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Trimethylchlorosilane-Mediated Mild α-Chlorination of 1,3-Dicarbonyl Compounds Promoted by Phenyliodonium Diacetate

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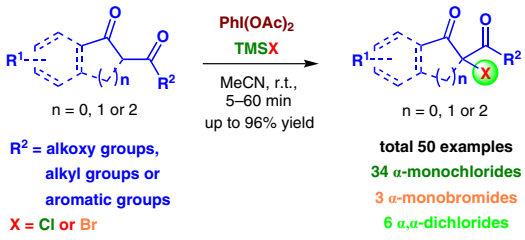

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Abstract Trimethylchlorosilane was used as chlorine source for the α-chlorination of 1,3-dicarbonyl compounds with phenyliodonium diacetate as oxidant at room temperature. The reaction allows the selective synthesis of α-monochlorinated products from different kinds of 1,3-dicarbonyl compounds in good yield. The potential possibility of this conversion for bromination has also been investigated.

Key words chlorination, 1,3-dicarbonyl compounds, phenyliodonium diacetate, trimethylchlorosilane, Umpolung strategy

In modern synthetic chemistry, α-halo-substituted 1,3-dicarbonyl compounds are a very important class of compounds, not only because of their occurrence in biologically active drugs, but also their usefulness as building blocks or versatile intermediates in organic synthesis.[1] The development of facile methodologies for their synthesis is very attractive. Although a number of efforts to develop the α-halogenation of 1,3-dicarbonyl compounds have been presented previously, selective α-monohalogenation of 1,3-dicarbonyl compounds without an α-substituent at the active methylene position remains a significant challenge. Various halogenating agents are commonly used, including Br_2,[2] *N*-halosuccinimides[3] and copper(II) bromide.[4] Most of these transformations normally need strong basic or acidic conditions, and produce the undesired dihalogenated compounds. Moreover, tedious workup and long reaction times are other drawbacks of these methods. Among the existing approaches to obtain α-chloro-1,3-dicarbonyl compounds, the use of trimethylchlorosilane (TMSCl) as chlorine source has been sparsely reported.[5] To access this chemical conversion, use of an oxidant is imperative.[6] Hence, a commercially available, environmentally benign and efficient oxidant is the key factor to promote chlorination using TMSCl as chlorine source.

In recent years, hypervalent organoiodine compounds have been widely used as mild, nontoxic and selective oxidative reagents for a variety of synthetically useful transformations.[7] Their chemical behaviors are similar to transition metals, and they usually act as an excellent leaving group. They have been regarded as multipurpose reagents in organic synthesis,[8] inducing α-fluorination of 1,3-dicarbonyl compounds[9] and C–C coupling reactions.[10] In 2009, Ibrahim's group reported a phenyliodonium diacetate [$PhI(OAc)_2$; PIDA] mediated Umpolung strategy to efficiently access α-halogenation of 1,3-dicarbonyl compounds with $TiCl_4$ as Lewis acidic halide source.[6a] Very recently, this group has described another effective halogenation and azidation of 1,3-dicarbonyl compounds with an $Et_4NX/PhI(OAc)_2$ or $Bu_4NN_3/PhI(OAc)_2$ system.[11] Herein, we would like to report the use of TMSCl as a mild and commercially available chlorine source for selective α-monochlorination of 1,3-dicarbonyl compounds in the presence of $PhI(OAc)_2$.

As shown in Table 1, our investigation began with β-keto ester **1aa** as model substrate in the reaction with $PhI(OAc)_2$ (**2**) and TMSCl (**3**) in acetonitrile at room temperature. The desired monochlorinated product **4aa** was obtained, as expected, in 20% yield when 1 equivalent of $PhI(OAc)_2$ and 1 equivalent of TMSCl were used (Table 1, entry 1). In an effort to increase the yield, different mole ratios of reagents (increased TMSCl) were checked (Table 1, en-

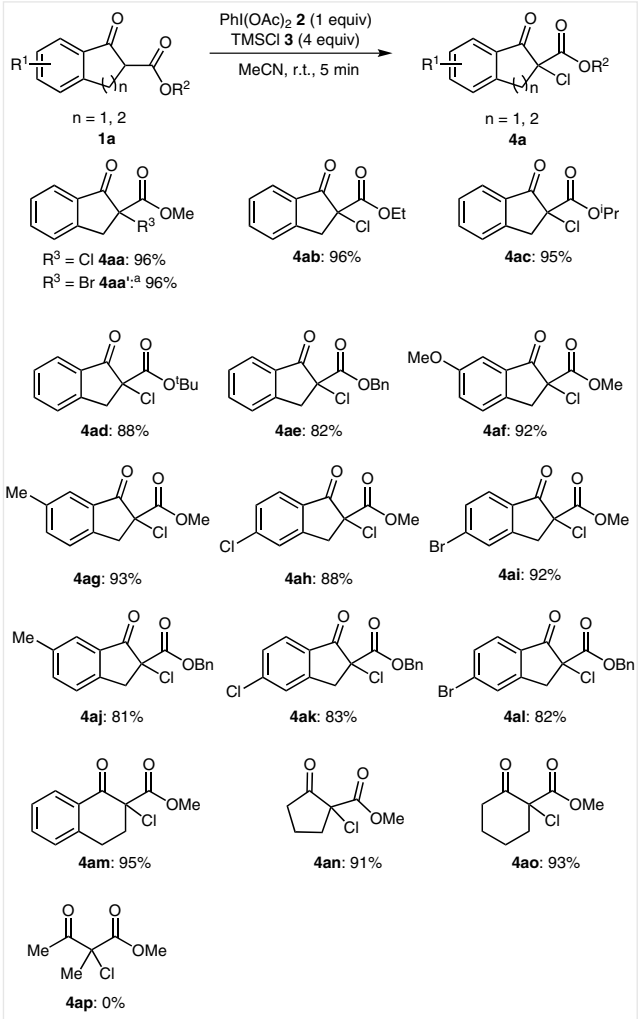
Table 1 Optimization of the Chlorination of β-Keto Ester **1aa**[a]

Entry	Mole ratio of **1aa**/**2**/**3**	Time (min)	Solvent	Yield[b] (%) of **4aa**
1	1:1:1	15	MeCN	20
2	1:1:2	10	MeCN	41
3	1:1:3	5	MeCN	77
4	1:1:4	5	MeCN	96
5	1:1:5	5	MeCN	96
6	1:0.2:4	5	MeCN	55
7	1:0.5:4	5	MeCN	62
8	1:1.5:4	5	MeCN	96
9[c]	1:1:4	5	MeCN	95
10[d]	1:1:4	60	MeCN	80
11[e]	1:1:4	90	MeCN	62
12[f]	1:1:4	150	MeCN	55
13	1:1:4	5	toluene	73
14	1:1:4	5	CH_2Cl_2	61
15	1:1:4	5	$CHCl_3$	54
16	1:1:4	5	DMF	0
17	1:1:4	5	MeOH	91
18	1:1:4	5	EtOH	85
19	1:1:4	5	EtOAc	89
20	1:1:4	5	1,4-dioxane	71
21	1:1:4	5	Et_2O	34
22	1:1:4	5	THF	56

[a] Reaction conditions: **1aa** (0.26 mmol), solvent (3 mL), r.t.
[b] Isolated yield.
[c] The reaction was carried out under argon atmosphere.
[d] The reaction was carried out at 0 °C.
[e] The reaction was carried out at –10 °C.
[f] The reaction was carried out at –20 °C.

tries 2–5). Gratifyingly, treatment of **1aa** with 1 equivalent of $PhI(OAc)_2$ and 4 equivalents of TMSCl led to chlorination within 5 minutes to give the product in an excellent yield of 96% (Table 1, entry 4). Then, diminishing the amount of $PhI(OAc)_2$ led to a dramatic decrease in the yield of the desired product **4aa**, to 55% or 62% (Table 1, entries 6 and 7). In contrast, no significant change in the yield was observed when the amount of $PhI(OAc)_2$ was increased to 1.5 equivalents (Table 1, entry 8). Furthermore, reaction under argon atmosphere did not affect the yield of the product (Table 1, entry 9). When the process was carried out at lower temperatures, the chlorination reaction did not occur effectively (Table 1, entries 10–12). Based on the preliminary optimized conditions, various solvents were also investigated (Table 1, entries 13–22). Accordingly, the reaction in methanol, ethanol or ethyl acetate also gave the product in good yield, although the results were inferior to the reaction in acetonitrile. The reaction in toluene, CH_2Cl_2, $CHCl_3$, 1,4-dioxane or THF only gave the desired product **4aa** in moderate yield.

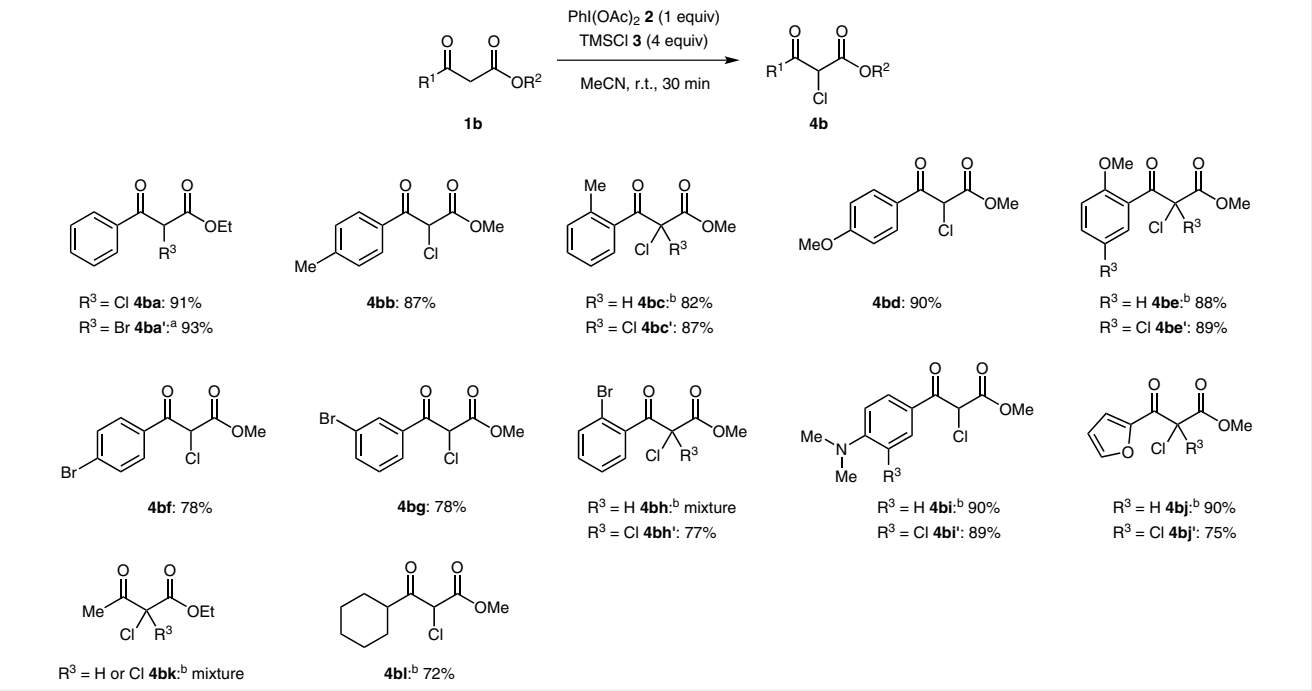
With efficient conditions for the chlorination of β-keto ester **1aa** in hand, the scope of the chlorination reaction was initially investigated with various mono-α-substituted β-keto esters (Scheme 1). First, different kinds of alkoxy groups in oxoindanecarboxylates were examined to investigate the effect of the size of the ester group on the reaction (Scheme 1, **4aa**–**4ae**). All of the examined ester alkoxy groups (MeO, EtO, *i*-PrO, *t*-BuO and BnO) gave the corresponding products in good yield. Thus, the size of the ester group has little influence on this transformation. Next, the reactions of various β-keto esters bearing an electron-donating or electron-withdrawing substituent at position 5



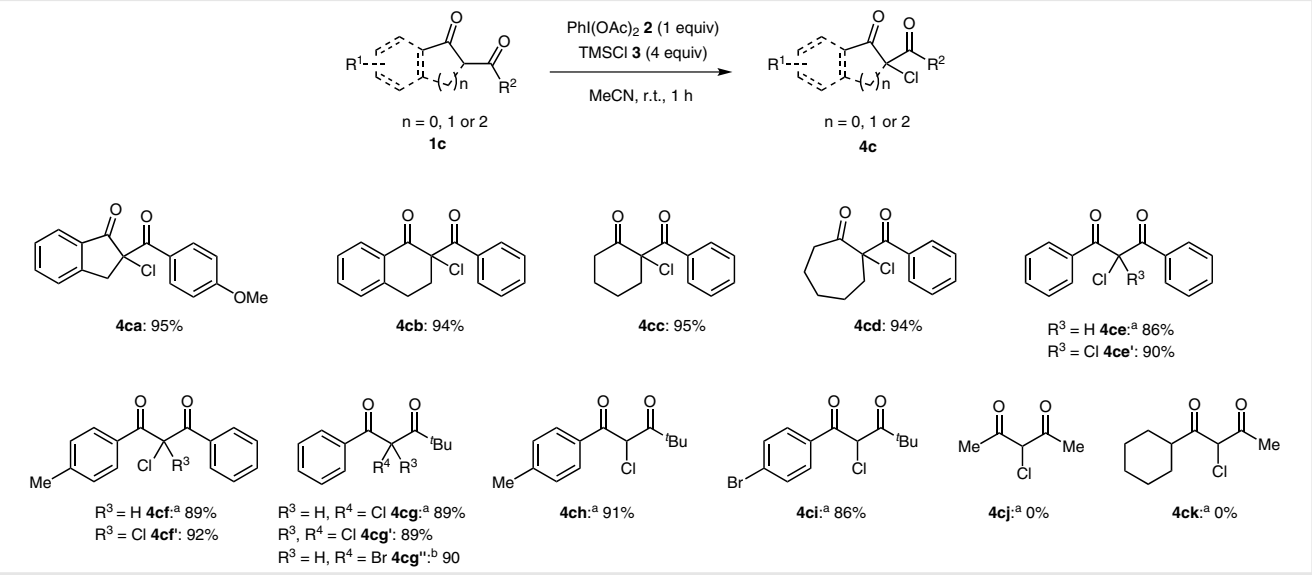
Scheme 1 Chlorination of mono-α-substituted β-keto esters. [a] TMSBr (4 equiv) was used instead of TMSCl, under the optimized conditions.

or 6 of the aromatic ring were performed under the optimized reaction conditions; all of the substrates provided the chlorinated products in excellent yield (Scheme 1, **4af**–**4al**). Additionally, β-keto esters derived from tetralone, cyclopentanone and cyclohexanone also produced the corresponding chlorides in excellent yield (Scheme 1, **4am**–**4ao**). However, methyl α-methylacetoacetate derivative **4ap** could not be obtained, and there was total recovery of the starting material. It should be noted that the bromination of **1aa** also occurred smoothly to form **4aa′** in high yield when TMSBr was used instead of TMSCl.

As mentioned above, the selective monochlorination of non-α-substituted 1,3-dicarbonyl compounds is a challenge. Hence, we focused further on the reaction of acyclic β-keto esters without an α-substituent to evaluate the generality of this method. Under the optimized conditions, it was found that the activity and conversion of acyclic β-keto esters were lower. Thus, the reaction time was prolonged to 30 minutes to allow reaction completion. As shown in Scheme 2, different kinds of β-keto esters were tested. Most of the benzoylacetates furnished the normal α-monochlorinated products in good yields (Scheme 2, **4ba**, **4bb**, **4bd**, **4bf** and **4bg**). However, if there was a substituent at the ortho position of the aromatic ring (Scheme 2, **1bc**, **1be** and **1bh**), α,α-dichlorinated products **4bc′** and **4bh′** were obtained exclusively under the optimized conditions, under which a furyl-β-diketonate also gave the dichloride product **4bj′**. Moreover, under the optimized conditions, chlorination occurred not only at the α-position of **1be**, but also at the aromatic cycle to form the trichloride **4be′**. To avoid this drawback, the amount of TMSCl was decreased. After careful investigation, 1 equivalent of TMSCl proved to be optimal, and allowed the desired monochlorination to occur completely (Scheme 2, **4bc**, **4be** and **4bj**). However, under these modified conditions, substrate **1bh** only generated an inseparable mixture, which contained monochloride as confirmed by NMR spectroscopy. Interestingly, when methyl 4-(dimethylamino)benzoylacetate (**1bi**) was subjected to the optimized conditions, chlorination occurred not only at the α-position of the keto ester, but also at the ortho position to the dimethylamino group on the phenyl ring to give the dichlorinated product **4bi′**. In this case, lowering the TMSCl loading to 1 equivalent resulted in a good selectivity for the α-position of the β-keto ester, resulting in the monochloride in 90% yield (Scheme 2, **4bi**). When **1ba** was exposed to the modified chlorination conditions, **4ba** was obtained in 71% yield after 12 hours. Hence, **4ba**, **4bb**, **4bd**, **4bf** and **4bg** were prepared with 4 equivalents of TMSCl in order to increase the yield and decrease the reaction time. Next, ethyl acetoacetate (**1bk**) and its analogue **1bl** were tested under the modified chlorination conditions; **1bl** smoothly gave the desired chloride **4bl** in 72% yield, but **1bk** provided a mixture of mono- and dichloride. Furthermore, as above, TMSBr could be used to form monobromide product **4ba′**, in this case in 93% yield.



Scheme 2 α-Monochlorination of β-keto esters without an α-substituent. [a] TMSBr (4 equiv) was used instead of TMSCl, under the optimized conditions. [b] The reaction was performed with TMSCl (1 equiv) for 2 h.

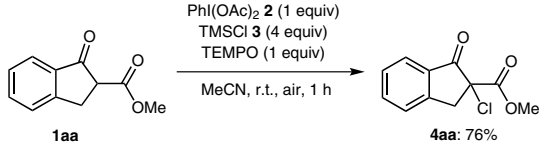


Scheme 3 Chlorination of 1,3-diketones. [a] The reaction was performed with TMSCl (1 equiv) for 2 h. [b] The reaction was performed with TMSBr (1 equiv) for 2 h.

As an extension of our approach, chlorinations of 1,3-diketones were examined (Scheme 3). 1,3-Diketones derived from indanone, tetralone, cyclohexanone or cycloheptanone could be smoothly chlorinated to give the products in excellent yield in a longer reaction time (1 h) (Scheme 3, **4ca**, **4cb**, **4cc** and **4cd**). Chloroindanone **4ca** could also be obtained with 1 equivalent of TMSCl in a lower yield (80%) after 12 hours. So, **4ca**, **4cb**, **4cc** and **4cd** were synthesized using 4 equivalents of TMSCl. Acyclic 1,3-diketones without a substituent at the methylene position only afforded dichlorinated compounds under the optimized reaction conditions (Scheme 3, **4ce′**–**4cg′**). Further investigation revealed that only monochlorination selectively occurred if the 1,3-diketones were reacted with 1 equivalent of $PhI(OAc)_2$ and 1 equivalent of TMSCl for 2 hours, to afford the corresponding α-monosubstituted chlorides in good yield (Scheme 3, **4ce**–**4ci**). However, acetoacetone (**1cj**) and analogue **1ck** failed to give the corresponding chlorides under the modified chlorination conditions. Thus, reaction of **1cj** resulted in an unstable product, while **1ck** produced an unidentified byproduct. In addition, the potential possibility for bromination was also checked. When **1cg** was treated with TMSBr instead of TMSCl under the modified chlorination conditions, the desired bromide **4cg″** was obtained in 90% yield as a white solid.

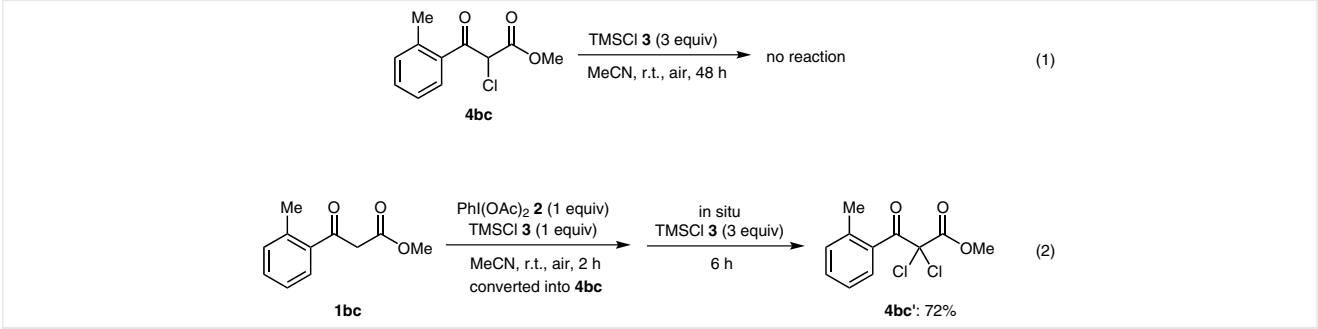
In general, $PhI(OAc)_2$-mediated halogenation or functionalization has been suggested to proceed through an Umpolung strategy.[6a,10b,11] A stoichiometric amount of $PhI(OAc)_2$ is used in this kind of transformation. However, in our preliminary investigation, when 0.2 or 0.5 equivalents of $PhI(OAc)_2$ were employed, the monochlorinated product **4aa** could be obtained in more than 50% yield (Table 1, entries 6 and 7). Meanwhile, six examples of dichlorinated products were obtained by using 1 equivalent of $PhI(OAc)_2$ (Schemes 2 and 3, **4bc′**, **4bh′**, **4bj′** and **4ce′**–**4cg′**). This indicates that 1 equivalent of oxidant is able to achieve more than 1 equivalent of chlorination. To gain some understanding of the mechanism of the $PhI(OAc)_2$-mediated chlorination, three sets of experiments were conducted.

In the first experiment, β-keto ester **1aa** was selected for chlorination with the addition of TEMPO under the optimized conditions (Scheme 4). While the addition of TEMPO had some impact on the yield of this reaction, **4aa** was still obtained in 76% yield. This result shows that the $PhI(OAc)_2$-promoted chlorination does not proceed via a radical pathway.



Scheme 4 Experiment to check for a radical pathway

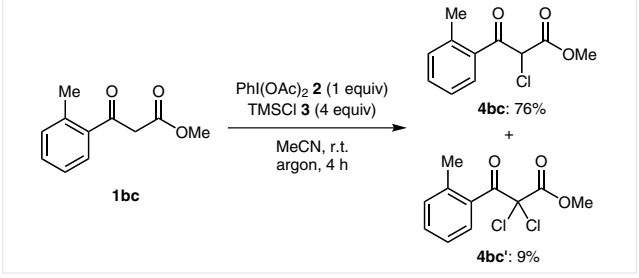
In the second set of experiments, monochloride **4bc** was subjected to 3 equivalents of TMSCl alone, without $PhI(OAc)_2$, in acetonitrile with stirring for 48 hours; dichloride **4bc′** was not observed (Scheme 5, eq 1). Hence, the dichlorination is not the result of further chlorination of the monochloride in the presence of excess TMSCl. Next, monochloride **4bc** was prepared first by using the modified conditions, then 3 equivalents of TMSCl were added until total consumption of **1bc**; after 6 hours, dichloride **4bc′** was



Scheme 5 Evidence in support of $PhI(OAc)_2$-mediated dichlorination

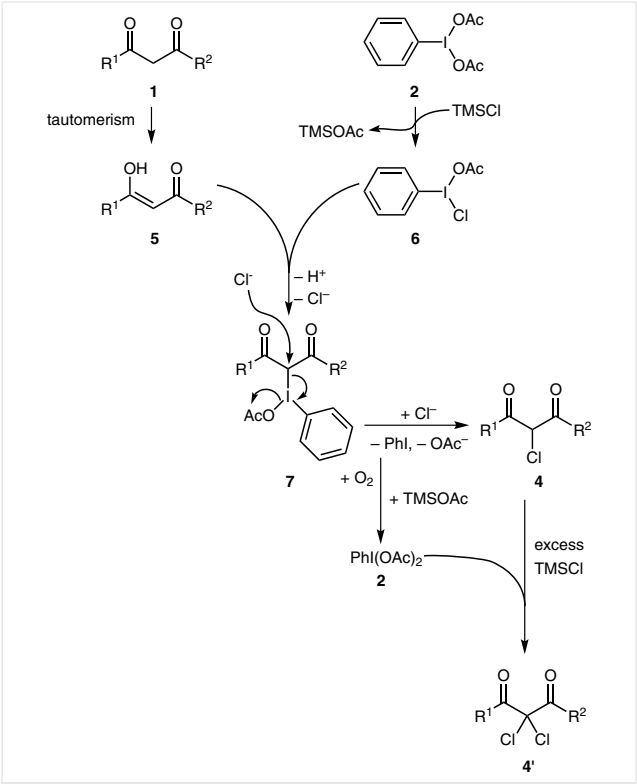
obtained in 72% yield (Scheme 5, eq 2). Through careful investigation, the formation of iodobenzene was confirmed by GC-MS. Both experiments strongly suggest that $PhI(OAc)_2$ promotes the chlorination, and produces iodobenzene via an ionic mechanism. However, the mechanism of dichlorination with 1 equivalent of $PhI(OAc)_2$ was still unclear. Further to $PhI(OAc)_2$ as oxidant, another oxidant might be the oxygen in air.

To prove if the oxygen in air participates in the chlorination reaction, chlorination of **1bc** was conducted using the optimized conditions under a strict argon atmosphere (Scheme 6). In this case, dichloride **4bc′** could only be obtained in 9% yield, with monochloride **4bc** formed in 76% yield. When compared with the result in Scheme 2, this result strongly supports the proposal that oxygen mediates this chlorination.[12] Considering the second set of experiments, we propose that oxygen could oxidize iodobenzene in situ to form $PhI(OAc)_2$ in order to achieve the dichlorination.



Scheme 6 Role of air as the oxidant

On the basis of the above experimental results and the related literature,[6a,10b,11–14] it is believed that the reaction proceeds by the formation of reactive intermediate **6** from $PhI(OAc)_2$ (**2**) and TMSCl. This λ^3-iodane is subsequently attacked by the enol **5**, obtained by tautomerization of 1,3-dicarbonyl compound **1**, to form intermediate **7**. Intermediate **7** undergoes an S_N2 reaction to give the desired product **4**, with simultaneous production of iodobenzene as coproduct (Scheme 7). Then, iodobenzene could be oxidized by oxygen in situ to provide $PhI(OAc)_2$, which promotes the chlorination again to produce dichlorinated compound **4′**.



Scheme 7 Possible pathway for the chlorination of 1,3-dicarbonyl compounds

In summary, an efficient chlorination of 1,3-dicarbonyl compounds promoted by phenyliodonium diacetate with trimethylchlorosilane as chlorine source has been disclosed. This method has the following advantages: wide substrate scope, mild reaction conditions, good selectivity for α-monochlorination, potential possibility for other halogenations, inexpensive chlorine source and benign oxidant. Further investigation of the more challenging ste-

reospecific chlorination with chiral hypervalent iodine compounds and further functional conversion of the products are underway.

All reactions were performed in flame-dried glassware with a magnetic stirring bar and sealed with a rubber septum. The solvents were distilled by standard methods. Reagents were obtained from commercial suppliers and used without further purification, unless otherwise noted. Flash column chromatography was carried out using Qingdao silica gel 60 (230–400 mesh). NMR experiments were carried out in $CDCl_3$. ^1H NMR and ^{13}C NMR spectra were recorded at 400 MHz or 600 MHz and 100 MHz or 150 MHz, respectively, on Varian Mercury 400 plus (400 MHz) and Agilent DD2-600 (600 MHz) spectrometers. Chemical shifts are reported as δ values relative to internal TMS (δ 0.00 for ^1H NMR) and chloroform (δ 77.0 for ^{13}C NMR) in parts per million (ppm). Melting points are uncorrected. Infrared spectra were recorded on a Perkin Elmer BX FT-IR spectrometer, and absorption frequencies are reported in reciprocal centimeters (cm^{-1}).

Compounds 4a, 4b and 4c; General Chlorination Procedure

To a solution of 1,3-dicarbonyl compound **1a**, **1b** or **1c** (0.26 mmol, 1 equiv) in MeCN (3 mL) was added TMSCl (1.04 mmol, 4 equiv). After the reaction mixture was stirred at r.t. for 10 min, $PhI(OAc)_2$ (0.26 mmol, 1 equiv) was added. The mixture was stirred at r.t. and monitored by TLC. After the starting material was no longer detected (TLC), the reaction mixture was poured into ice–water (10 mL). The mixture was extracted with CH_2Cl_2 and the combined organic phases were dried over Na_2SO_4, filtered and concentrated in vacuo. The residue was purified by flash column chromatography to afford compound **4a**, **4b** or **4c**.

Methyl 2-Chloro-1-oxo-2,3-dihydro-1*H*-indene-2-carboxylate (4aa)

Yield: 58 mg (96%); yellow oil.

IR (neat): 3440, 2956, 1759, 1730, 1600, 1286, 1246, 1017, 867, 754 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.86 (d, *J* = 7.6 Hz, 1 H), 7.73–7.70 (m, 1 H), 7.51–7.46 (m, 2 H), 4.12 (d, *J* = 18.0 Hz, 1 H), 3.82 (s, 3 H), 3.58 (d, *J* = 17.6 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 194.9, 167.5, 150.5, 136.5, 132.3, 128.6, 126.3, 125.9, 67.8, 54.0, 43.3.

HRMS (ESI): *m*/*z* calcd for $C_{11}H_{13}ClNO_3$ $[M + NH_4]^+$: 242.0578; found: 242.0575.

Ethyl 2-Chloro-1-oxo-2,3-dihydro-1*H*-indene-2-carboxylate (4ab)

Yield: 59 mg (96%); yellow oil.

IR (neat): 3440, 2983, 1761, 1716, 1600, 1463, 1280, 1243, 1025, 886 cm^{-1}.

^1H NMR (600 MHz, $CDCl_3$): δ = 7.86 (d, *J* = 7.2 Hz, 1 H), 7.71 (t, *J* = 7.2 Hz, 1 H), 7.50–7.46 (m, 2 H), 4.28 (q, *J* = 7.2 Hz, 2 H), 4.10 (d, *J* = 18.0 Hz, 1 H), 3.57 (d, *J* = 18.0 Hz, 1 H), 1.265 (t, *J* = 7.2 Hz, 3 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 195.0, 167.0, 150.5, 136.3, 132.4, 128.5, 126.2, 125.8, 67.9, 63.3, 43.3, 13.9.

HRMS (ESI): *m*/*z* calcd for $C_{12}H_{15}ClNO_3$ $[M + NH_4]^+$: 256.0735; found: 256.0732.

Isopropyl 2-Chloro-1-oxo-2,3-dihydro-1*H*-indene-2-carboxylate (4ac)

Yield: 62 mg (95%); yellow oil.

IR (neat): 3440, 2983, 1759, 1730, 1600, 1465, 1276, 1100, 1000, 922 cm^{-1}.

^1H NMR (600 MHz, $CDCl_3$): δ = 7.86 (d, *J* = 7.2 Hz, 1 H), 7.70 (t, *J* = 7.2 Hz, 1 H), 7.50–7.46 (m, 2 H), 5.13–5.07 (m, 1 H), 4.06 (d, *J* = 17.4 Hz, 1 H), 3.55 (d, *J* = 18.0 Hz, 1 H), 1.25 (d, *J* = 2.4 Hz, 3 H), 1.24 (d, *J* = 2.4 Hz, 3 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 195.1, 166.5, 150.5, 136.2, 128.5, 126.2, 125.8, 71.4, 68.1, 43.3, 21.4, 21.3.

HRMS (ESI): *m*/*z* calcd for $C_{13}H_{17}ClNO_3$ $[M + NH_4]^+$: 270.0891; found: 270.0888.

tert-Butyl 2-Chloro-1-oxo-2,3-dihydro-1*H*-indene-2-carboxylate (4ad)

Yield: 61 mg (88%); white solid; mp 75–76 °C.

IR (neat): 3433, 2980, 1749, 1708, 1600, 1452, 1369, 1250, 1153, 1007, 831 cm^{-1}.

^1H NMR (600 MHz, $CDCl_3$): δ = 7.85 (d, *J* = 7.2 Hz, 1 H), 7.69 (t, *J* = 7.2 Hz, 1 H), 7.49–7.45 (m, 2 H), 4.02 (d, *J* = 18.0 Hz, 1 H), 3.54 (d, *J* = 17.4 Hz, 1 H), 1.40 (s, 9 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 195.5, 165.8, 150.6, 136.1, 132.7, 128.4, 126.2, 125.7, 84.3, 68.7, 43.5, 27.6.

HRMS (ESI): *m*/*z* calcd for $C_{14}H_{19}ClNO_3$ $[M + NH_4]^+$: 284.1048; found: 284.1051.

Benzyl 2-Chloro-1-oxo-2,3-dihydro-1*H*-indene-2-carboxylate (4ae)

Yield: 64 mg (82%); yellow oil.

IR (neat): 3455, 3052, 1757, 1722, 1605, 1452, 1273, 1170, 1096, 1022 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.84 (d, *J* = 7.6 Hz, 1 H), 7.67 (t, *J* = 7.6 Hz, 1 H), 7.44 (t, *J* = 7.2 Hz, 2 H), 7.32–7.26 (m, 5 H), 5.22 (dd, *J* = 19.6, 12.8 Hz, 2 H), 4.06 (d, *J* = 18.0 Hz, 1 H), 3.54 (d, *J* = 17.6 Hz, 1 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 194.8, 166.9, 150.4, 136.4, 134.7, 132.4, 128.6, 128.5, 128.4, 127.8, 126.3, 125.8, 68.5, 68.0, 43.3.

HRMS (ESI): *m*/*z* calcd for $C_{17}H_{17}ClNO_3$ $[M + NH_4]^+$: 318.0891; found: 318.0888.

Methyl 2-Chloro-6-methoxy-1-oxo-2,3-dihydro-1*H*-indene-2-carboxylate (4af)

Yield: 61 mg (92%); white solid; mp 95–97 °C.

IR (neat): 3484, 2958, 1757, 1708, 1490, 1301, 1170, 1105, 852 cm^{-1}.

^1H NMR (600 MHz, $CDCl_3$): δ = 7.37 (d, *J* = 8.4 Hz, 1 H), 7.30–7.26 (m, 2 H), 4.02 (d, *J* = 17.4 Hz, 1 H), 3.86 (s, 3 H), 3.81 (s, 3 H), 3.49 (d, *J* = 17.4 Hz, 1 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 194.9, 167.6, 160.2, 143.4, 133.6, 127.0, 126.0, 106.7, 68.5, 55.7, 54.0, 42.8.

HRMS (ESI): *m*/*z* calcd for $C_{12}H_{12}ClO_4$ $[M + H]^+$: 255.0419; found: 255.0422.

Methyl 2-Chloro-6-methyl-1-oxo-2,3-dihydro-1*H*-indene-2-carboxylate (4ag)

Yield: 58 mg (93%); white solid; mp 81–82 °C.

IR (neat): 3425, 2954, 1766, 1715, 1620, 1492, 1413, 1249, 1017, 931, 831 cm^{-1}.

^1H NMR (600 MHz, $CDCl_3$): δ = 7.65 (s, 1 H), 7.52 (d, *J* = 7.8 Hz, 1 H), 7.37 (d, *J* = 7.8 Hz, 1 H), 4.05 (t, *J* = 17.4 Hz, 1 H), 3.80 (s, 3 H), 3.51 (d, *J* = 17.4 Hz, 1 H), 2.43 (s, 3 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 194.9, 167.6, 147.9, 138.8, 137.7, 132.5, 125.9, 125.7, 68.3, 54.0, 43.1, 21.0.

HRMS (ESI): *m*/*z* calcd for $C_{12}H_{12}ClO_3$ $[M + H]^+$: 239.0469; found: 239.0470.

Methyl 2,5-Dichloro-1-oxo-2,3-dihydro-1*H*-indene-2-carboxylate (4ah)

Yield: 59 mg (88%); white solid; mp 119–120 °C.

IR (neat): 3441, 2596, 1762, 1720, 1598, 1423, 1249, 1012, 889 cm^{-1}.

^1H NMR (600 MHz, $CDCl_3$): δ = 7.72 (d, *J* = 8.4 Hz, 1 H), 7.68 (s, 1 H), 7.62 (d, *J* = 7.8 Hz, 1 H), 4.10 (d, *J* = 18.0 Hz, 1 H), 3.82 (s, 3 H), 3.55 (d, *J* = 18.0 Hz, 1 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 193.7, 167.2, 151.9, 132.4, 132.1, 131.3, 129.6, 127.0, 67.7, 54.2, 42.9.

HRMS (ESI): *m*/*z* calcd for $C_{11}H_8Cl_2O_3K$ $[M + K]^+$: 296.9482; found: 296.9481.

Methyl 5-Bromo-2-chloro-1-oxo-2,3-dihydro-1*H*-indene-2-carboxylate (4ai)

Yield: 72 mg (92%); white solid; mp 118–119 °C.

IR (neat): 3421, 2956, 1764, 1720, 1600, 1420, 1249, 1205, 1182, 1014, 844 cm^{-1}.

^1H NMR (600 MHz, $CDCl_3$): δ = 7.79 (d, *J* = 7.8 Hz, 1 H), 7.49 (s, 1 H), 7.46 (d, *J* = 8.4 Hz, 1 H), 4.10 (d, *J* = 17.4 Hz, 1 H), 3.82 (s, 3 H), 3.54 (d, *J* = 18.0 Hz, 1 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 193.5, 167.2, 151.9, 143.2, 130.8, 129.5, 127.0, 126.5, 67.7, 54.2, 43.0.

HRMS (ESI): *m*/*z* calcd for $C_{11}H_{12}BrClNO_3$ $[M + NH_4]^+$: 319.9684; found: 319.9680.

Benzyl 2-Chloro-6-methyl-1-oxo-2,3-dihydro-1*H*-indene-2-carboxylate (4aj)

Yield: 66 mg (81%); yellow oil.

IR (neat): 3452, 2924, 1762, 1728, 1617, 1478, 1278, 1166, 1087, 1017, 821 cm^{-1}.

^1H NMR (600 MHz, $CDCl_3$): δ = 7.65 (s, 1 H), 7.50 (d, *J* = 6.0 Hz, 1 H), 7.34–7.28 (m, 6 H), 5.23 (dd, *J* = 26.4, 12.0 Hz, 2 H), 4.01 (d, *J* = 17.4 Hz, 1 H), 3.50 (d, *J* = 17.4 Hz, 1 H), 2.42 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 194.8, 167.0, 147.8, 138.8, 137.7, 134.8, 132.6, 128.6, 128.4, 127.9, 125.9, 128.8, 68.5, 68.4, 43.0, 21.1.

HRMS (ESI): *m*/*z* calcd for $C_{18}H_{19}ClNO_3$ $[M + NH_4]^+$: 332.1048; found: 332.1051.

Benzyl 2,5-Dichloro-1-oxo-2,3-dihydro-1*H*-indene-2-carboxylate (4ak)

Yield: 72 mg (83%); white solid; mp 84–85 °C.

IR (neat): 3425, 2918, 1759, 1725, 1595, 1255, 1183, 1023, 886, 833, 737 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.78 (d, *J* = 8.4 Hz, 1 H), 7.44 (d, *J* = 10.4 Hz, 2 H), 7.36–7.28 (m, 5 H), 5.24 (dd, *J* = 19.2, 12.0 Hz, 2 H), 4.04 (d, *J* = 17.6 Hz, 1 H), 3.52 (d, *J* = 18.0 Hz, 1 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 193.4, 166.6, 151.8, 143.2, 134.6, 130.9, 129.5, 128.6, 128.5, 128.0, 127.0, 126.6, 68.8, 67.9, 43.0.

HRMS (ESI): *m*/*z* calcd for $C_{17}H_{16}Cl_2NO_3$ $[M + NH_4]^+$: 352.0502; found: 352.0507.

Benzyl 5-Bromo-2-chloro-1-oxo-2,3-dihydro-1*H*-indene-2-carboxylate (4al)

Yield: 81 mg (82%); white solid; mp 86–87 °C.

IR (neat): 3437, 3052, 1761, 1715, 1590, 1435, 1247, 1184, 1022, 875, 742 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.71–7.57 (m, 3 H), 7.34–7.27 (m, 5 H), 5.27–5.20 (m, 2 H), 4.04 (d, *J* = 18.0 Hz, 1 H), 3.52 (d, *J* = 18.0 Hz, 1 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 193.6, 166.5, 151.9, 134.6, 132.3, 132.1, 131.3, 129.6, 128.6, 128.5, 128.0, 127.0, 68.8, 67.8, 42.8.

HRMS (ESI): *m*/*z* calcd for $C_{17}H_{16}BrClNO_3$ $[M + NH_4]^+$: 395.9997; found: 396.0001.

Methyl 2-Chloro-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylate (4am)

Yield: 59 mg (95%); yellow oil.

IR (neat): 2954, 1767, 1689, 1600, 1447, 1302, 1256, 1217, 1044, 956, 730 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 8.10 (d, *J* = 8.0 Hz, 1 H), 7.55 (t, *J* = 7.6 Hz, 1 H), 7.37 (t, *J* = 7.6 Hz, 1 H), 7.28 (d, *J* = 7.4 Hz, 1 H), 3.85 (s, 3 H), 3.32–3.25 (m, 1 H), 3.05–2.97 (m, 2 H), 2.57–2.51 (m, 1 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 187.5, 168.0, 142.5, 134.4, 129.5, 129.0, 128.7, 127.3, 70.7, 53.8, 35.0, 25.5.

HRMS (ESI): *m*/*z* calcd for $C_{12}H_{12}ClO_3$ $[M + H]^+$: 239.0469; found: 239.0472.

Methyl 1-Chloro-2-oxocyclopentanecarboxylate (4an)

Yield: 42 mg (91%); yellow oil.

IR (neat): 3380, 1654, 1400, 1078 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 3.84 (s, 3 H), 2.80–2.73 (m, 1 H), 2.62–2.54 (m, 1 H), 2.45–2.36 (m, 2 H), 2.23–2.08 (m, 2 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 206.0, 167.7, 69.5, 53.8, 38.4, 35.3, 19.1.

HRMS (ESI): *m*/*z* calcd for $C_7H_{10}ClO_3$ $[M + H]^+$: 177.0313; found: 177.0309.

Methyl 1-Chloro-2-oxocyclohexanecarboxylate (4ao)

Yield: 46 mg (93%); yellow oil.

IR (neat): 3454, 2956, 1741, 1447, 1243, 1211, 1072, 958, 754 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 3.85 (s, 3 H), 2.92–2.84 (m, 1 H), 2.83–2.76 (m, 1 H), 2.47–2.40 (m, 1 H), 2.20–2.14 (m, 1 H), 2.02–1.87 (m, 3 H), 1.81–1.73 (m, 1 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 199.6, 167.8, 73.3, 53.6, 39.5, 38.6, 26.6, 21.9.

HRMS (ESI): *m*/*z* calcd for $C_8H_{11}ClO_3Na$ $[M + Na]^+$: 213.0289; found: 213.0285.

Ethyl 2-Chloro-3-oxo-3-phenylpropanoate (4ba)

Yield: 54 mg (91%); yellow oil.

IR (neat): 2985, 1767, 1678, 1595, 1442, 1295, 1162, 1022, 823, 683 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.00 (dd, *J* = 8.0, 0.8 Hz, 2 H), 7.64 (t, *J* = 7.2 Hz, 1 H), 7.51 (d, *J* = 8.0 Hz, 2 H), 5.63 (s, 1 H), 4.29 (q, *J* = 7.2 Hz, 2 H), 1.24 (t, *J* = 7.2 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 188.2, 165.2, 134.3, 133.3, 129.2, 128.8, 63.1, 57.9, 13.8.

HRMS (ESI): *m*/*z* calcd for $C_{11}H_{12}ClO_3$ [M + H]$^+$: 227.0469; found: 227.0466.

Methyl 2-Chloro-3-oxo-3-(*p*-tolyl)propanoate (4bb)

Yield: 51 mg (87%); yellow oil.

IR (neat): 3447, 2956, 1774, 1678, 1612, 1442, 1273, 1162, 1003, 846, 712 cm^{-1}.

^{1}H NMR (600 MHz, $CDCl_3$): δ = 7.89 (d, *J* = 7.8 Hz, 2 H), 7.30 (d, *J* = 7.2 Hz, 2 H), 5.64 (s, 1 H), 3.82 (s, 3 H), 2.43 (s, 3 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 187.7, 165.8, 145.6, 130.7, 129.6, 129.3, 57.6, 53.7, 21.7.

HRMS (ESI): *m*/*z* calcd for $C_{11}H_{15}ClNO_3$ [M + NH_4]$^+$: 244.0735; found: 244.0736.

Methyl 2,2-Dichloro-3-oxo-3-(*o*-tolyl)propanoate (4bc')

Yield: 59 mg (87%); yellow oil.

IR (neat): 2956, 1770, 1715, 1600, 1435, 1242, 1003, 852, 720, 631 cm^{-1}.

^{1}H NMR (600 MHz, $CDCl_3$): δ = 7.75 (d, *J* = 7.8 Hz, 1 H), 7.42 (t, *J* = 7.8 Hz, 1 H), 7.31 (d, *J* = 7.8 Hz, 1 H), 7.24 (t, *J* = 7.8 Hz, 1 H), 3.87 (s, 3 H), 2.46 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 188.0, 164.5, 139.8, 132.4, 132.2, 132.0, 128.0, 125.2, 81.7, 54.9, 21.0.

HRMS (ESI): *m*/*z* calcd for $C_{11}H_{11}Cl_2O_3$ [M + H]$^+$: 261.0034; found: 261.0033.

Methyl 2-Chloro-3-(4-methoxyphenyl)-3-oxopropanoate (4bd)

Yield: 57 mg (90%); yellow oil.

IR (neat): 2956, 2836, 1759, 1683, 1590, 1508, 1265, 1170, 1027, 983, 843 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.99 (d, *J* = 8.8 Hz, 2 H), 6.97 (d, *J* = 8.8 Hz, 2 H), 5.61 (s, 1 H), 3.89 (s, 3 H), 3.83 (s, 3 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 186.6, 165.9, 164.5, 131.8, 126.1, 114.2, 57.6, 55.6, 53.7.

HRMS (ESI): *m*/*z* calcd for $C_{11}H_{12}ClO_4$ [M + H]$^+$: 243.0419; found: 243.0418.

Methyl 2,2-Dichloro-3-(5-chloro-2-methoxyphenyl)-3-oxopropanoate (4be')

Yield: 72 mg (89%); yellow oil.

IR (neat): 2954, 1772, 1708, 1582, 1487, 1391, 1281, 1194, 1007, 852, 816, 639 cm^{-1}.

^{1}H NMR (600 MHz, $CDCl_3$): δ = 7.87 (d, *J* = 2.4 Hz, 1 H), 7.51 (dd, *J* = 9.0, 2.4 Hz, 1 H), 6.93 (d, *J* = 9.0 Hz, 1 H), 3.85 (s, 3 H), 3.82 (s, 3 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 183.1, 163.7, 156.1, 135.0, 132.2, 126.9, 123.6, 113.4, 84.8, 55.4, 54.4.

HRMS (ESI): *m*/*z* calcd for $C_{11}H_9Cl_3O_4Na$ [M + Na]$^+$: 334.9430; found: 334.9431.

Methyl 3-(4-Bromophenyl)-2-chloro-3-oxopropanoate (4bf)

Yield: 59 mg (78%); yellow oil.

IR (neat): 3457, 2956, 1769, 1686, 1579, 1447, 1265, 1192, 1071, 986, 843 cm^{-1}.

^{1}H NMR (600 MHz, $CDCl_3$): δ (20:1 tautomer ratio) = 12.76* (s, 1 H), 7.87 (d, *J* = 7.2 Hz, 2 H), 7.66 (d, *J* = 6.6 Hz, 2 H), 5.57 (s, 1 H), 3.93* (s, 3 H), 3.84 (s, 3 H); asterisk denotes minor tautomer peaks.

^{13}C NMR (150 MHz, $CDCl_3$): δ = 187.2, 165.5, 132.3, 131.9, 130.7, 129.9, 57.7, 53.9.

HRMS (ESI): *m*/*z* calcd for $C_{10}H_{12}BrClNO_3$ [M + NH_4]$^+$: 307.9684; found: 307.9681.

Methyl 3-(3-Bromophenyl)-2-chloro-3-oxopropanoate (4bg)

Yield: 59 mg (78%); yellow oil.

IR (neat): 2951, 1766, 1683, 1563, 1414, 1290, 1199, 993, 863 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.13 (s, 1 H), 7.92 (d, *J* = 8.0 Hz, 1 H), 7.78–7.75 (m, 1 H), 7.40 (t, *J* = 8.0 Hz, 1 H), 5.58 (s, 1 H), 3.85 (s, 3 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 186.9, 165.3, 137.2, 134.9, 132.2, 130.4, 127.7, 123.2, 57.5, 53.9.

HRMS (ESI): *m*/*z* calcd for $C_{10}H_{12}BrClNO_3$ [M + NH_4]$^+$: 307.9684; found: 307.9684.

Methyl 3-(2-Bromophenyl)-2,2-dichloro-3-oxopropanoate (4bh')

Yield: 65 mg (77%); yellow oil.

IR (neat): 3447, 2961, 1770, 1722, 1579, 1452, 1246, 1022, 838, 764 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.70–7.63 (m, 2 H), 7.41–7.35 (m, 2 H), 3.94 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 188.5, 163.9, 136.0, 133.9, 132.3, 128.3, 126.8, 120.6, 80.8, 55.1.

HRMS (ESI): *m*/*z* calcd for $C_{10}H_{11}BrCl_2NO_3$ [M + NH_4]$^+$: 341.9294; found: 341.9297.

Methyl 2-Chloro-3-(3-chloro-4-(dimethylamino)phenyl)-3-oxopropanoate (4bi')

Yield: 67 mg (89%); yellow oil.

IR (neat): 3428, 2954, 2845, 1771, 1678, 1591, 1515, 1430, 1293, 1170, 971, 949, 740 cm^{-1}.

^{1}H NMR (600 MHz, $CDCl_3$): δ = 7.98 (d, *J* = 2.4 Hz, 1 H), 7.82 (dd, *J* = 8.4, 2.4 Hz, 1 H), 6.99 (d, *J* = 8.4 Hz, 1 H), 5.56 (s, 1 H), 3.84 (s, 3 H), 2.99 (s, 6 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 185.7, 165.8, 155.1, 132.7, 129.0, 126.1, 125.6, 118.2, 57.4, 53.8, 42.9.

HRMS (ESI): *m*/*z* calcd for $C_{12}H_{14}Cl_2NO_3$ [M + H]$^+$: 290.0345; found: 290.0346.

Methyl 2,2-Dichloro-3-(furan-2-yl)-3-oxopropanoate (4bj')

Yield: 46 mg (75%); yellow oil.

IR (neat): 3137, 2972, 1769, 1700, 1569, 1460, 1261, 1234, 1015, 864, 764, 697, 658 cm^{-1}.

^{1}H NMR (600 MHz, $CDCl_3$): δ = 7.65 (d, *J* = 1.2 Hz, 1 H), 7.49 (d, *J* = 3.6 Hz, 1 H), 6.62 (dd, *J* = 1.2, 3.6 Hz, 1 H), 3.89 (s, 3 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 171.9, 164.0, 147.9, 147.2, 122.0, 113.0, 80.9, 54.9.

HRMS (ESI): *m*/*z* calcd for $C_8H_6Cl_2O_4Na$ [M + Na]$^+$: 258.9535; found: 258.9537.

Methyl 2-Chloro-3-cyclohexyl-3-oxopropanoate (4bl)

Yield: 41 mg (72%); yellow oil.

IR (neat): 3463, 2945, 2866, 1775, 1734, 1445, 1246, 1005, 858, 843 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ (3:1 tautomer ratio) = 12.46* (d, *J* = 1.2 Hz, 1 H), 4.93 (s, 1 H), 3.83 (s, 3 H), 2.86–2.79 (m, 1 H), 1.91–1.79 (m, 4 H), 1.75–1.68* (m, 4 H), 1.54–1.17 (m, 6 H); asterisk denotes minor tautomer peaks.

^{13}C NMR (100 MHz, $CDCl_3$): δ (3:1 tautomer ratio) = 201.5, 165.6, 59.4, 53.6, 52.7*, 47.6, 41.0*, 28.8, 28.6, 28.4*, 25.8*, 25.7*, 25.5, 25.4, 25.3; asterisk denotes minor tautomer peaks.

HRMS (ESI): *m*/*z* calcd for $C_{10}H_{15}ClNaO_3$ [M + Na]$^+$: 241.0602; found: 241.0598.

2-Chloro-2-(4-methoxybenzoyl)-2,3-dihydro-1*H*-inden-1-one (4ca)

Yield: 74 mg (95%); white solid; mp 98–99 °C.

IR (neat): 3064, 2930, 1744, 1600, 1473, 1265, 1177, 1022, 858, 757, 594 cm^{-1}.

^{1}H NMR (600 MHz, $CDCl_3$): δ = 8.16 (d, *J* = 9.0 Hz, 2 H), 7.83 (d, *J* = 7.8 Hz, 1 H), 7.68 (t, *J* = 7.8 Hz, 1 H), 7.49 (d, *J* = 7.8 Hz, 1 H), 7.45 (t, *J* = 7.8 Hz, 1 H), 6.92 (d, *J* = 9.0 Hz, 2 H), 4.37 (d, *J* = 16.8 Hz, 1 H), 3.86 (s, 3 H), 3.58 (d, *J* = 17.4 Hz, 1 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 196.3, 189.7, 163.8, 150.3, 136.3, 133.1, 133.0, 128.5, 126.1, 125.9, 125.7, 113.5, 73.6, 55.5, 43.3.

HRMS (ESI): *m*/*z* calcd for $C_{17}H_{14}ClO_3$ [M + H]$^+$: 301.0626; found: 301.0623.

2-Benzoyl-2-chloro-3,4-dihydronaphthalen-1(2*H*)-one (4cb)

Yield: 70 mg (94%); white solid; mp 93–95 °C.

IR (neat): 3410, 2935, 1681, 1656, 1595, 1447, 1296, 1221, 1170, 1044, 809, 698 cm^{-1}.

^{1}H NMR (600 MHz, $CDCl_3$): δ = 8.05 (d, *J* = 7.8 Hz, 1 H), 7.96 (d, *J* = 7.8 Hz, 2 H), 7.53 (q, *J* = 7.8 Hz, 2 H), 7.41 (t, *J* = 7.8 Hz, 2 H), 7.35 (t, *J* = 7.8 Hz, 1 H), 7.27 (d, *J* = 8.4 Hz, 1 H), 3.32–3.27 (m, 1 H), 3.21–3.10 (m, 2 H), 2.60–2.56 (m, 1 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 192.8, 190.2, 142.5, 134.4, 134.3, 133.1, 130.7, 130.1, 128.8, 128.7, 128.2, 127.3, 75.0, 35.7, 26.1.

HRMS (ESI): *m*/*z* calcd for $C_{17}H_{14}ClO_2$ [M + H]$^+$: 285.0677; found: 285.0676.

2-Benzoyl-2-chlorocyclohexanone (4cc)

Yield: 58 mg (95%); yellow oil.

IR (neat): 3462, 2949, 1732, 1685, 1584, 1448, 1244, 1122, 883, 683 cm^{-1}.

^{1}H NMR (600 MHz, $CDCl_3$): δ = 7.97 (d, *J* = 7.2 Hz, 2 H), 7.54 (t, *J* = 7.2 Hz, 1 H), 7.42 (t, *J* = 7.8 Hz, 2 H), 3.07–3.04 (m, 1 H), 2.81–2.78 (m, 1 H), 2.24–2.19 (m, 1 H), 2.14–2.09 (m, 1 H), 2.01–1.98 (m, 1 H), 1.96–1.83 (m, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 203.4, 190.7, 134.2, 133.6, 130.0, 128.5, 77.1, 41.3, 41.1, 28.3, 22.9.

HRMS (ESI): *m*/*z* calcd for $C_{13}H_{14}ClO_2$ [M + H]$^+$: 237.0677; found: 237.0674.

2-Benzoyl-2-chlorocycloheptanone (4cd)

Yield: 61 mg (94%); yellow oil.

IR (neat): 3381, 2931, 1732, 1693, 1596, 1448, 1236, 1126, 941, 865, 759, 698 cm^{-1}.

^{1}H NMR (600 MHz, $CDCl_3$): δ = 7.93 (d, *J* = 7.8 Hz, 2 H), 7.54 (t, *J* = 7.8 Hz, 1 H), 7.42 (t, *J* = 7.8 Hz, 2 H), 3.02–3.00 (m, 1 H), 2.62–2.57 (m, 1 H), 2.49–2.44 (m, 1 H), 2.42–2.38 (m, 1 H) 1.96–1.82 (m, 4 H), 1.78–1.71 (m, 1 H), 1.44–1.40 (m, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 205.3, 191.7, 133.6, 133.2, 130.1, 128.3, 79.3, 40.2, 37.3, 27.7, 24.2, 23.8.

HRMS (ESI): *m*/*z* calcd for $C_{14}H_{16}ClO_2$ [M + H]$^+$: 251.0833; found: 251.0836.

2,2-Dichloro-1,3-diphenylpropane-1,3-dione (4ce′)

Yield: 68 mg (90%); yellow oil.

IR (neat): 3396, 3071, 1699, 1595, 1442, 1238, 1207, 1180, 1000, 821, 685, 636 cm^{-1}.

^{1}H NMR (600 MHz, $CDCl_3$): δ = 7.97 (d, *J* = 7.8 Hz, 4 H), 7.54 (t, *J* = 7.8 Hz, 2 H), 7.40 (t, *J* = 7.8 Hz, 4 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 185.3, 134.2, 131.5, 130.4, 128.7, 87.5.

HRMS (ESI): *m*/*z* calcd for $C_{15}H_{10}Cl_2O_2Na$ [M + Na]$^+$: 314.9950; found: 314.9954.

2,2-Dichloro-1-phenyl-3-(*p*-tolyl)propane-1,3-dione (4cf′)

Yield: 73 mg (92%); yellow oil.

IR (neat): 3727, 2918, 1695, 1604, 1442, 1244, 1192, 1000, 838, 698 cm^{-1}.

^{1}H NMR (600 MHz, $CDCl_3$): δ = 7.96 (d, *J* = 7.2 Hz, 2 H), 7.87 (d, *J* = 8.4 Hz, 2 H), 7.53 (t, *J* = 7.2 Hz, 1 H), 7.39 (t, *J* = 8.4 Hz, 2 H), 7.19 (d, *J* = 8.4 Hz, 2 H), 2.36 (s, 3 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 185.3, 184.9, 145.5, 134.1, 131.5, 130.6, 130.4, 129.4, 128.8, 128.6, 87.9, 21.7.

HRMS (ESI): *m*/*z* calcd for $C_{16}H_{12}Cl_2O_2Na$ [M + Na]$^+$: 329.0107; found: 329.0109.

2,2-Dichloro-4,4-dimethyl-1-phenylpentane-1,3-dione (4cg′)

Yield: 63 mg (89%); yellow oil.

IR (neat): 3429, 2974, 2913, 1718, 1706, 1597, 1457, 1226, 1064, 835, 681 cm^{-1}.

^{1}H NMR (600 MHz, $CDCl_3$): δ = 8.01 (d, *J* = 7.8 Hz, 2 H), 7.62 (t, *J* = 7.2 Hz, 1 H), 7.49 (t, *J* = 7.8 Hz, 2 H), 1.26 (s, 9 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 199.4, 185.0, 134.3, 131.8, 130.5, 128.8, 88.5, 45.4, 29.1.

HRMS (ESI): *m*/*z* calcd for $C_{13}H_{18}Cl_2NO_2$ [M + NH_4]$^+$: 290.0709; found: 290.0710.

Modified Chlorination of 1,3-Dicarbonyl Compounds 1bc, 1be, 1bi, 1bj and 1ce–1ci; General Procedure

To a solution of a 1,3-dicarbonyl compound (0.26 mmol, 1 equiv) in MeCN (3 mL) was added TMSCl (0.26 mmol, 1 equiv). After the reaction mixture was stirred at r.t. for 10 min, $PhI(OAc)_2$ (0.26 mmol, 1 equiv) was added. The mixture was stirred at r.t. and monitored by TLC. After the starting material was no longer detected (TLC, 5–60 min), the reaction mixture was poured into ice–water (10 mL). The mixture was extracted with CH_2Cl_2 and the combined organic phases

were dried over Na_2SO_4, filtered and concentrated in vacuo. The residue was purified by flash column chromatography to afford the desired monochlorinated compound.

Methyl 2-Chloro-3-oxo-3-(*o*-tolyl)propanoate (4bc)

Yield: 48 mg (82%); yellow oil.

IR (neat): 3447, 2956, 1768, 1686, 1447, 1293, 1165, 976, 831, 764, 728 cm^{-1}.

^1H NMR (600 MHz, $CDCl_3$): δ (5:1 tautomer ratio) = 12.44* (s, 1 H), 7.68 (d, *J* = 7.8 Hz, 1 H), 7.45 (t, *J* = 7.2 Hz, 1 H), 7.35–7.29 (m, 2 H), 7.26–7.23* (m, 2 H), 5.61 (s, 1 H), 3.93* (s, 3 H), 3.81 (s, 3 H), 2.52 (s, 3 H), 2.36* (s, 3 H); asterisk denotes minor tautomer peaks.

^{13}C NMR (150 MHz, $CDCl_3$): δ (5:1 tautomer ratio) = 190.8, 171.5*, 170.0*, 165.8, 140.4, 135.8*, 133.7, 133.3*, 132.7, 132.4, 130.3*, 129.9*, 128.9, 128.0*, 125.8, 125.5*, 59.3, 53.7, 53.0*, 21.2, 19.1*; asterisk denotes minor tautomer peaks.

HRMS (ESI): *m*/*z* calcd for $C_{11}H_{15}ClNO_3$ $[M + NH_4]^+$: 244.0735; found: 244.0732.

Methyl 2-Chloro-3-(2-methoxyphenyl)-3-oxopropanoate (4be)

Yield: 55 mg (88%); yellow oil.

IR (neat): 3494, 3024, 2965, 1745, 1595, 1452, 1305, 1163, 1016, 910, 761 cm^{-1}.

^1H NMR (600 MHz, $CDCl_3$): δ = 7.91 (dd, *J* = 7.8, 1.8 Hz, 1 H), 7.56 (dt, *J* = 7.8, 1.8 Hz, 1 H), 7.07 (dt, *J* = 7.8, 1.2 Hz, 1 H), 6.99 (d, *J* = 8.4 Hz, 1 H), 5.73 (s, 1 H), 3.91 (s, 3 H), 3.79 (s, 3 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 188.2, 166.2, 158.6, 135.4, 131.9, 123.9, 121.3, 111.6, 62.4, 55.4, 53.3.

HRMS (ESI): *m*/*z* calcd for $C_{11}H_{12}ClO_4$ $[M + H]^+$: 243.0419; found: 243.0418.

Methyl 2-Chloro-3-(4-(dimethylamino)phenyl)-3-oxopropanoate (4bi)

Yield: 60 mg (90%); yellow oil.

IR (neat): 3484, 2964, 1771, 1633, 1584, 1388, 1290, 1192, 1005, 839, 702 cm^{-1}.

^1H NMR (600 MHz, $CDCl_3$): δ = 7.89 (d, *J* = 9.6 Hz, 2 H), 6.66 (d, *J* = 9.0 Hz, 2 H), 5.61 (s, 1 H), 3.81 (s, 3 H), 3.09 (s, 6 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 185.7, 166.4, 154.1, 131.7, 120.6, 110.8, 57.4, 53.5, 39.9.

HRMS (ESI): *m*/*z* calcd for $C_{12}H_{15}ClNO_3$ $[M + H]^+$: 256.0735; found: 256.0732.

Methyl 2-Chloro-3-(furan-2-yl)-3-oxopropanoate (4bj)

Yield: 47 mg (90%); yellow oil.

IR (neat): 3137, 2963, 1766, 1679, 1567, 1466, 1289, 1168, 1015, 767, 685 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.69 (dd, *J* = 0.8, 1.6 Hz, 1 H), 7.43 (dd, *J* = 0.8, 3.6 Hz, 1 H), 6.64 (dd, *J* = 1.6, 3.6 Hz, 1 H), 5.51 (s, 1 H), 3.84 (s, 3 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 176.6, 165.3, 149.6, 147.9, 120.4, 113.1, 57.5, 53.8.

HRMS (ESI): *m*/*z* calcd for $C_8H_{11}ClNO_4$ $[M + NH_4]^+$: 220.0368; found: 220.0371.

2-Chloro-1,3-diphenylpropane-1,3-dione (4ce)

Yield: 58 mg (86%); white solid; mp 71–72.5 °C.

IR (neat): 3450, 3041, 1707, 1681, 1579, 1447, 1290, 1261, 1212, 1163, 938, 831, 752, 694 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 8.00 (d, *J* = 7.6 Hz, 4 H), 7.60 (t, *J* = 7.6 Hz, 2 H), 7.47 (t, *J* = 8.0 Hz, 4 H), 6.42 (s, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 189.3, 134.3, 133.8, 129.3, 129.0, 62.9.

HRMS (ESI): *m*/*z* calcd for $C_{15}H_{15}ClNO_2$ $[M + NH_4]^+$: 276.0786; found: 276.0789.

2-Chloro-1-phenyl-3-(*p*-tolyl)propane-1,3-dione (4cf)

Yield: 63 mg (89%); white solid; mp 77–79 °C.

IR (neat): 3450, 2933, 1730, 1656, 1600, 1508, 1413, 1261, 1027, 864, 752, 588 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.99 (d, *J* = 7.2 Hz, 2 H), 7.90 (d, *J* = 8.4 Hz, 2 H), 7.59 (t, *J* = 7.2 Hz, 1 H), 7.46 (t, *J* = 7.6 Hz, 2 H), 7.26 (d, *J* = 8.0 Hz, 2 H), 6.40 (s, 1 H), 2.40 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 189.3, 188.9, 145.6, 134.2, 133.8, 131.3, 129.7, 129.4, 129.2, 128.9, 63.0, 21.8.

HRMS (ESI): *m*/*z* calcd for $C_{16}H_{17}ClNO_2$ $[M + NH_4]^+$: 290.0942; found: 290.0939.

2-Chloro-4,4-dimethyl-1-phenylpentane-1,3-dione (4cg)

Yield: 55 mg (89%); white solid; mp 95–96 °C.

IR (neat): 3440, 2970, 1733, 1669, 1595, 1457, 1314, 1180, 1053, 989, 835, 716, 676 cm^{-1}.

^1H NMR (600 MHz, $CDCl_3$): δ = 8.01 (d, *J* = 7.8 Hz, 2 H), 7.63 (t, *J* = 7.8 Hz, 1 H), 7.51 (t, *J* = 7.8 Hz, 2 H), 6.04 (s, 1 H), 1.22 (s, 9 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 203.9, 189.8, 134.2, 133.8, 129.3, 128.9, 59.4, 44.8, 26.8.

HRMS (ESI): *m*/*z* calcd for $C_{13}H_{19}ClNO_2$ $[M + NH_4]^+$: 256.1099; found: 256.1098.

2-Chloro-4,4-dimethyl-1-(*p*-tolyl)pentane-1,3-dione (4ch)

Yield: 60 mg (91%); white solid; mp 93–94 °C.

IR (neat): 3443, 2968, 2924, 1723, 1673, 1306, 1190, 1067, 994, 846 cm^{-1}.

^1H NMR (600 MHz, $CDCl_3$): δ = 7.91 (d, *J* = 8.4 Hz, 2 H), 7.30 (d, *J* = 7.8 Hz, 2 H), 6.00 (s, 1 H), 2.43 (s, 3 H), 1.21 (s, 9 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 203.9, 189.4, 145.4, 131.3, 129.6, 129.5, 59.6, 44.8, 26.9, 21.8.

HRMS (ESI): *m*/*z* calcd for $C_{14}H_{17}ClO_2Na$ $[M + Na]^+$: 275.0809; found: 275.0811.

1-(4-Bromophenyl)-2-chloro-4,4-dimethylpentane-1,3-dione (4ci)

Yield: 71 mg (86%); white solid; mp 96–97 °C.

IR (neat): 3440, 2968, 1723, 1673, 1576, 1395, 1287, 1183, 1067, 996, 852 cm^{-1}.

^1H NMR (600 MHz, $CDCl_3$): δ = 7.89 (d, *J* = 8.4 Hz, 2 H), 7.65 (d, *J* = 7.8 Hz, 2 H), 5.92 (s, 1 H), 1.21 (s, 9 H).

^{13}C NMR (150 MHz, $CDCl_3$): δ = 203.8, 189.1, 132.5, 132.2, 130.9, 129.7, 59.6, 45.0, 26.8.

HRMS (ESI): *m*/*z* calcd for $C_{13}H_{14}BrClO_2Na$ $[M + Na]^+$: 338.9758; found: 338.9761.

Compounds 4aa′ and 4ba′; General Bromination Procedure

To a solution of 1,3-dicarbonyl compound **1aa** or **1ba** (0.26 mmol, 1 equiv) in MeCN (3 mL) was added TMSBr (1.04 mmol, 4 equiv). After the reaction mixture was stirred at r.t. for 10 min, $PhI(OAc)_2$ (0.26 mmol, 1 equiv) was added. The mixture was stirred at r.t. After TLC indicated the disappearance of starting material, the reaction mixture was poured into ice–water (10 mL). The mixture was extracted with CH_2Cl_2 and the combined organic phases were dried over Na_2SO_4, filtered and concentrated in vacuo. The residue was purified by flash column chromatography to afford the desired compound **4aa′** or **4ba′**.

Methyl 2-Bromo-1-oxo-2,3-dihydro-1*H*-indene-2-carboxylate (4aa′)

Yield: 67 mg (96%); yellow oil.

IR (neat): 3434, 2954, 1760, 1712, 1595, 1463, 1277, 1244, 1037, 959, 754 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.87 (d, *J* = 7.6 Hz, 1 H), 7.70 (t, *J* = 7.6 Hz, 1 H), 7.48 (d, *J* = 6.0 Hz, 2 H), 4.23 (d, *J* = 18.4 Hz, 1 H), 3.83 (s, 3 H), 3.69 (d, *J* = 18.4 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 195.0, 167.6, 150.1, 136.3, 132.1, 128.6, 126.3, 126.0, 58.1, 54.3, 43.8.

HRMS (ESI): *m*/*z* calcd for $C_{11}H_{13}BrNO_3$ $[M + NH_4]^+$: 286.0073; found: 286.0076.

Ethyl 2-Bromo-3-oxo-3-phenylpropanoate (4ba′)

Yield: 65 mg (93%); yellow oil.

IR (neat): 3504, 2970, 1794, 1685, 1590, 1457, 1303, 1264, 1187, 1031, 936, 798 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 8.00 (d, *J* = 7.6 Hz, 2 H), 7.63 (t, *J* = 7.2 Hz, 1 H), 7.50 (t, *J* = 8.0 Hz, 2 H), 5.68 (s, 1 H), 4.28 (q, *J* = 7.2 Hz, 2 H), 1.25 (t, *J* = 7.2 Hz, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 188.1, 165.1, 134.2, 133.3, 129.1, 128.8, 63.2, 46.3, 13.8.

HRMS (ESI): *m*/*z* calcd for $C_{11}H_{15}BrNO_3$ $[M + NH_4]^+$: 288.0230; found: 288.0234.

2-Bromo-4,4-dimethyl-1-phenylpentane-1,3-dione (4cg″)

To a solution of **1cg** (0.26 mmol, 1 equiv) in MeCN (3 mL) was added TMSBr (0.26 mmol, 1 equiv). After the reaction mixture was stirred at r.t. for around 10 min, $PhI(OAc)_2$ (0.26 mmol, 1 equiv) was added. The mixture was stirred at r.t. After TLC indicated the disappearance of starting material (2 h), the reaction mixture was poured into ice–water (10 mL). The mixture was extracted with CH_2Cl_2 and the combined organic phases were dried over Na_2SO_4, filtered and concentrated in vacuo. The residue was purified by flash column chromatography (petroleum ether–EtOAc, 40:1) to afford the desired compound **4cg″**.

Yield: 66 mg (90%); white solid; mp 101–103 °C.

IR (neat): 3451, 2971, 1731, 1668, 1589, 1306, 1056, 997, 685 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 8.03 (d, *J* = 7.2 Hz, 2 H), 7.64 (t, *J* = 7.2 Hz, 1 H), 7.51 (t, *J* = 7.2 Hz, 2 H), 6.19 (s, 1 H), 1.22 (s, 9 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 203.2, 189.5, 134.2, 133.7, 129.2, 128.9, 49.1, 44.7, 26.9.

HRMS (ESI): *m*/*z* calcd for $C_{13}H_{19}BrNO_2$ $[M + NH_4]^+$: 300.0594; found: 300.0591.

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Supporting Information

Supporting information for this article is available online at http://dx.doi.org/10.1055/s-0035-1561572.

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