, 10H), 0.63 – 1.94 (m, 23H), 1.66 (s, 3H), 0.94 (s, 3H), 0.93 (s, 3H), 0.77 (s, 3H), 0.76 (s, 3H), 0.73 (s, 3H); $^{13}$C NMR (101 MHz, CDCl$_3$): $\delta$ (ppm) 176.4, 150.8, 135.1, 133.9, 129.8, 128.84, 128.80, 128.78, 123.3, 109.4, 78.9, 55.6, 55.3, 50.5, 50.1, 48.6, 46.8, 44.9, 44.8, 42.4, 40.7, 38.8, 38.7, 38.2, 37.7, 37.1, 34.8, 34.3, 33.5, 30.8, 29.4, 27.9, 27.4, 25.6, 20.9, 19.4, 18.3, 16.1, 15.8, 15.4, 14.6; ESIMS: m/z 781.70 [100%, (M+H)$^+$], HRMS-ESI: calculated for C$_{48}$H$_{72}$N$_6$O$_3$ [M+Na]$^+$ 803.5558, found 803.5558.

Preparation of 63c: Procedure similar to that of 63a. Yield: 88%; white solid; mp 134 – 136 °C; $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ (ppm) 7.60 (s, 1H), 7.34 – 7.42 (m, 5H),
6.86 (s, 1H), 6.24 (t, J = 5.6 Hz, 1H), 5.34 (s, 2H), 4.73 (s, 1H), 4.58 (s, 1H), 4.52 (dd, J = 5.6, 15.1 Hz, 1H), 4.42 (dd, J = 5.6, 15.1 Hz, 1H), 3.66 (m, 4H), 3.06 – 3.19 (m, 2H), 2.17 – 2.35 (m, 5H), 2.26 (s, 3H), 0.63 – 1.93 (m, 24H), 1.67 (s, 3H), 0.94 (s, 3H), 0.93 (s, 3H), 0.76 (s, 6H), 0.73 (s, 3H); $^{13}$C NMR (101 MHz, CDCl$_3$): δ (ppm) 176.3, 168.8, 150.8, 145.1, 134.6, 133.8, 129.6, 128.8, 128.7, 128.7, 123.5, 109.3, 78.8, 55.7, 55.3, 54.7, 50.5, 50.1, 48.5, 46.7, 45.8, 42.4, 40.7, 38.8, 38.7, 38.2, 37.7, 37.1, 34.7, 34.3, 33.5, 30.8, 29.4, 27.9, 27.4, 25.6, 20.9, 19.5, 18.3, 16.1, 15.8, 15.4, 14.6; ESIMS: m/z 779.70 [100%, (M+H)$^+$], HRMS-ESI: calculated for C$_{48}$H$_{70}$N$_6$O$_3$ [M+Na]$^+$ 801.5402, found 801.5443.

Preparation of 63d: Procedure similar to that of 63a. Yield: 90%; cream color solid; mp 119 – 122 °C; $^1$H NMR (400 MHz, CDCl$_3$): δ (ppm) 9.95 (s, 1H), 7.96 (s, 1H), 7.58 (s, 1H), 7.24 – 7.41 (m, 5H), 6.33 (s, 1H), 4.72 (s, 1H), 4.55 – 4.64 (m, 3H), 4.51 (dd, J = 5.5, 15.0 Hz, 1H), 4.43 (dd, J = 5.5, 15.0 Hz, 1H), 3.69 – 3.83 (m, 2H), 3.33 (s, 2H), 3.06 – 3.20 (m, 2H), 2.29 – 2.42 (m, 4H), 2.07 (brs, 3H), 2.07 (s, 6H), 0.63 – 1.95 (m, 25H), 1.67 (s, 3H), 0.94 (s, 3H), 0.93 (s, 3H), 0.80 (s, 3H), 0.79 (s, 3H), 0.74 (s, 3H); $^{13}$C NMR (101 MHz, CDCl$_3$): δ (ppm) 176.4, 168.5, 150.8, 144.9, 140.1, 135.6, 130.5, 129.0, 128.2, 127.9, 122.9, 109.4, 78.9, 56.1, 55.6, 55.3, 54.0, 52.5, 50.6, 50.1, 49.2, 46.8, 45.0, 42.4, 41.7, 40.7, 39.9, 38.8, 38.7, 38.2, 37.7, 37.2, 34.7, 34.3, 33.5, 30.9, 29.4,
27.9, 27.4, 25.6, 20.9, 19.4, 18.2, 16.1, 15.8, 15.4, 14.6; ESIMS: m/z 824.75 [100%, (M+H)+], HRMS-ESI: calculated for C_{50}H_{77}N_{7}O_{3} [M+Na]^+ 846.5980, found 846.5983.

Preparation of 63e: Procedure similar to that of 63a. Yield: 89%; cream color solid; mp 130 – 132 °C; \textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}): δ (ppm) 9.86 (t, J = 4.0 Hz, 1H), 7.92 (s, 1H), 7.58 (s, 1H), 7.20 – 7.39 (m, 5H), 6.26 (t, J = 5.7 Hz, 1H), 4.73 (s, 1H), 4.58 (s, 1H), 4.46 – 4.56 (m, 3H), 4.40 (dd, J = 5.6, 15.0 Hz, 1H), 3.79 – 3.91 (m, 2H), 3.34 (s, 2H), 3.08 – 3.18 (m, 2H), 2.21 – 2.48 (m, 10H), 2.25 (s, 3H), 0.64 – 1.92 (m, 25H), 1.67 (s, 3H), 0.94 (s, 3H), 0.93 (s, 3H), 0.80 (s, 3H), 0.76 (s, 3H), 0.74 (s, 3H); \textsuperscript{13}C NMR (101 MHz, CDCl\textsubscript{3}): δ (ppm) 176.5, 168.7, 150.8, 145.3, 140.8, 135.2, 129.3, 128.9, 128.3, 128.0, 123.1, 109.4, 78.8, 55.6, 55.3, 54.8, 54.6, 52.1, 50.5, 50.1, 49.7, 46.8, 45.7, 42.4, 40.7, 39.2, 38.8, 38.7, 38.2, 37.8, 37.2, 34.7, 34.3, 33.5, 30.8, 29.4, 27.9, 27.4, 25.6, 20.9, 19.4, 18.2, 16.2, 15.8, 15.4, 14.6; ESIMS: m/z 822.70 [100%, (M+H)^+], HRMS-ESI: calculated for C_{50}H_{75}N_{7}O_{3} [M+Na]^+ 844.5824, found 844.5852.
Preparation of 63f: Procedure similar to that of 63a. Yield: 90%; gray color solid; mp 185 – 187 °C; \(^1\)H NMR (400 MHz, CDCl\(_3\)): \(\delta\) (ppm) 7.63 (d, \(J = 15.6\) Hz, 1H), 7.60 (s, 1H), 7.45 – 7.53 (m, 2H), 7.33 – 7.60 (m, 3H), 6.38 (d, \(J = 15.6\) Hz, 1H), 6.24 – 6.35 (m, 2H), 4.71 (s, 1H), 4.57 (s, 1H), 4.38 – 4.54 (m, 4H), 3.86 – 3.93 (m, 2H), 3.06 – 3.17 (m, 2H), 2.26 – 2.39 (m, 1H), 0.62 – 1.94 (m, 24H), 1.65 (s, 3H), 0.92 (s, 6H), 0.78 (s, 3H), 0.75 (s, 3H), 0.73 (s, 3H); \(^{13}\)C NMR (101 MHz, CDCl\(_3\)): \(\delta\) (ppm) 176.7, 166.4, 150.7, 145.5, 141.6, 134.6, 129.8, 128.8, 127.8, 123.4, 120.0, 109.4, 78.9, 55.6, 55.3, 50.5, 50.1, 49.7, 46.7, 42.4, 40.7, 39.5, 38.8, 38.7, 38.2, 37.8, 37.1, 34.7, 34.3, 33.4, 30.8, 29.4, 27.9, 27.4, 25.6, 20.9, 19.4, 18.2, 16.1, 15.8, 15.4, 14.6; ESIMS: m/z calculated for C\(_{44}\)H\(_{63}\)N\(_5\)O\(_3\) (M+H\(^+\)) 710.50, found 710.65.

**Preparation of succinic acid hemiester 64a.** A stirred solution of alcohol 63a (110 mg, 0.1 mmol), DMAP (19 mg, 0.1 mmol), and succinic anhydride (31 mg, 0.3 mmol) in toluene (4.0 mL) was refluxed overnight. Upon completion (TLC), the
reaction mixture was concentrated in vacuo, diluted with water, and extracted with ethyl acetate (2 x 10.0 mL). The combined extracts were washed with brine (10.0 mL), dried over anhydrous Na\textsubscript{2}SO\textsubscript{4}, concentrated under reduced pressure, and purified using column chromatography (silica gel, hexanes:ethyl acetate, 1:3) to obtain 109 mg (87%) of pure succinic acid hemi ester 64a as a white solid. Mp 122 – 125 °C; \textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}): δ (ppm) 8.07 (s, 1H), 7.73 (s, 1H), 7.58 – 7.63 (m, 2H), 7.41 – 7.47 (m, 3H), 6.71 (t, J = 5.9 Hz, 1H), 5.34 (s, 2H), 4.71 (s, 1H), 4.57 (s, 1H), 4.43 – 4.50 (m, 3H), 3.84 (s, 3H), 3.10 (dt, J = 4.3, 11.1 Hz, 1H), 2.57 – 2.69 (m, 4H), 2.32 (dt, J = 3.6, 12.3 Hz, 1H), 0.65 – 1.98 (m, 23H), 1.66 (s, 3H), 0.92 (s, 3H), 0.80 (s, 3H), 0.78 (s, 3H), 0.75 (s, 3H), 0.68 (s, 3H); \textsuperscript{13}C NMR (101 MHz, CDCl\textsubscript{3}): δ (ppm) 176.6, 176.3, 171.9, 166.9, 150.9, 146.1, 144.9, 133.5, 130.0, 129.7, 128.9, 124.7, 123.4, 109.3, 81.4, 55.6, 55.5, 52.6, 50.4, 50.1, 46.9, 46.8, 42.4, 40.6, 38.4, 38.1, 37.8, 37.7, 37.0, 34.2, 34.0, 33.3, 30.8, 29.4, 29.3, 29.1, 27.8, 25.5, 23.6, 20.9, 19.4, 18.1, 16.5, 16.1, 15.7, 14.6; ESIMS: m/z 811.65 [100%, (M+H)+], HRMS-ESI: calculated for C\textsubscript{48}H\textsubscript{66}N\textsubscript{4}O\textsubscript{7} [M+H]\textsuperscript{+} 811.5004, found 811.5038.

Preparation of succinic acid hemiester 64b: Procedure similar to that of 64a. Yield: 80%; cream color solid; mp 130 – 132 °C; \textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}): δ (ppm) 7.60 (s,
1H), 7.33 – 7.43 (m, 5H), 6.99 (s, 1H), 6.29 (m, 1H), 5.33 (s, 2H), 4.72 (s, 1H), 4.58 (s, 1H), 4.39 – 4.50 (m, 3H), 3.55 – 3.70 (m, 2H), 3.07 – 3.18 (m, 1H), 3.05 (brs, 3H), 2.70 (m, 1H), 2.29 – 2.77 (m, 8H), 2.24 – 2.40 (m, 4H), 0.63 – 1.94 (m, 23H), 1.66 (s, 3H), 0.92 (s, 3H), 0.80 (s, 6H), 0.76 (s, 3H), 0.75 (s, 3H); 13C NMR (101 MHz, CDCl3): δ (ppm) 176.5, 176.3, 172.6, 150.8, 145.4, 135.1, 133.8, 129.8, 129.7, 128.9, 128.7, 113.9, 109.5, 80.9, 55.6, 55.4, 50.1, 48.6, 46.8, 43.8, 42.4, 40.7, 38.3, 38.2, 37.8, 37.7, 37.0, 34.6, 34.2, 33.4, 30.8, 30.1, 30.0, 29.7, 29.4, 27.9, 25.5, 23.6, 20.9, 19.4, 18.1, 16.5, 16.2, 15.8, 14.6; ESIMS: m/z calculated for C52H76N6O6 (M+H)+ 881.59, found 881.58.

Preparation of succinic acid hemiester 64c: Procedure similar to that of 64a. Yield: 83%; cream color solid; mp 142 – 145 °C; 1H NMR (400 MHz, CDCl3): δ (ppm) 7.61 (s, 1H), 7.36 – 7.44 (m, 5H), 6.88 (s, 1H), 6.58 (t, J = 5.7 Hz, 1H), 5.34 (s, 2H), 4.72 (s, 1H), 4.58 (s, 1H), 4.43 – 4.50 (m, 3H), 3.73 (brs, 4H) 3.12 (dt, J = 5.4, 11.0 Hz, 1H), 2.57 – 2.65 (m, 4H), 2.26 – 2.53 (m, 5H), 2.36 (s, 3H), 0.72 – 1.96 (m, 23H), 1.67 (s, 3H), 0.93 (s, 3H), 0.82 (s, 3H), 0.81 (s, 3H), 0.77 (s, 3H), 0.74 (s, 3H); 13C NMR (101 MHz, CDCl3): δ (ppm) 176.6, 175.8, 172.3, 168.9, 150.8, 145.4, 135.1, 133.7, 129.1, 128.9, 128.7, 123.5, 109.4, 81.1, 55.6, 55.4, 53.8, 50.4, 50.1, 48.6, 46.8, 44.7, 42.4, 40.7, 38.4, 38.1, 37.8, 37.7, 37.0, 34.5, 34.2, 33.4, 30.8, 29.8, 29.6, 29.4, 27.9, 25.5, 23.6,
20.9, 19.4, 18.1, 16.5, 16.2, 15.8, 14.6; ESIMS: m/z calculated for C_{52}H_{74}N_{6}O_{6} (M+H)^{+} 879.57, found 879.65.

Preparation of succinic acid hemiester 64d: Procedure similar to that of 64a. Yield: 82%; white solid; mp 114 – 116 °C; \(^1\)H NMR (400 MHz, CDCl\(_3\)): δ (ppm) 9.68 (s, 1H), 7.91 (s, 1H), 7.60 (s, 1H), 7.27 – 7.39 (m, 3H), 7.20 – 7.25 (m, 2H), 6.66 (t, J = 5.5 Hz, 1H), 4.72 (s, 1H), 4.58 (s, 1H), 4.40 – 4.57 (m, 5H), 3.73 – 3.85 (m, 2H), 3.34 (s, 2H), 3.12 (dt, J = 4.2, 10.8 Hz, 1H), 2.40 – 2.68 (m, 8H), 2.34 (m, 1H), 2.28 (s, 6H), 2.05 (s, 3H), 0.72 – 1.98 (m, 23H), 1.66 (s, 3H), 0.92 (s, 3H), 0.81 (s, 9H), 0.77 (s, 3H); \(^{13}\)C NMR (101 MHz, CDCl\(_3\)): δ (ppm) 176.5 (2C), 172.7, 168.5, 150.8, 145.3, 140.3, 135.5, 130.3, 129.0, 128.3, 127.9, 123.0, 109.4, 80.9, 55.6, 55.4, 55.2, 53.9, 53.5, 53.1, 50.6, 50.5, 50.1, 49.4, 46.7, 44.1, 42.4, 41.4, 40.7, 39.6, 38.4, 38.2, 37.8, 37.7, 37.1, 34.6, 34.2, 33.4, 30.9, 29.4, 27.9, 25.5, 23.7, 20.9, 19.4, 18.1, 16.5, 16.2, 15.8, 14.6; ESIMS: m/z calculated for C_{54}H_{81}N_{7}O_{6} (M+H)^{+} 924.63, found 924.70.

Preparation of succinic acid hemiester 64e: Procedure similar to that of 64a. Yield:
84%; cream color solid; mp 132 – 134 °C; $^1$H NMR (400 MHz, CDCl$_3$): δ 9.64 (m, 1H), 7.94 (s, 1H), 7.64 (s, 1H), 7.28 – 7.40 (m, 3H), 7.19 – 7.23 (m, 2H), 6.52 (t, $J$ = 5.0 Hz, 1H), 4.72 (s, 1H), 4.59 (s, 1H), 4.38 – 4.51 (m, 5H), 3.88 – 3.92 (m, 2H), 3.38 (s, 2H), 3.11 (dt, $J$ = 4.4, 11.0 Hz, 1H), 2.40 – 2.76 (m, 10H), 2.44 (s, 3H), 2.33 (m, 3H), 0.71 – 1.95 (m, 23H), 1.67 (s, 3H), 0.93 (s, 3H), 0.81 (s, 6H), 0.79 (s, 3H), 0.75 (s, 3H); $^{13}$C NMR (101 MHz, CDCl$_3$): δ 176.7 (2C), 172.6, 168.5, 150.7, 145.7, 141.5, 134.9, 128.9, 128.7, 128.5, 128.3, 123.5, 109.5, 80.9, 55.6, 55.4, 54.2, 53.3, 50.6, 50.4, 50.1, 50.0, 46.8, 44.0, 42.4, 40.7, 39.0, 38.3, 38.2, 37.8, 37.7, 37.1, 34.6, 34.3, 33.4, 30.8, 29.7, 29.4, 27.9, 25.5, 23.6, 20.9, 19.4, 18.1, 16.5, 16.2, 15.8, 14.6; ESIMS: m/z calculated for C$_{54}$H$_{79}$N$_7$O$_6$ (M+H)$^+$ 922.62, found 922.75.

Preparation of succinic acid hemiester 64f: Procedure similar to that of 64a. Yield: 81%; yellow solid; mp 141 – 144 °C; $^1$H NMR (400 MHz, CDCl$_3$): δ (ppm) 7.64 (d, $J$ = 15.6 Hz, 1H), 7.63 (s, 1H), 7.46 – 7.52 (m, 2H), 7.34 – 7.38 (m, 3H), 6.60 – 6.69 (m, 1H), 6.40 (d, $J$ = 15.5 Hz, 1H), 6.26 – 6.34 (m, 1H), 4.70 (s, 1H), 4.57 (s, 1H), 4.39 – 4.54 (m, 5H), 3.80 – 3.97 (m, 2H), 3.09 (dt, $J$ = 4.1, 11.0 Hz, 1H), 2.59 – 2.70 (m, 4H), 2.22 – 2.33 (m, 1H), 0.66 – 1.91 (m, 23H), 1.65 (s, 3H), 0.91 (s, 3H), 0.80 (s, 3H), 0.79 (s, 6H), 0.71 (s, 3H); $^{13}$C NMR (101 MHz, CDCl$_3$): δ (ppm) 176.9 (2C), 172.2, 166.6, 150.7, 145.3, 141.8, 134.5, 129.9, 128.8, 127.9, 123.6, 119.9, 109.5, 81.4, 55.6, 55.4, 50.4, 50.0, 49.8,
46.8, 42.4, 40.7, 39.5, 38.3, 38.1, 37.8, 37.7, 37.0, 34.3, 34.2, 33.3, 30.8, 29.6, 29.3, 27.8, 25.5, 23.6, 20.9, 19.4, 18.1, 16.5, 16.2, 15.7, 14.6; ESIMS: m/z 810.75 [100%, (M+H)^+] 
HRMS-ESI: calculated for C_{48}H_{67}N_{5}O_{6} [M+H]^+ 832.4984, found 832.5026.
Chapter 4

Spectral Characterization

Figure 28. 400 MHz $^1$H NMR of Compound 56 in CDCl$_3$
Figure 29. 101 MHz $^{13}$C NMR of Compound 56 in CDCl$_3$
Figure 30. 400 MHz $^1$H NMR of Compound 57 in DMSO-d$_6$
Figure 31. 101 MHz $^{13}$C NMR of Compound 57 in DMSO-$d_6$
Figure 32. 400 MHz $^1$H NMR of Compound 58 in CDCl$_3$
Figure 33. 101 MHz $^{13}$C NMR of Compound 58 in CDCl$_3$
Figure 34. 400 MHz $^1$H NMR of Compound 59 in CDCl$_3$. 
Figure 35. 101 MHz $^{13}$C NMR of Compound 59 in CDCl$_3$
Figure 36. 400 MHz $^1$H NMR of Compound 51b in CDCl$_3$
Figure 37. 101 MHz $^{13}$C NMR of Compound 51b in CDCl$_3$
Figure 38. 400 MHz $^1$H NMR of Compound 51c in CDCl$_3$
Figure 39. 101 MHz $^{13}$C NMR of Compound 51c in CDCl$_3$
Figure 40. 400 MHz $^1$H NMR of Compound 51d in CDCl$_3$
Figure 41. 101 MHz $^{13}$C NMR of Compound 51d in CDCl$_3$
Figure 42. 400 MHz $^1$H NMR of Compound 51e in CDCl$_3$
Figure 43. 101 MHz $^{13}$C NMR of Compound 51e in CDCl$_3$
Figure 44. 400 MHz $^1$H NMR of Compound 62a in CDCl$_3$
Figure 45. 101 MHz $^{13}$C NMR of Compound 62a in CDCl$_3$
Figure 46. 400 MHz $^1$H NMR of Compound 62b in CDCl$_3$
Figure 47. 101 MHz $^{13}$C NMR of Compound 62b in CDCl$_3$
Figure 48. 400 MHz $^1$H NMR of Compound 62c in CDCl$_3$
Figure 49. 101 MHz $^{13}$C NMR of Compound 62c in CDCl$_3$
Figure 50. 400 MHz $^1$H NMR of Compound 62d in CDCl$_3$
Figure 51. 101 MHz $^{13}$C NMR of Compound 62d in CDCl$_3$
Figure 52. 400 MHz $^1$H NMR of Compound 62e in CDCl$_3$
Figure 53. 101 MHz $^{13}$C NMR of Compound 62e in CDCl$_3$
Figure 54. 400 MHz $^1$H NMR of Compound 62f in CDCl$_3$
Figure 55. 101 MHz $^{13}$C NMR of Compound 62f in CDCl$_3$
Figure 56. 400 MHz $^1$H NMR of Compound 63a in CDCl$_3$
Figure 57. 101 MHz $^{13}$C NMR of Compound 63a in CDCl$_3$
Figure 58. 400 MHz $^1$H NMR of Compound $63b$ in CDCl$_3$
Figure 59. 101 MHz $^{13}$C NMR of Compound 63b in CDCl$_3$
Figure 60. 400 MHz $^1$H NMR of Compound 63c in CDCl$_3$
Figure 61. 101 MHz $^{13}$C NMR of Compound 63c in CDCl$_3$
Figure 62. 400 MHz $^1$H NMR of Compound 63d in CDCl$_3$
Figure 63. 101 MHz $^{13}$C NMR of Compound 63d in CDCl$_3$
Figure 64. 400 MHz $^1$H NMR of Compound 63e in CDCl$_3$
Figure 65. 101 MHz $^{13}$C NMR of Compound 63e in CDCl$_3$
Figure 66. 400 MHz $^1$H NMR of Compound 63f in CDCl$_3$
Figure 67. 101 MHz $^{13}$C NMR of Compound 63f in CDCl$_3$
Figure 68. 400 MHz $^1$H NMR of Compound 64a in CDCl$_3$
Figure 69. 101 MHz $^{13}$C NMR of Compound 64a in CDCl$_3$
Figure 70. 400 MHz $^1$H NMR of Compound 64b in CDCl$_3$
Figure 71. 101 MHz $^{13}$C NMR of Compound 64b in CDCl$_3$
Figure 72. 400 MHz $^1$H NMR of Compound 64c in CDCl$_3$
Figure 73. 101 MHz $^{13}$C NMR of Compound 64c in CDCl$_3$
Figure 74. 400 MHz $^1$H NMR of Compound 64d in CDCl$_3$
Figure 75. 101 MHz $^{13}\text{C}$ NMR of Compound 64d in CDCl$_3$
Figure 76. 400 MHz $^1$H NMR of Compound 64e in CDCl$_3$
Figure 77. 101 MHz $^{13}$C NMR of Compound 64e in CDCl$_3$
Figure 78. 400 MHz $^1$H NMR of Compound 64f in CDCl$_3$
Figure 79. 101 MHz $^{13}$C NMR of Compound 64f in CDCl$_3$
References


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