Quinoline synthesis: scope and regiochemistry of photocyclisation of substituted benzylidencyclopentanone O-alkyl and O-acetyloximes.

Mark Austin, Oliver J. Egan, Raymond Tully and Albert C. Pratt*

Introduction

The quinoline nucleus is widely distributed in nature and is important in the fields of medicinal chemistry and agrochemicals. Consequently, though there are numerous syntheses available for quinoline derivatives, versatile routes to new quinoline intermediates from readily accessible precursors are of interest. Among these have been a limited number of reports of quinoline formation from photocyclisation of β-phenyl-α,β-unsaturated oximino systems (Scheme 1). The open-chain oxime 1a, O-benzoyloximes 1b–e and O-acetyloximes 1f–i underwent 6π-electron cyclisation, involving both the carbon-nitrogen double bond and the β-aryl group, followed by elimination of water or benzoic acid, to yield the corresponding quinolines 2a–g, respectively. In contrast, O-methyloximes 1j and 1k underwent only competing geometrical isomerisation at the carbon-carbon and carbon-nitrogen double bonds on direct and triplet sensitised excitation resulting, in both cases, in a photostationary state comprising the four possible geometrical isomers, but without accompanying cyclisation.

Prerequisites for photocyclisation are (a) a Z-configuration at the α,β-double bond, achieved by initial geometrical photoisomerisation, and (b) significant contribution from conformers with an s-cis orientation at the R1-CR2 single bond. Systems with this bond within a ring are forced to adopt an s-cis conformation. Quinoline formation has been reported where the bond is incorporated within a dihydrophenanthrene oracenaphthene ring, involving formation of 2l and 2m from

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† Electronic Supplementary Information (ESI) available: Experimental details and spectral data for the precursors; additional quinoline data. See http://dx.doi.org/10.1039/b000000x/

Scheme 1 Quinolines from photocyclisation of oximino systems.

Irradiation of substituted 2-benzylidencyclopentanone O-alkyl and O-acetyloximes in methanol provides a convenient synthesis of alkyl, alkoxy, hydroxy, acetoxy, amino, dimethylamino and benzo substituted annulated quinolines. para-Substituents yield 6-substituted-2,3-dihydro-1H-cyclopenta[b]quinolines with 8-substituted products being obtained from ortho-substituted starting materials.

Reactions of meta-substituted precursors are highly regioselective, with alkyl substituents leading to 5-substituted 2,3-dihydro-1H-cyclopenta[b]quinolines and more strongly electron-donating substituents generally resulting in 7-substituted products. 2-Furylmethylene and 2-thienylmethylene analogues yield annulated furo- and thieno-[2,3-e]pyridines respectively. Sequential E- to Z- benzylidene group isomerisation and six π-electron cyclisation steps result in formation of a short-lived dihydroquinoline intermediate which spontaneously aromatises by elimination of an alcohol or acetic acid. For 2-benzylidencyclopentanone O-allyloxime, singlet excited states are involved in both steps.

Experimental

Received/Acceptance Data

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Scheme 1


11 and 1m respectively, or within a cycloalkane, involving formation of 4a-f from 3a-f.  

A broad range of potential quinoline precursors is accessible by oximation of readily available \( \alpha \)-benzylidene ketones. Aryl ring ortho- or para-substitution should lead to quinolines substituted at the 5- or 7-ring carbons respectively whereas meta-substitution provides the possibility for formation of either 6- or 8-substituted quinolines. 

We have used a range of ortho- and para-substituted benzylidencyclopentanone O-alkyloximes and O-acetyloximes (Scheme 3) to examine the scope of the photocyclisation/elimination reaction as a route to annulated benzylidenecyclopentanones accompanied by the slower formation of quinoline 2,3-dihydro-1H-cyclopenta[b]quinolines.

Results

Unsubstituted benzylidencyclopentanone O-alkyloximes

Irradiation of \( E,E-O \)-alkyloxime 5\(^2\) in methanol resulted in initial \( E,Z \)-isomerisation at the carbon-nitrogen and carbon-carbon double bonds (Scheme 2). However isomerisation was accompanied by the slower formation of quinoline 7 as final product, involving photocyclisation of the \( E,Z \)-isomer (and/or the ZZ-isomer) to dihydroquinoline 6, followed by rapid elimination of allyl alcohol. Quinoline 7 was also obtained from the corresponding \( O \)-methyloxime 8.

![Scheme 2](image)

Scheme 2 Cyclisations without aryl substituents.

Unlike 5 and 8, \( E,2 \)-diphenylmethylenecyclopentanone \( O \)-methylxime 9 has an appropriately \( Z \)-oriented phenyl group and does not require an additional \( E/Z \)-photoisomerisation step prior to photocyclisation. On irradiation 9 rapidly formed a mixture of two products, one of which (Z-9) on further irradiation transformed to the other, final product 9-phenyl-2,3-dihydro-1H-cyclopenta[b]quinoline 10. Taking advantage of the suitably oriented phenyl group in 9, thermal cyclisation was attempted. However no reaction occurred on prolonged heating of 9 in methanol or in ethylene glycol (bp 198 °C) under reflux.

\( \text{ortho- and para-Substituted benzylidene systems} \)

The ortho- and para-methyl-, and ortho- and para-methoxybenzylidene \( O \)-methylxoximes 11a-d cyclised to the corresponding 6- and 8-substituted\(^3\) 2,3-dihydro-1H-cyclopenta[b]quinolines 12a-d on irradiation in methanol (Scheme 3). Similarly the \( para \)-hydroxy-, \( para \)-acetoxy-, and \( para \)-N,N-dimethylamino-benzylidene \( O \)-acetyloximes 11e-g and the \( para \)-amino-benzylidene oxime 11h cyclised to the quinolines 12e-h respectively. In each case, TLC analysis showed the initial formation of a number of products, presumed to be the various geometrical isomers and, on further irradiation, these underwent conversion to the corresponding 2,3-dihydro-1H-cyclopenta[b]quinoline.

2-Benzylidencyclohexanone \( O \)-methyloxime similarly yielded tetrahydroacridine 4e.

In marked contrast ortho- and para-nitro-, ortho- and para-chloro- and para-cyano-benzylidencyclopentanone \( O \)-methyloximes 11i-m, and 2,4-difluorobenzylidene \( O \)-acetyloxime 11n were converted to complex mixtures whose separation was not pursued further.

![Scheme 3](image)

Scheme 3 Cyclisations involving ortho- and para-substituents.

<table>
<thead>
<tr>
<th>R(^1)</th>
<th>R(^2)</th>
<th>X</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11a</td>
<td>Me</td>
<td>H</td>
<td>OMe</td>
</tr>
<tr>
<td>11b</td>
<td>H</td>
<td>Me</td>
<td>OMe</td>
</tr>
<tr>
<td>11c</td>
<td>OMe</td>
<td>H</td>
<td>OMe</td>
</tr>
<tr>
<td>11d</td>
<td>H</td>
<td>OMe</td>
<td>OMe</td>
</tr>
<tr>
<td>11e</td>
<td>H</td>
<td>OH</td>
<td>OAc</td>
</tr>
<tr>
<td>11f</td>
<td>H</td>
<td>OAc</td>
<td>OAc</td>
</tr>
<tr>
<td>11g</td>
<td>H</td>
<td>NMe(_2)</td>
<td>OAc</td>
</tr>
<tr>
<td>11h</td>
<td>H</td>
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<td>OH</td>
</tr>
<tr>
<td>11i</td>
<td>NO(_2)</td>
<td>H</td>
<td>OMe</td>
</tr>
<tr>
<td>11j</td>
<td>H</td>
<td>NO(_2)</td>
<td>OMe</td>
</tr>
<tr>
<td>11k</td>
<td>Cl</td>
<td>H</td>
<td>OMe</td>
</tr>
<tr>
<td>11l</td>
<td>H</td>
<td>Cl</td>
<td>OMe</td>
</tr>
<tr>
<td>11m</td>
<td>H</td>
<td>CN</td>
<td>OMe</td>
</tr>
<tr>
<td>11n</td>
<td>F</td>
<td>F</td>
<td>OAc</td>
</tr>
</tbody>
</table>

*Yields are reported for recrystallised products.*
Other \( \pi \)-systems

Other \( \pi \)-systems may replace the 2\( \pi \)-electron contribution of the \( \beta \)-phenyl group in these systems (Scheme 4). Thus 2-(1-naphthylmethylene)cyclopentanone O-methyloxime yielded fused benzol[\( f \)]quinoline 13 and 2-(1-phenothiazinylmethylene)cyclopentanone O-acetyloxime was converted to the novel pyrido[3,2-\( a \)]cinnamylidenecyclopentanone \( \text{O}-\text{acetyloxime} \). Compound 17, a photoisomer of 2-cinnamylidencyclopentanone \( \text{O}-\text{acetyloxime} \), also cyclised, yielding pyridine 18 and requiring the adoption of an \( s \)-cis arrangement for the open-chain dienyl unit in addition to prior \( E,Z \)-isomerisation at the 2-\( \text{exo} \) methylene unit to achieve a viable cyclic transition state for carbon-nitrogen bond formation.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Scheme_4}
\caption{Scheme 4 Other cyclisations.}
\end{figure}

\subsection*{meta-Substituted benzylidene systems}

Cyclisation is possible for \( \text{meta-} \)-substituted benzylidene derivatives either from rotamer 19, giving 5-substituted-2,3-dihydro-1\( H \)-cyclopenta[\( b \)]quinoline 21, or from rotamer 22, giving the 7-substituted isomer 24 (Scheme 5).

A \( \text{meta-} \)-methyl substituent results in closure at the aryl 2-position, ortho to the methyl group (Scheme 6). 2-(3-

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Scheme_5}
\caption{Scheme 5 Alternatives with \( \text{meta-} \)-substituents.}
\end{figure}

\begin{table}
\centering
\begin{tabular}{cccc}
\hline
\( R^1 \) & \( R^2 \) & \( X \) & Yield \( (\% \)\) & Yield \( (\% \)\) \\
\hline
25a & Me & H & OAc & 26a & 32 \\
25b & Me & Me & OAc & 26b & 17 \\
25c & Me & OMe & OAc & 26c & 15 \\
25d & Bu' & H & OAc & 26d & 13 \\
25e & OMe & H & OMe & 27e & 63 \\
25f & OMe & H & OAc & 27f & 63 \\
25g & OMe & OMe & OAc & 27g & 21 \\
25h & OMe & Me & OAc & 27h & 57 \\
25i & OH & H & OAc & 27i & 30 \\
25j & NMe2 & H & OAc & 27j & 6 \\
25k & NH2 & H & OH & 27k & 26 \\
25l & OAc & H & OAc & 26l' \( (R' = \text{OH}) \) & 17 & 20 \\
25m & NO2 & H & OAc & - & - \\
25n & Cl & H & OAc & - & - \\
25o & CN & H & OAc & - & - \\
25p & F & H & OAc & - & - \\
\hline
\end{tabular}
\caption{Yields are reported for recrystallised products.}
\end{table}

\subsection*{Scheme 6 Cyclisations with \( \text{meta-} \)-substituents.}

Other electron-donating substituents having a nitrogen or oxygen in the \( \text{meta-} \)-position of the benzylidene group similarly resulted in closure at the aryl-6 position (Scheme 6).

Thus 3-hydroxy- and 3,\( N,N \)-dimethylaminobenzylidene \( O- \)\( \text{methylo}xime \) yielded a single photoproduct, 5-methyl compound 26a. Inclusion of an additional ring substituent, a \( \text{para-} \)-methyl or \( \text{para-} \)-methoxy group, similarly resulted in closure at the 2-position, with 3,4-dimethyl- and 3-methyl-4-methoxy substrates 25b and 25c giving 5,6-dimethyl- and 5-methyl-6-methoxy-2,3-dihydro-\( 1H \)-cyclopenta[\( b \)]quinolines 26b and 26c respectively. Increasing the steric demand of the \( \text{meta-} \)alkyl substituent again resulted in strong preference for cyclisation/elimination involving the crowded aryl 2-position, with \( \text{meta-} \)-t-butyl compound 25d giving 5-t-butyl-2,3-dihydro-1\( H \)-cyclopenta[\( b \)]quinoline 26d.\( 9 \)

In contrast, a \( \text{meta-} \)-methoxy group results in closure at the aryl 6-position, \( \text{para-} \)to the methoxy substituent. Both 3-methoxybenzylidene \( O-\text{methylo}xime \) 25e and \( O-\text{acetylo}xime \) 25f yielded a single photoproduct, 7-methoxy compound 27e. Incorporation of an additional substituent, methyl or methoxy, in the \( \text{para-} \)-position again resulted in closure at the aryl 6-position, with 3,4-dimethoxy and 3-methoxy-4-methoxy compounds 25g and 25h giving 6,7-dimethoxy- and 6-methyl-7-methoxy-2,3-dihydro-1\( H \)-cyclopenta[\( b \)]quinolines 27g and 27h respectively. 2,5-Dimethoxybenzylidene O-acetyloxime 28 (Scheme 7), with the position \( \text{para-} \)to the \( \text{meta-} \)-methoxy group blocked by the 2-methoxy substituent, cyclised at the vacant \( \text{ortho} \) site to give 5,8-dimethoxy-2,3-dihydro-1\( H \)-cyclopenta[\( b \)]quinoline 29.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Scheme_6}
\caption{Scheme 6 Cyclisations with \( \text{meta-} \)-substituents.}
\end{figure}
acetyloximes 25i and 25j, also the 3-aminobenzylidene oxime 25k, photocyclised to the corresponding 7-substituted products 27i-k, respectively.

In contrast to these cyclisations from which a single product was isolated, irradiation of 3-acetoxybenzylidene O-acetyloxime 25i resulted in competitive closure, involving both the aryl-6 and aryl-2 positions, and giving both 7-acetoxy and 5-hydroxy products 27i and 26i'. The deacetylation step leading to 26i' must have occurred subsequent to cyclisation since, if loss of acetyl from 25i had preceded cyclisation, the resulting initially-formed 3-hydroxybenzylidene O-acetyloxime 25i would have cyclised to 7-hydroxy compound 27i rather than to 5-hydroxy compound 26i'. No accompanying photo-Fries rearrangement products were isolated from this reaction.

As observed for the analogous ortho- and para-substituted benzylidenecyclopentanone derivatives 11j-n, irradiation of 3-nitro-, 3-chloro-, 3-cyano- and 3-fluoro-benzylidene O-acetyloximes 25m-p proved not to be synthetically useful.

Only complex product mixtures were obtained and these were not investigated further.

2-(2-Naphthylmethylene)cyclopentanone O-acetyloxime 30a and O-methyloxime 30b (Scheme 7) cyclised at the naphthyl 1-position to give 9,10-dihydro-Stilbene-β-aroylbenzol[b]cyclopental[b]quinoline 31, rather than at the naphthyl 3-position.13

Discussion

Excited state considerations

The inclusion of various concentrations (up to 1.0 M) of the triplet quencher isoprene in methanol solutions of E.E-5 did not affect the course of product evolution, consistent with both the isomerisation and cyclisation processes arising from singlet excited states on direct irradiation. The four geometrical isomers of O-allyloxime 5 exhibit strong UV absorption in the 300nm region, probably due to the π,π* band of the conjugated α,β-unsaturated system submerging the much weaker n,π* band. With π,π* transitions in such systems being generally localised at the carbon-nitrogen double bond it is likely that cyclisation of 5 requires a lowest energy π,π* excited state. In ethyl acetate cyclisation of 5 does not occur,1 suggesting a lowest energy n,π* transition in this solvent. Methanol may assist the formation of quinoline 7 from 5 by hydrogen bonding to the nitrogen lone pair of the O-allyloxime thereby ensuring a lowest energy π,π* excited state and methanol may also facilitate elimination of allyl alcohol from dihydroaromatic intermediate 6. In acetonitrile formation of 7 from 5 is approximately 25 times less rapid, consistent with hydrogen-bonding playing a role in facilitating the photocyclisation/elimination process. The rate of quinoline formation was approximately doubled for both meta- and para-N,N-dimethylaminobenzylidene O-acetyloximes, 25j and 11g respectively, by inclusion of a small amount of trifluoroacetic acid but, whereas the yield of quinoline 27j from meta-dimethylaminobenzylidene oxime acetate 25j improved (from 6% to 35%) in the presence of the acid, no improvement in cyclisation yield (26%) was observed for para-dimethylaminobenzylidene oxime acetate 11g. Methanol with added mineral acid has been used as the medium for quinoline formation from oximes 3a-d,e.10

Analogy with stilbene cyclisation

The photocyclisation/elimination process for quinoline synthesis is analogous to the well-established conrotatory photocyclisation process for 1,3,5-hexatrienes, the most studied being the oxidative photoconversion of stilbenes to phenanthrenes14,15,16 via dihydrophenanthrene intermediates which aromatise either in the presence of oxygen or, more commonly, in the presence of an added oxidant such as iodicene. Though chloro, fluoro and cyano substituents are compatible with stilbene photoconversion to phenanthrenes,14c,15,17 also with quinoline formation from p-chlorophenyl O-benzoyloxime 1e,7 this is not the case for quinoline formation from benzylidenecyclopentanone oxime ethers or acetates 11k-n and 25n-p. Possibilities for this difference in behaviour include (a) enhanced intersystem crossing for these particular β-aryl-α,β-unsaturated oxide derivatives, with alternative reaction pathways being available to the triplet excited state,17 (b) the nature of their lowest excited singlet states, with n,π* states being generally less amenable to 6π-electron cyclisation and (c) the intervention of other reaction pathways, possibly involving radicals and leading to alternative reaction outcomes. The lack of photocyclisation when electron-withdrawing groups are present on the β-aryl ring may imply the necessity for a polarised transition state in which electron density is transferred through the π-system from the aryl ring to the oximino nitrogen, facilitating aryl-nitrogen bond formation and detachment of the leaving group.

Regioselectivity

In general 2-naphthyl homologues of stilbene (Scheme 8) have been found15 to undergo oxidative photocyclisation at the 1-naphthyl position, though more recent studies have shown that reaction may also occur at the naphthyl 3-position.

Scheme 8 Alternative cyclisation options from ground state rotamers.
Thus the ground state rotamers 32 and 33 of Z-di(2-naphthyl)ethene undergo competitive 1,1′- and 1,3′-cyclisation respectively to give the corresponding dihydrophenanthrenes on excitation\(^\text{19,20,21}\) and oxidative conditions can be adjusted to yield predominantly dibenzo[c,g]phenanthrene or dibenzo[b,g]phenanthrene respectively.\(^\text{19,21}\) Prediction of the preferred cyclisation route for diarylethenes has been assisted by the use of calculated free valence numbers or electronic overlap populations\(^\text{22}\) as measures of reactivity for electrocyclic processes, with most success being for polycyclic aromatic substituents.

Though more favourable substituent-dependent frontier orbital overlap in the transition state for cyclisation of one of the rotamers of a meta-substituted stilbene may play a contributing part in determining regioselectivity, it would not seem to be a determining one since, for many meta-substituted stilbenes, approximately equal amounts of the corresponding 2- and 4-substituted phenanthenes are found.\(^\text{14c,23}\) Recent consideration of the photocyclisations of styrylpyridines and 2-aminostyrylpyridines\(^\text{24}\) has pointed to the role of rotamers and led to the suggestion that the regiochemical outcome for a meta-substituted stilbene analogue is determined by the relative rates of oxidation and ring-opening of the intermediate dihydrophenanthrenes. Similar substituent-related competition between ring-opening and elimination steps for the non-aromatic intermediates from meta-substituted benzylidencyclopentanone oxime derivatives, 20 and 23 from rotamers 19 and 22 respectively (Scheme 5), probably also determines whether 5-substituted or 7-substituted products, 21 or 24 respectively, are obtained. The nature and interactions of these substituent effects has yet to be determined.

Other observations

The nature of the group eliminated does not affect the cyclisation outcome. Both O-allyloxime 5 and O-acetyloxime 8 yielded 2,3-dihydro-1H-cyclopenta[b]quinoline 7 (24% and 29%, respectively). Similarly O-acetyloxime 30a and O-methyloxime 30b yielded 9,10-dihydro-8H-benzol[\(\text{f}\)]cyclopenta[b]quinoline 31 and 7-methoxy-2,3-dihydro-1H-cyclopenta[b]quinoline 27e was obtained from both O-methyloxime 25e and O-acetyloxime 25f. Initial studies were undertaken with O-methyloximes but, when it became apparent that the cyclisation outcome was independent of the nature of the leaving group, the more readily prepared O-acetyloximes were subsequently used.

Photocyclisation of the O-acetyloximes 34 of 2-phenylbenzaldehyde, 2-phenylacetophenone and 2-phenylbenzophenone to the corresponding phenanthenes 35 (Scheme 9) has recently been reported.\(^\text{25}\) The 2-vinyl analogues are similarly converted to the corresponding isoquinolines. These outcomes may also be rationalised by a six \(\pi\)-electron cyclisation process. However iminyl radicals 36 have been proposed as intermediates in the formation of 35, generated by nitrogen-oxygen bond photocleavage. Such homolysis, yielding acyloxy and aryliminyl radicals, occurs in the photochemistry of O-acyloxime derivatives of simple aromatic carbonyl compounds such as benzaldehyde, acetophenone, benzophenone and 9-fluorenone and has been used as a convenient source of carbon-centred radicals for synthetic investigations\(^\text{26,27}\) and as a photochemical source of amines for polymer cross-linking, the amines resulting from hydrolysis of the imines formed following nitrogen-oxygen bond cleavage.\(^\text{28}\)

Whether the phenanthenes 35 are formed by a six \(\pi\)-electron photocyclisation process in competition with radical formation, or are formed through the intermediacy of photogenerated iminyl radicals 36, is unclear. Iminyl radicals may be readily generated by a variety of non-photochemical routes,\(^\text{29}\) and there is precedence for radicals analogous to 36 undergoing closure to phenanthenes and quinolines\(^\text{30}\) though five-membered ring formation has been reported to accompany quinoline formation in favourable cases.\(^\text{31}\)

\[
\text{\[\text{Scheme 9.}\]}
\]

Benzaldehyde O-alkyloximes undergo very inefficient carbon-nitrogen bond photocleavage on direct or triplet sensitised excitation,\(^\text{32}\) though the efficiency of radical formation from benzaldehyde O-acyloximes can be increased by the use of triplet photosensitisers.\(^\text{33}\) However, given that the compounds which comprise the present study lack the phenone O-acyl or O-alkyloxime functionality which seems to be essential for such cleavage on direct excitation, it can be concluded that these cyclisations proceed by the proposed six \(\pi\)-electron photocyclisation.\(^\text{34}\) This conclusion is supported by the absence of reports of nitrogen-oxygen bond homolysis on direct or triplet sensitised excitation of a wide range of other O-alkyl and O-acyloximes such as acetophenone O-methyloxime,\(^\text{35}\) acetonaphthone O-methyloxime,\(^\text{36}\) \(\beta\)-phenyl-\(\alpha,\beta\)-unsaturated oximino systems 1a-m,\(^\text{4,10}\) \(\beta\)-ionone O-ethyloxime,\(^\text{37}\) \(\beta,\gamma\)-unsaturated oxime acetates\(^\text{38}\) and cholesterol O-acetyloximes.\(^\text{39}\)

Conclusions

This photocyclisation/elimination process provides a convenient route to a wide variety of substituted 2,3-dihydro-1H-cyclopenta[b]quinolines from readily accessible precursors and has the potential for extension to the synthesis of numerous novel fused pyridines/quinolines of biomolecular interest derived, for example, from terpenoid or steroidal ketones.

Acknowledgements

Enterprise Ireland, Forbairt, the Irish American Partnership and Dublin City University are gratefully acknowledged for supporting this work.

Experimental Section
Preparations involved reaction of the required oxime with cyclopentanone with the appropriate aromatic aldehyde.

Preparations involved reaction of the ketones with hydroxylamine hydrochloride in pyridine.

Preparations involved reaction of the required oxime with excess dimethyl sulphate in the presence of sodium hydride.

Preparations involved reaction of the required oxime with acetyl chloride in pyridine.

A methanol solution (250-350 cm$^3$) of the appropriate O-methylxime. O-acetyl oxime or oxime (2.5-10.0x10$^{-2}$ M) was irradiated under the standard conditions. Reaction progress was monitored by TLC using light petroleum/ethyl acetate [ethanol in the cases of 12g, 14 and 27j]. In general a number of products appeared soon after irradiation began and on continued irradiation one of these became the sole/predominant product, at which time irradiation was discontinued. Removal of the methanol yielded the crude 2,3-dihydro-1H-cyclo pentanone[b]quinoline. Purification was by recrystallisation or by chromatography on silica, with light petroleum/ethyl acetate as eluent, prior to recrystallisation. Unless otherwise stated, recrystallisation was from light petroleum/ethyl acetate.

2,3-Dihydro-1H-cyclo pentanone[b]quinoline 7 (24% from 5; 29% from 8), mp 60-61 °C (lit., 41 60-61 °C); δ$_H$ 2.18 (2H, qn, J 7.4, CH$_2$CH$_2$CH$_2$), 3.06 (2H, t, J 7.4, CH$_2$Ar), 3.14 (2H, t, J 7.4, CH$_2$Ar), 7.43 (1H, t, J 7.7) and 7.59 (1H, t, J 7.9) (ar-H-7 and ar-H-6), 7.70 (1H, d, J 7.7, ar-H-8), 7.85 (1H, br s, ar-H-9) and 8.00 (1H, d, J 7.9, ar-H-5); δ$_C$ 23.62, 30.50, 34.60 (3 x CH$_2$), 125.49, 124.73, 123.80 and 128.51 (benzenoid-CH), 130.29 (pyridyl-CH), 127.37, 135.77, 147.48 and 167.91 (quaternary Cs).

9-Phenyl-2,3-dihydro-1H-cyclo pentanone[b]quinoline 10 (72%), mp 132-134 °C (methanol) (lit., 32 134-135 °C); δ$_H$ 2.16 (2H, qn, J 7.5, CH$_2$CH$_2$CH$_2$), 2.90 (2H, t, J 7.5, CH$_2$Ar), 3.24 (2H, t, J 7.5, CH$_2$Ar), 7.36 (3H, m), 7.49 (3H, m) and 7.62 (2H, m) (8 x ar-H), 8.08 (1H, d, J 8.4, ar-H-5; δ$_C$ 23.42, 30.22, 35.08 (3 x CH$_3$), 125.39, 125.54, 126.09, 127.88, 128.13, 128.39, 126.68, 129.18, 133.55, 136.62, 142.59, 147.81 and 167.31 (13 x ar-C).

8-Methyl-2,3-dihydro-1H-cyclo pentanone[b]quinoline 12a (35%), mp 64-65 °C (light petroleum); δ$_H$ 2.21 (2H, qn, J 7.4, CH$_2$CH$_2$CH$_2$), 2.65 (3H, s, Me), 3.11 (2H, t, J 7.5, CH$_2$Ar), 3.16 (2H, t, J 7.5, CH$_2$Ar), 7.28 (1H, d, J 8.4, ar-H-7), 7.50 (1H, t, J 8.4, ar-H-6), 7.87 (1H, d, J 8.4, ar-H-5) and 8.07 (1H, s, ar-H-9); δ$_C$ 18.83 (Me), 23.65, 30.72 and 34.50 (3 x CH$_3$), 126.12, 126.53, 127.45, 126.89, 127.94, 133.98, 135.22, 147.68 and 167.23 (9 x ar-C).

8-Methyl-2,3-dihydro-1H-cyclo pentanone[b]quinoline 12b (37%), mp 86-88 °C (light petroleum); δ$_H$ 2.20 (2H, qn, J 7.5, CH$_2$CH$_2$CH$_2$), 2.54 (3H, s, Me), 3.07 (2H, t, J 7.5, CH$_2$Ar), 3.15 (2H, t, J 7.5, CH$_2$Ar), 7.30 (1H, d, J 8.2, ar-H-7), 7.63 (1H, d, J 8.2, ar-H-8), 7.79 (1H, s, ar-H-5) and 7.85 (1H, s, ar-H-9); δ$_C$ 21.82 (Me), 23.66, 30.48 and 34.63 (3 x CH$_3$), 125.37, 127.07, 127.70, 128.98, 130.15, 131.93, 134.73, 138.49 and 167.80 (9 x ar-C).

8-Methoxy-2,3-dihydro-1H-cyclo pentanone[b]quinoline 12c (48%), mp 76-77 °C (light petroleum); δ$_H$ 2.21 (2H, qn, J 7.6, CH$_2$CH$_2$CH$_2$), 3.09 (2H, t, J 7.6, CH$_2$Ar), 3.15 (2H, t, J 7.6, CH$_2$Ar), 3.99 (3H, s, MeO), 6.81 (1H, d, J 8.1, ar-H-7), 7.51 (1H, t, J 8.1, ar-H-6), 7.61 (1H, d, J 8.1, ar-H-5) and 8.35 (1H, s, ar-H-9); δ$_C$ 23.61, 30.64, 34.59 (3 x CH$_3$), 55.68 (Ome), 103.62, 119.56, 120.89, 125.06, 128.17, 134.76, 148.34, 155.07 and 168.05 (9 x ar-C).

6-Methoxy-2,3-dihydro-1H-cyclo pentanone[b]quinoline 12d (53%), mp 58-60 °C (light petroleum); δ$_H$ 2.20 (2H, qn, J 7.5, CH$_2$CH$_2$CH$_2$), 3.06 (2H, t, J 7.5, CH$_2$Ar), 3.15 (2H, t, J 7.5, CH$_2$Ar), 3.93 (3H, s, OMe), 7.12 (1H, dd, J 8.8, 2.2, ar-H-7), 7.37 (1H, d, J 2.2, ar-H-5), 7.62 (1H, d, J 8.8, ar-H-8) and 7.82 (1H, s, ar-H-9); δ$_C$ 23.58, 30.32, 34.59 (3 x CH$_3$), 55.35 (Ome), 106.95, 118.20, 122.34, 128.30, 130.23, 133.31, 148.98, 159.86 and 167.98 (9 x ar-C).

Hydroxy-2,3-dihydro-1H-cyclo pentanone[b]quinoline 12e (36%), mp 168-169 °C; δ$_H$ (CD$_3$)$_2$SO 2.09 (2H, qn, J 7.5, CH$_2$CH$_2$CH$_2$), 2.93-3.01 (4H, m, 2 x CH$_2$Ar), 7.00 (1H, dd, J 8.8, 2.2, ar-H-7), 7.24 (1H, d, J 2.2, ar-H-5), 7.50 (1H, d, J 8.8, ar-H-8), 7.73 (1H, s, ar-H-9) and 9.65 (1H, br s, OH); δ$_C$ (CD$_3$)$_2$SO 22.64, 29.27, 33.59 (3 x CH$_3$), 109.30, 117.16, 120.73, 127.36, 129.43, 131.50, 148.06, 157.06 and 166.67 (9 x ar-C).

Acetoxy-2,3-dihydro-1H-cyclo pentanone[b]quinoline 12f (36%), mp 96-97 °C; δ$_H$ 2.21 (2H, qn, J 7.6, CH$_2$CH$_2$CH$_2$), 2.36 (3H, s, MeO), 3.08 (2H, td, J 7.6, J$_d$ 1.0, CH$_2$Ar), 3.08 (2H, t, J 7.6, CH$_2$Ar), 7.24 (1H, dd, J 8.8, 2.4, ar-H-7), 7.71-7.74 (2H, m, ar-H-5/8) and 7.88 (1H, br s, ar-H-9); δ$_C$ 21.19
6-N,N-Dimethylamino-2,3-dihydropyridine

6-Methylpyridine-2,3-dihydropyridine (15%), mp 62-64°C (light petroleum); δ 1.70 (9H, s, CMe2); 2.20 (2H, q, J 7.6, CH2CH2CH3), 3.07 (2H, t, J 7.6, CH2Ar), 3.14 (2H, q, J 7.6, ArCH2), 3.76 (1H, d, J 7.6, arH-7), 7.58 (2H, coincident doublets, J 7.6, arH-6 and arH-8) and 7.83 (1H, s, arH-9); δ 22.61, 26.88, 29.39, 30.03, 33.82 (3H, s, CMe3, CMe2C and CMe); 123.73, 123.78, 125.35, 127.04, 129.50, 132.94, 145.59, 146.31 and 163.70 (9 x arC).

7-Methyl-2,3-dihydro-1H-cyclopenta[j]quinolone (27e) (63% from both 25f and 25e), mp 96-97°C (light petroleum) (lit.49 99-100°C); δ 2.72 (2H, q, J 7.9, CH2CH2CH3), 3.58 (2H, q, J 7.9, ArCH2), 3.65 (2H, q, J 7.9, ArCH2), 4.42 (3H, s, OMe), 7.53 (1H, d, J 2.5, arH-8), 7.81 (1H, dd, J 8.9, 2.5, arH-6), 8.32 (1H, s, arH-9), and 8.45 (1H, d, J 8.9, arH-5); δ 23.28, 30.18, 33.93 (3 x CH3), 55.06 (OMe), 105.16, 120.07, 127.87, 128.93, 129.46, 135.52, 143.05, 156.70 and 164.98 (9 x arC).

6,7-Dihydro-2,3-dihydro-1H-cyclopenta[j]quinolone (27g) (21%), mp 99-100°C (lit.50 112-113°C; lit.51 120-121°C); δ 2.12 (2H, q, J 7.6, CH2CH2CH3), 2.98 (2H, t, J 7.6, CH2), 3.04 (2H, t, J 7.6, CH2), 3.92 (3H, s, OMe), 3.94 (3H, s, OMe), 6.92 (1H, s, arH-8), 7.31 (1H, s, arH-5) and 7.68 (1H, s, arH-9); δ 23.59, 30.46, 34.34 (3 x CH3), 55.90, 55.94 (both OMe), 105.21, 127.53, 129.10, 133.69, 143.99, 148.82, 151.34 and 165.24 (9 x arC).

6-Methyl-7-methoxy-2,3-dihydro-1H-cyclopenta[j]quinolone (27h) (57%), mp 129-130°C; δ 1.10

5-Methyl-2,3-dihydropyridine (18%); mp 129-130°C; δ 1.10
H \textit{5-hydroxy-2,3-dihydro-1}δ(26%), mp 121-122

H \textit{7-Acetoxy-2,3-dihydro-1}

\textit{Cyclopenta[b]quinoline} 27j

H \textit{5,8-Dimethoxy-2,3-dihydro-1}

\textit{Cyclopenta[b]quinoline} 31 (74% from 30a; 72% from 30b), mp 115-116°C; δH 2.23 (2H, q, J 7.9, CH\textsubscript{2}CH\textsubscript{2}CH\textsubscript{3}), 3.07 (2H, t, J 7.9, ArCH\textsubscript{2}), 3.26 (2H, t, J 7.9, ArCH\textsubscript{2}), 7.59 (1H, d, J 8.5), 7.70 (3H, m), 7.84 (1H, s, ArH-7), 7.89 (1H, dd, J 7.9, 0.9Hz) and 9.35 (1H, d, J 8.5); δC 23.57, 30.49, 34.70 (3 x CH\textsubscript{3}), 124.12, 124.90, 125.52, 126.30, 126.48, 127.34, 127.55, 130.60, 131.42, 133.20, 135.85, 145.32 and 166.14 (13 x arC).

\textbf{Notes and references}

§ Compound 5 was obtained as a single isomer on reaction of 2-benzylideneoctacone with O-allyldihydroxylamine. In ethyl acetate 5 underwent only \textit{E,Z}-photoreversion to a photostationary state comprising the \textit{E,E} (19%), \textit{Z,E} (48%), \textit{E,Z} (23%) and \textit{Z,Z} (10%) isomers. These were separated chromatographically and their stereochemistries assigned.

¶ The analogous open-chain O-acetyloxime of 4,4-diphenylbut-3-en-2-one (PhC=C=HMe=NOAc) undergoes conversion to 2-methyl-4-phenylquinoline at 187°C. Semi-empirical calculations have been used in support of a pericyclic mechanism involving disrotatory closure to an intermediate analogous to 6, followed by subsequent intramolecular elimination of acetic acid via a cyclic transition state. O-Methylxylene undergoes closure/elimination above 120°C to yield 24.2. The low activation barrier was ascribed to aromatic stabilisation of the cyclised intermediate due to generation of a phenanthrene unit prior to methanol elimination. In the case of 9 however no such stabilisation is possible.

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§§ Nomenclature convention results in different numbering of the aromatic ring positions for quinolines and 2,3-dihydro-1\textit{H}-cyclopenta(b)quinolines. 2-Benzopyrano[2,3-b]quinoline 31 was obtained following similar formation and cyclisation.

\# Prior to recrystallisation, the \textit{H}-NMR spectrum of the chromatographed product showed it to be 5-r-butyl-2,3-dihydro-1\textit{H}-cyclopenta(b)quinoline (92%) together with a small amount of another t-butyl-containing component (8%), possibly the other regioisomer.

†† For the currently included substituents this seems likely only for the nitro group. There do not appear to have been any reports of oxidative photocyclisations of nitrostilbenes.

‡‡ The principle of non-equilibration of excited rotomers (NEER) implies that the ground state populations of 32 and 33 determine the excited state populations. 18

§§ In the presence of excited 1,5-dimethoxynaphthalene (DMN) as a single electron transfer agent, \textit{t}=unsaturated ketone \textit{O}-acyl and \textit{O}-methylxoximes are converted to radical anions which cyclise by an iminyl radical mechanism to 3,4-dihydro-2-yrroles. Alternatively triplet energy transfer from excited DMN may result in the iminyl radical formation and cyclisation. 34 Such reaction conditions were absent from the present study.


