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ARTICLE *in* THE JOURNAL OF ORGANIC CHEMISTRY · OCTOBER 2015

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Batch and Flow Synthesis of Pyrrolo[1,2-*a*]-quinolines via an Allene-Based Reaction Cascade

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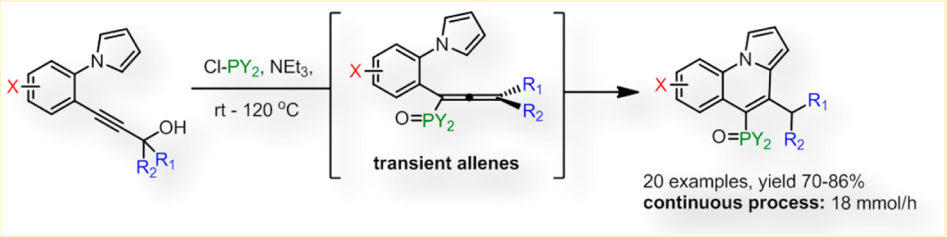
Supporting Information



ABSTRACT: An efficient reaction cascade delivering a series of pyrrolo[1,2-*a*]quinolines bearing phosphonate or phosphine oxide moieties is presented. This sequence exploits the *in situ* transformation of propargylic alcohols into transient allenes by means of a strategic [2,3]-sigmatropic rearrangement followed by trapping of the resulting allenes by an adjacent pyrrole ring. Furthermore, the initial small scale batch process was successfully translated into a continuous flow process allowing efficient preparation of selected pyrrolo[1,2-*a*]quinolines on multigram scale without any safety concerns due to the reaction's inherent exothermic profile.

INTRODUCTION

The efficient synthesis and functionalization of valuable heterocyclic architectures bearing different diversification sites constitutes one of the major challenges in modern medicinal chemistry in its aim to identify suitable scaffolds that can be used as potential lead structures toward new bioactive molecules.[1] While approaches in the past have primarily focused on elaborating classic heterocyclic systems (indoles, imidazoles, pyridines etc.) as core structures, the pressure imposed on modern medicinal chemists to discover new drug-like molecules means that new approaches are required in order to rapidly gain access to heterocyclic structures covering underrepresented chemical space. The tricyclic pyrrolo[1,2-*a*]quinoline system (Figure 1) represents such a scaffold that has not been studied widely, likely due to limited robust synthetic strategies for its modular assembly. In addition, most of the reported methods require transition metal catalysis or strong Lewis acids to affect the cyclization reaction,[2] rendering these options less amenable to simple and cheap scale up. Still, because of its embedded quinoline and indolizine substructures, which can be found in numerous natural products and active pharmaceutical ingredients,[3] structures based on the pyrrolo-[1,2-*a*]quinoline scaffold are predisposed with drug-like features.

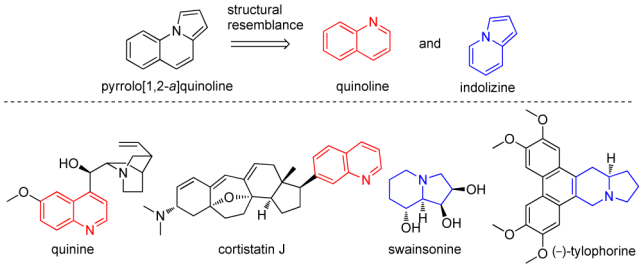


Figure 1. Structural motifs of pyrrolo[1,2-*a*]quinolines as common features of bioactive molecules.

We set out to design and develop a new synthetic strategy that would allow for the efficient preparation of a series of pyrrolo[1,2-*a*]quinolines bearing a variety of different functional patterns. In addition, we intended to introduce different phosphorus-based functionalities which would serve a dual purpose: (1) as a means toward the synthesis effort and (2) as an important motif often encountered in bioactive agents.[4] Our synthetic strategy outlined in Scheme 1 is based on a reaction cascade that converts propargylic alcohols via a [2,3]-sigmatropic rearrangement of the intermediate phosphites into transient allenes that are subsequently trapped by an adjacent pyrrole nucleophile.

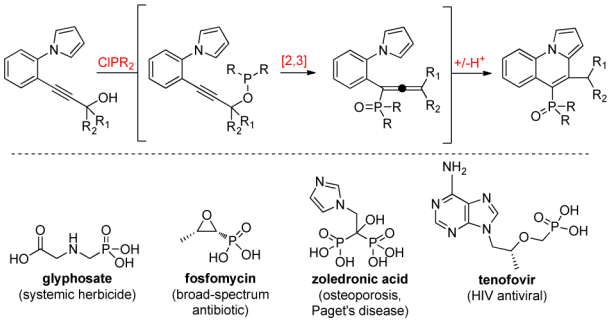
RESULTS AND DISCUSSION

The conversion of propargylic alcohols into allenes bearing phosphine oxides or phosphonates via a [2,3]-sigmatropic rearrangements is a well-established process[5] and has been used recently to yield various heterocycles including indoles,[6] benzofurans,[7] pyrroles,[8] triazoles[9] and chromene derivatives, here we report on the extension of this reaction into a new class of hererocyle.[10]

Received: August 26, 2015
Published: October 19, 2015

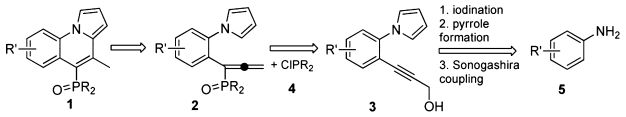
DOI: 10.1021/acs.joc.5b01982
J. Org. Chem. 2015, 80, 10806–10816

Scheme 1. Reaction Cascade toward Desired Products and Selected Phosphonate Containing Bioactive Compounds



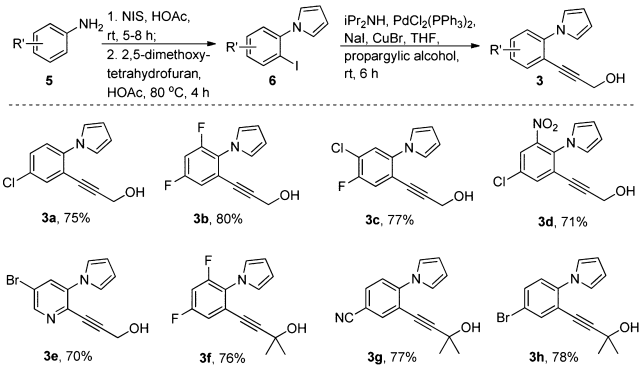
We initiated our study by devising the retrosynthetic strategy outlined in Scheme 2. As such the desired pyrrolo[1,2-*a*]quinoline products **1** were envisaged to arise from intermediate allenes **2** that in turn would be formed *in situ* from various propargylic alcohols **3** and chlorophosphine derivatives **4**. The propargylic alcohols **3** would be accessed from a selection of substituted anilines **5** via a three step sequence consisting of regioselective iodination, Paal–Knorr pyrrole formation and a subsequent Sonogashira cross coupling reaction. This synthetic approach allows maximization of the functional components which can be introduced to the main framework using robust and efficient chemical transformations.

Scheme 2. Retrosynthetic Strategy toward 1



Pleasingly it was found that a variety of anilines could be ortho-iodinated in high yield and regioselectivity when employing stoichiometric amounts of *N*-iodosuccinimide (NIS) in the presence of acetic acid as solvent (Scheme 3).

Scheme 3. Synthesis of Substrates[a]



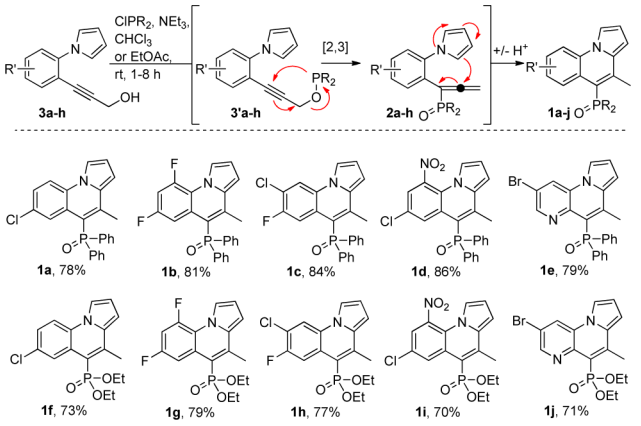
[a]20–50 mmol scale, aggregate yield over 3 steps.

In cases where either diiodinated byproducts or other regioisomers were formed, it was found that these were difficult to remove at this stage but that the resulting mixtures could be used in the subsequent transformations without issue.

Next, the conversion of the amino group of the iodoaniline intermediates into a pyrrole ring was carried out by treatment with 2,5-dimethoxytetrahydrofuran in acetic acid at elevated temperatures (80 °C). The desired pyrrole derivatives **6** were generated rapidly and reliably on synthetically useful scales (10–50 mmol) in a very efficient transformation. In order to furnish the corresponding propargylic alcohols **3a–h**, a standard protocol for Sonogashira cross coupling reactions using *N*,*N*-diisopropylamine as base and $PdCl_2(PPh_3)_2$ with CuBr/NaI as catalyst system was chosen and proved effective in delivering the key building blocks needed in this study (see SI for further information). Importantly, this protocol tolerated the presence of less reactive chloride and bromide substituents on the substrates thus enabling future derivatization efforts. At this stage chromatographic purification could if required be used in order to remove any minor impurities generated in the preceding sequence.

With a selection of different propargylic alcohols in hand we next turned our attention to studying their conversion to transient allene species mediated by a [2,3]-sigmatropic rearrangement. For this purpose we decided to treat our substrates with two different phosphine species, chlorodiphenylphosphine (**4a**) or diethyl chlorophosphite (**4b**), in the presence of triethylamine as base. At ambient temperature rapid consumption of the propargylic alcohol starting material was observed by tlc when using either chloroform or ethyl acetate as solvent, delivering the corresponding allene intermediates **2** that would subsequently be trapped by the adjacent pyrrole ring. Typically, the desired tricyclic pyrrolo[1,2-*a*]quinoline structure **1** would form within 2–8 h. It is interesting to note that the allenes derived from chlorodiphenylphosphine (**4a**) underwent cyclization considerably faster (2–3 h) than those derived from diethyl chlorophosphite (**4b**, > 4 h), whereas the nature of the substituent on the aromatic ring had little effect on the cyclization step. Overall, these results confirm the feasibility of using allenes as precursors toward more elaborate heterocyclic systems that can be isolated in high yield after aqueous workup and chromatographic purification (Scheme 4).

Scheme 4. Synthesis of Tricyclic Pyrrolo[1,2-*a*]quinolines



It was also shown that this rearrangement/cyclization cascade could be extended in order to furnish the intriguing pyrrolo[1,2-*a*][1,5]naphthyridine scaffold whose structure was confirmed by single crystal X-ray diffraction experiments (Figure 2).

We next evaluated the impact of introducing further substitution on the allene intermediate by utilizing propargylic alcohols **3f–h** as substrates in our cascade protocol. To this end, solutions of the alcohol substrates were treated again with either chlorodiphenylphosphine (**4a**) or diethyl chlorophos-

DOI: 10.1021/acs.joc.5b01982
J. Org. Chem. 2015, 80, 10806–10816

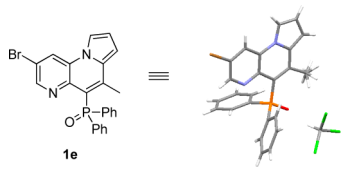


Figure 2. X-ray structure of **1e** ($CHCl_3$ solvate; methyl group distorted).

phite (**4b**) in the presence of stoichiometric amounts of triethylamine. The intermediate tetrasubstituted allene species formed as expected; however, its subsequent conversion into the desired pyrrolo[1,2-*a*]quinoline structure did not occur even after prolonged periods of time (48 h) or at slightly elevated temperature (55 °C). As these tetrasubstituted allenes were stable entities we decided to isolate and purify them in order to further study this unexpected outcome. As a consequence of their crystalline nature we were thus able to secure a single crystal X-ray structure of **2f** allowing us to postulate the reason behind their reluctance to cyclize (Figure 3).

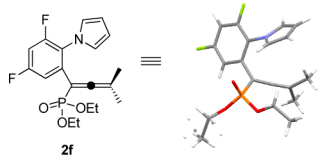


Figure 3. X-ray structure of **2f** (one ethyl group distorted).

As expected, the proximal gem-dimethyl group is oriented perpendicular to the aryl and phosphite substituents on the distal part of the allene. Consequently, this forces the pyrrole ring out of plane with respect to the aryl system in order to minimize steric hindrance, resulting in a larger distance between the pyrrole and the central allene carbon and thus preventing the cyclization reaction. We reasoned that it may still be possible to induce cyclization using higher temperatures which would overcome this barrier leading to the formation of the desired pyrrolo[1,2-*a*]quinolines bearing an isopropyl substituent.

Heating a selection of the crude allene species at 120 °C in a Biotage microwave reactor for a short period of time (1 h) quickly confirmed the viability of this approach by generating the desired products (Scheme 5). In the cases of phosphonates **1k**, **1m** and **1o** a single aromatic product was formed, whereas for systems bearing the phosphine oxide motif a ∼ 1:1 mixture of products **1l**/**1l′** (etc.) was obtained.[11] Furthermore, the triethylammonium hydrochloride formed in the initial phosphorylation step appears to act as a proton transfer catalyst as in its absence formation of the cyclized species was not observed.

In order to further investigate the intricate balance between the specific substitution pattern on the propargylic alcohol and the resulting allene reactivity and final product distribution we decided to evaluate a number of further cases. As such a selection of propargylic substrates based on the pyrrolo-2,4-difluorobenzene scaffold were prepared using the aforementioned Sonogashira approach. Besides having either two hydrogens (Table 1, entry 1) or two methyl groups (Table 1, entry 2) in the propargylic position we were thus able to study substrates possessing one methyl group and one hydrogen

Scheme 5. Synthesis of Pyrrolo[1,2-*a*]quinolines via Tetrasubstituted Allenes

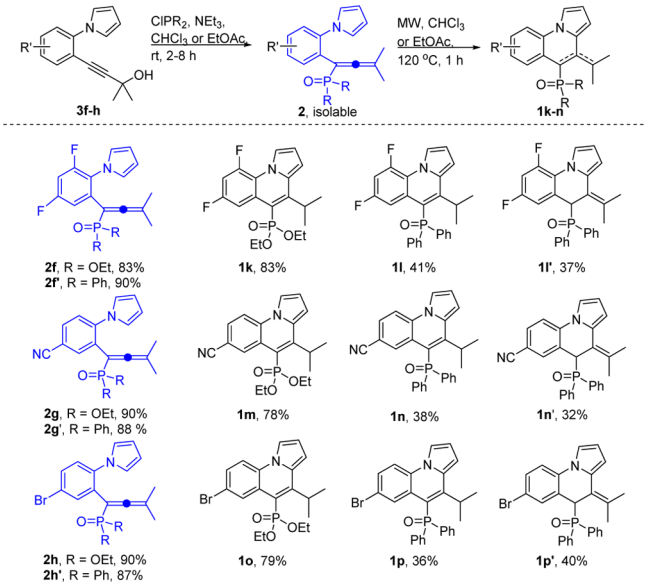
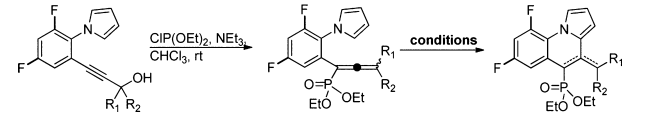


Table 1. Comparative Study on the Influence of Steric Bulk on the Cyclization Process



entry	substitution pattern	allene stability	cyclization conditions	yield (%)[a] and endo/exo ratio
1	$R_1 = R_2 = H$	transient	rt, 4 h	79, n.a.
2	$R_1 = R_2 = Me$	stable	MW, 120 °C, 1.5 h	83, 1:0
3	$R_1 = H$, $R_2 = Me$	unstable	rt, 12 h	85, 1:0.7[b]
4	$R_1 = Me$, $R_2 = Ph$	stable	MW, 120 °C, 2.5 h[c]	74, 0.15:1[d]

[a]Combined isolated yield. [b]Exocyclic alkene has *Z*-geometry. [c]In the presence of 1.0 equiv NEt_3·HCl. [d]Exocyclic alkene has *E*-geometry.

(Table 1, entry 3) as well as one methyl group and one phenyl ring (Table 1, entry 4) as bulky substituents (Table 1).

Consistent with our expectations we observed the clean rearrangement of the propargylic substrates into the corresponding allene structures upon treatment with diethyl chlorophosphite (**4b**) and triethylamine. While the allene intermediate bearing one hydrogen and one methyl group was shown to slowly undergo cyclization at room temperature (Table 1, entry 3), its derivative possessing a phenyl group instead of the hydrogen required much more forcing conditions (Table 1, entry 4). As such we further surmised that trisubstituted allenes (Table 1, entry 3) are capable of undergoing the cyclization reaction toward the desired tricyclic products at room temperature by minimizing steric interactions between the pendent group and the pyrrole ring. Finally, cyclization of the sterically most demanding tetrasubstituted allene (Table 1, entry 4) did not occur under the microwave conditions previously established (Table 1, entry 2); however, adding triethylammonium chloride as a proton transfer catalyst proved effective in forcing the cyclization to occur under prolonged microwave radiation. As expected, the ratio of exo-

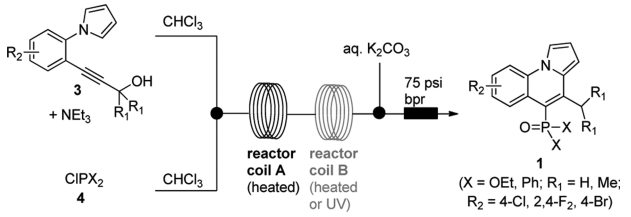
DOI: 10.1021/acs.joc.5b01982
J. Org. Chem. 2015, 80, 10806−10816

versus endocyclic alkene product would for this substrate strongly favor the exocyclic structure.

Having established that a variety of different pyrrolo[1,2-*a*]quinolines can be prepared effectively through the intermediacy of highly substituted allenes, we turned our attention toward translating this batch procedure into a continuous flow protocol. This decision was driven by the expectation that such a flow procedure would be valuable as it would deliver the desired heterocyclic products not only on gram scale, but also through a faster and cleaner process.[12] Additionally, as we had commonly noted a temperature increase to ∼40 °C when performing the above reaction cascade in batch on small scales (1 mmol), we anticipated this to become more problematic when scaling up. We therefore wished to harness the benefits of continuous processing which renders improvements through superior heat and mass transfer[13] as well as improved safety profiles[14] when compared to batch based scale up approaches.

We elected to use a Vaportec-E-series flow system which was configured as shown in Scheme 6 so that two streams

Scheme 6. Flow Reactor Configuration



containing mixtures of the starting materials would combine in a T-piece prior to entering into a heated flow coil in which the cascade reaction would take place. Upon exiting the heated reactor the crude product stream would rapidly cool before being mixed with a quenching stream (aqueous K_2CO_3) and the product being collected (Scheme 6).

Because of the long-term stability concerns regarding the chlorophosphine/phosphite (**4a**/**4b**) reagents in ethyl acetate, we opted to use chloroform as the reaction solvent. Consequently, stock solution A was prepared by combining the propargylic alcohol substrate (1.0 equiv, 1.0 M $CHCl_3$) with triethylamine (1.3 equiv, 1.3 M $CHCl_3$) and a second stock solution B was prepared from the chlorophosphine/phosphite reagent (1.3 equiv, 1.3 M $CHCl_3$).

Aiming to establish as to whether this flow approach would succeed in accelerating and improving the previous batch procedure, we decided to study the conversion of substrates **3a**, **3b** and **3h** into their corresponding pyrrolo[1,2-*a*]quinoline derivatives (**1f**, **1b** and **1o**). Starting with substrates **3a** and **3b** we were pleased to see their clean conversion into products **1f** and **1b** respectively, when using a single heated reactor coil (10 mL internal volume) at slightly elevated temperature (80 °C) within a short residence time of 1 h (Table 2, entries 1 and 2). Compared to the previous batch experiments we noted a slightly cleaner and consequently higher yielding reaction (see Scheme 4) which we ascribe to the better heat transfer in the T-mixer leading to minimal side reactions. Overall, this simple flow protocol enabled preparation of **1f** and **1b** continuously at a rate of 18 mmol/h allowing for the effective production of 8.3 g of **1f** and 3.5 g of **1b** as a proof of concept.

Having established a basic flow process we next turned our attention to the more challenging task of converting substrate

Table 2. Results for Continuous Flow Procedure

entry	transformation	conditions	mmol/h	yield (%)
1	3a → 1f	*flow*, 80 °C, 1 h t_{Res}	18	79
2	3b → 1b	*flow*, 80 °C, 1 h t_{Res}	18	85
3	3h → 1o	*batch*, rt, 12 h, then MW (1.5 h, 120 °C)	<0.4	79
4	3h → 1o	*flow*, 80 °C, 0.5 h t_{Res} + 0.5 h at 120 °C	18	30–40
5	3h → 1o	*flow*, 80 °C, 0.5 h t_{Res} + 0.5 h, UV (75 W), 80 °C	18	60

3h into product **1o** for which our previous batch efforts had indicated an inhibited cyclization step (Table 2, entry 3). In analogy to the previous two flow sequences (Table 2, entries 1 and 2) we realized the clean formation of allene intermediate **2h** when using a single coil reactor at 80 °C (0.5−1 h t_{Res}), albeit without significant amounts of the desired cyclization product **1o** (<5%). We therefore added a further coil reactor operating at a higher temperature (120 °C, 0.5 h t_{Res}) downstream to the first in order to force the cyclization step to occur. Although this setup increased the formation of **1o** to about 30−40% (Table 2, entry 4), these results were not satisfactory as the crude product still contained the allene intermediate (**2h**, ∼40%) and several unidentified side products (∼20%).[15,16] Anticipating that more forcing conditions would inevitably lead to the formation of more side products, we turned our attention to employing a reactor configuration where a UV-flow reactor would be placed after the initial coiled reactor thus aiming to realize the formation of allene intermediate **2h** in the first reactor followed by its conversion into **1o** facilitated in the UV-flow reactor. The use of a photochemical activation of the allene portion was inspired by reports in the literature describing the benefits of triggering reactions of allenes mediated by light.[17] Using the aforementioned Vaportec E-series flow system in conjunction with its UV-flow reactor unit we were able to quickly screen a number of different conditions with respect to lamp power settings (65−140 W), temperature of the UV-flow reactor (20−85 °C) as well as different light filters (see SI for full information). Upon further experimentation it became apparent that this combination of a thermal coiled reactor with a second UV reactor was beneficial increasing the conversion of **3h** into **1o** to the region of ∼60% with smaller amounts of intermediate **2h** (20%) and few side products being present (Table 1, entry 5). Although conditions for quantitative formation of **1o** were not identified for this specific substrate, flow chemical processing was established as a valuable means to either continuously prepare allene intermediate **2h** or pyrrolo-[1,2-*a*]quinoline **1o** allowing to generate multigram quantities (5−10 g) of either species within a single working day. Furthermore, a simpler flow setup utilizing only one coiled reactor had established a continuous process for the production of pyrrolo[1,2-*a*]quinolines **1f** and **1b** with a throughput of 18 mmol/h, which would not have been possible with the initially established batch procedure due to the exothermic reaction profile observed for small scale reactions (1−4 mmol, temperature rise by >20 °C).

In conclusion, we have developed an efficient reaction sequence converting simple propargylic alcohols in the presence of different chlorophosphine and phosphite species into a selection of tricyclic pyrrolo[1,2-*a*]quinolines. This new reaction cascade proceeds through the intermediacy of highly

DOI: 10.1021/acs.joc.5b01982
J. Org. Chem. 2015, 80, 10806−10816

substituted allenes demonstrating their value as reactive intermediates toward the construction of important yet underrepresented heterocyclic architectures. Furthermore, we extended on the initial small scale batch procedure by devising an efficient continuous flow protocol enabling the production of selected products at mesoscale (18 mmol/h), providing gram quantities of these heterocyclic entities for future studies regarding chemical modifications as well as biological evaluations.

EXPERIMENTAL SECTION

In a general procedure, the desired aniline derivative (**5**, 50 mmol, 1.0 equiv) was dissolved in glacial acetic acid (10 mL) and combined with *N*-iodosuccinimide (50 mmol, 1.0 equiv). The resulting reaction mixture was stirred at room temperature and monitored by ^{1}H NMR spectroscopy until complete conversion of the substrate was achieved (typically 2−6 h). The crude reaction product was then neutralized by pouring into a saturated aqueous solution of K_2CO_3, followed by extraction using EtOAc. The combined organic layers were dried over anhydrous Na_2SO_4, filtered and evaporated using a rotary evaporator. The iodinated aniline products were typically isolated as black oils and used directly in the next step.

In a general procedure, to the crude iodoaniline product (25 mmol, 1.0 equiv) dissolved in glacial acetic acid (10 mL) was added 2,5-dimethoxytetrahydrofuran (30 mmol, 1.2 equiv). The resulting mixture was heated at 80 °C until full conversion of the starting material into the desired pyrrole derivative was accomplished (monitored by ^{1}H NMR spectroscopy; typically 1−4 h). After cooling to room temperature, the crude mixture was neutralized by pouring into saturated aqueous K_2CO_3, followed by extraction with EtOAc, drying of the combined organic layers over anhydrous Na_2SO_4 and evaporation of the volatiles. The desired products (**6**) were isolated as dark colored solids and used directly in the next step.

In a general procedure, to a solution of the aryl iodide substrate (**6**, 10 mmol, 1.0 equiv) in dry THF (8 mL) was added $HNiPr_2$ (12 mmol, 1.2 equiv). To this solution either propargyl alcohol (12 mmol, 1.2 equiv) or 2-methyl-3-butyn-2-ol (12 mmol, 1.2 equiv) were added followed by addition of $PdCl_2(PPh_3)_2$ (0.3 mmol), CuBr (0.5 mmol) and NaI (0.5 mmol). The resulting reaction mixture was stirred at 50 °C for 4−6 h until complete consumption of the starting material was observed by TLC. The reaction mixture was filtered over a plug of silica before aqueous extraction with EtOAc. The combined organic layers were dried over anhydrous Na_2SO_4, filtered and evaporated to yield the crude product. Silica gel chromatography (10−20% EtOAc/hexanes) was subsequently used to yield clean product (**3a−j**).

3-(5-Chloro-2-(1*H*-pyrrol-1-yl)phenyl)prop-2-yn-1-ol, (3a): brown solid, 75% yield (4.3 g on 25 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.50 (1H, d, J = 2.4 Hz), 7.34 (1H, dd, J = 8.6, 2.4 Hz), 7.22 (1H, d, J = 8.6 Hz), 7.04 (2H, t, J = 2.2 Hz), 6.33 (2H, t, J = 2.2 Hz), 4.36 (2H, s), 2.01 (1H, s). ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.7 (C), 133.3 (CH), 131.9 (C), 129.6 (CH), 126.1 (CH), 121.7 (2CH), 118.9 (C), 109.7 (2CH), 93.1 (C), 81.3 (C), 51.4 (CH_2). IR (neat, cm^{-1}) 3448 (broad), 1739 (w), 1496 (s), 1389 (m), 1329 (m), 1115 (m), 1069 (m), 1018 (s), 920 (m), 738 (s). LC-MS (ESI) m/z = 231.9 (M+H). HR-MS (TOF ES$^+$) calculated for $C_{13}H_{11}NOCl$ 232.0529, found 232.0526 (Δ = −1.3 ppm). Melting range 78.3−81.1 °C.

3-(4-Chloro-5-fluoro-2-(1*H*-pyrrol-1-yl)phenyl)prop-2-yn-1-ol, (3b): yellow oil, 77% yield (4.8 g on 25 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 (1H, d, J = 6.7 Hz), 7.30 (1H, d, J = 8.9 Hz), 7.01 (2H, t, J = 2.2 Hz), 6.37−6.31 (2H, m), 4.36 (2H, s), 2.18 (1H, s). ^{13}C NMR (101 MHz, $CDCl_3$) δ 155.9 (CF, d, J = 250 Hz), 138.9 (C, d, J = 3 Hz), 127.2 (CH), 122.1 (C, d, J = 19 Hz), 121.8 (2CH), 120.8 (CH, d, J = 24 Hz), 117.6 (C, d, J = 9 Hz), 109.9 (2CH), 93.6 (C), 80.6 (C, d, J = 2 Hz), 51.3 (CH_2). ^{19}F NMR (376 MHz, $CDCl_3$) δ −117.62 (s). IR (neat, cm^{-1}) 3326 (broad), 1738 (w), 1492 (s), 1391 (m), 1273 (m), 1181 (s), 1069 (s), 1025 (s), 884 (s), 719 (s), 601 (m). LC-MS (ESI) m/z = 250.0 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{13}H_{10}NOFCl$ 250.0435, found 250.0440 (Δ = 0.5 ppm).

3-(3,5-Difluoro-2-(1*H*-pyrrol-1-yl)phenyl)prop-2-yn-1-ol, (3c): brown oil, 80% yield (4.7 g on 25 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.04 (1H, ddd, J = 8.4, 2.8, 1.7 Hz), 6.96 (1H, ddd, J = 9.7, 8.2, 2.9 Hz), 6.86 (2H, q, J = 1.9 Hz), 6.33 (2H, t, J = 2.1 Hz), 4.30 (2H, d, J = 6.1 Hz), 1.91 (1H, t, J = 6.1 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 160.6 (CF, dd, J = 250, 13 Hz), 157.3 (CF, dd, J = 253, 13 Hz), 127.5 (C, m), 123.1 (C, dd, J = 12, 3 Hz), 122.6 (2CH, d, J = 2 Hz), 115.3 (CH, dd, J = 24, 4 Hz), 109.2 (2CH), 105.6 (CH, dd, J = 26, 25 Hz), 93.9 (C), 80.3 (C, m), 51.3 (CH_2). ^{19}F NMR ($CDCl_3$, 367 MHz) δ (s) −110.11 (d, J = 7.4 Hz), −117.74 (d, J = 7.4 Hz). IR (neat, cm^{-1}) 3341 (broad), 3081 (w), 1597 (m), 1505 (s), 1439 (m), 1310 (m), 1196 (m), 1134 (s), 1067 (s), 1000 (s), 858 (s), 723 (s), 597 (m). LC-MS (ESI) m/z = 234.6 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{13}H_{10}NOF_2$ 234.0730, found 234.0733 (Δ = 1.3 ppm).

3-(5-Chloro-3-nitro-2-(1*H*-pyrrol-1-yl)phenyl)prop-2-yn-1-ol, (3d): yellow oil, 71% yield (3.9 g on 20 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.77 (1H, d, J = 2.4 Hz), 7.69 (1H, d, J = 2.4 Hz), 6.74 (2H, app t, J = 2.0 Hz), 6.34 (2H, app t, J = 2.0 Hz), 4.31 (3H, s), 1.66 (1H, br s). ^{13}C NMR (101 MHz, $CDCl_3$) δ 147.6 (C), 135.8 (CH), 134.1 (C), 133.9 (C), 125.4 (C), 124.2 (CH), 122.2 (2CH), 110.5 (2CH), 95.5 (C), 79.1 (C), 51.2 (CH_2). IR (neat, cm^{-1}) 3349 (broad), 3076 (w), 1540 (s), 1497 (s), 1355 (s), 1171 (m), 1098 (m), 1046 (s), 922 (m), 723 (s), 692 (s), 519 (s). LC-MS (ESI) m/z = 277.0 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{13}H_{10}N_2O_3Cl$ 277.0380, found 277.0374 (Δ = −2.2 ppm).

3-(5-Bromo-(1*H*-pyrrol-1-yl)pyridine-2-yl)prop-2-yn-1-ol, (3e): yellow solid, 70% yield (4.8 g on 20 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.57 (1H, d, J = 2.0 Hz), 7.81 (1H, d, J = 2.0 Hz), 7.09 (2H, app t, J = 2.4 Hz), 6.37 (2H, app t, J = 2.4 Hz), 4.44 (2H, s), 1.83 (1H, br s). ^{13}C NMR (101 MHz, $CDCl_3$) δ 148.6 (CH), 139.4 (C), 135.1 (C), 134.8 (CH), 121.4 (2CH), 120.1 (C), 111.0 (2CH), 93.4 (C), 81.9 (C), 51.5 (CH_2). IR (neat, cm^{-1}) 3252 (m), 3044 (w), 1571 (m), 1487 (m), 1112 (m), 1065 (m), 1029 (m), 934 (m), 794 (w), 721 (s), 609 (m). LC-MS (ESI) m/z = 277.0 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{12}H_{10}N_2OBr$ 276.9976, found 276.9982 (Δ = 2.2 ppm). mp 115 °C (decomposition).

4-(3,5-Difluoro-2-(1*H*-pyrrol-1-yl)phenyl)-2-methylbut-3-yn-2-ol, (3f) yellow oil, 76% yield (2.0 g on 10 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.01 (1H, ddd, J = 8.4, 2.8, 1.7 Hz), 6.94 (1H, ddd, J = 9.7, 8.3, 2.8 Hz), 6.84 (2H, td, J = 2.2, 1.3 Hz), 6.33 (2H, t, J = 2.2 Hz), 2.34 (1H, s), 1.45 (6H, s). ^{13}C NMR (101 MHz, $CDCl_3$) δ 160.6 (CF, dd, J = 250, 13 Hz), 157.3 (CF, dd, J = 253, 13 Hz), 127.6 (C, dd, J = 13, 4 Hz), 123.6 (C, dd, J = 12, 3 Hz), 122.6 (2CH, d, J = 1 Hz), 114.8 (CH, dd, J = 24, 4 Hz), 109.2 (2CH), 105.3 (CH, dd, J = 26, 25 Hz), 100.4 (C), 76.9 (C, dd, J = 5, 3 Hz), 65.3 (C), 30.7 ($2CH_3$). ^{19}F NMR ($CDCl_3$, 367 MHz) δ −110.17 (d, J = 7.4 Hz), −117.81 (d, J = 7.4 Hz). IR (neat, cm^{-1}) 3368 (broad), 2983 (w), 1592 (m), 1507 (s), 1439 (m), 1222 (m), 1128 (s), 1069 (m), 1016 (m), 999 (s), 951 (m), 859 (m), 722 (s), 617 (m). LC-MS (ESI) m/z = 284.3 (M+Na). HR-MS (TOF-ES$^+$) calculated for $C_{15}H_{14}NOF_2$ 262.1043, found 262.1055 (Δ = 4.6 ppm).

3-(3-Hydroxy-3-methylbut-1-yn-1-yl)-4-(1*H*-pyrrol-1-yl)-benzonitrile, (3g): white solid, 77% yield (3.8 g on 20 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.81 (1H, d, J = 2.0 Hz), 7.63 (1H, dd, J = 8.4, 2.0 Hz), 7.39 (1H, d, J = 8.4 Hz), 7.17−7.12 (2H, m), 6.36 (2H, t, J = 2.2 Hz), 1.97 (1H, s), 1.55 (6H, s). ^{13}C NMR (101 MHz, $CDCl_3$) δ 145.1 (C), 137.8 (CH), 132.6 (CH), 125.1 (CH), 121.3 (2CH), 118.2 (C), 117.5 (C), 110.6 (2CH), 109.9 (C), 100.6 (C), 77.5 (C), 65.6 (C), 30.8 ($2CH_3$). IR (neat, cm^{-1}) 3451 (m), 2981 (w), 2239 (m), 1598 (m), 1502 (s), 1393 (m), 1335 (s), 1061 (m), 922 (m), 913 (m), 837 (m), 733 (s), 618 (m). LC-MS (ESI) m/z = 273.1 (M+Na). HR-MS (TOF-ES$^+$) calculated for $C_{16}H_{14}N_2ONa$ 273.1004, found 273.1004 (Δ = 0.0 ppm). Melting range 122.0−123.1 °C.

4-(5-Bromo-2-(1*H*-pyrrol-1-yl)phenyl)-2-methylbut-3-yn-2-ol, (3h): yellow oil, 78% yield (11.7 g on 50 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.62 (1H, d, J = 2.3 Hz), 7.46 (1H, dd, J = 8.6, 2.3 Hz), 7.14 (1H, d, J = 8.5 Hz), 7.05−6.99 (2H, m), 6.34−6.28

DOI: 10.1021/acs.joc.5b01982
J. Org. Chem. 2015, 80, 10806−10816

(2H, m), 2.55 (1H, s), 1.51 (6H, s). ^{13}C NMR (101 MHz, $CDCl_3$) δ 141.2 (C), 136.0 (CH), 132.3 (CH), 126.2 (CH), 121.6 (2CH), 119.5 (C), 119.3 (C), 109.6 (2CH), 99.7 (C), 77.9 (C), 65.4 (C), 30.8 ($2CH_3$). IR (neat, cm^{-1}) 3371 (broad), 2980 (w), 1496 (s), 1328 (m), 1162 (m), 1108 (m), 1064 (m), 964 (m), 926 (s), 910 (m), 818 (m), 723 (s), 550 (m). LC-MS (ESI) m/z = 325.9 (M+Na). HR-MS (TOF-ES$^+$) calculated for $C_{15}H_{14}NOBrNa$ 326.0166, found 326.0177 (Δ = −3.4 ppm).

4-(3,5-Difluoro-2-(1*H*-pyrrol-1-yl)phenyl)but-3-yn-ol, (3i): brown oil, 79% yield (4.9 g, on 25 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.02 (1H, ddd, J = 8.4, 2.8, 1.7 Hz), 6.95 (1H, ddd, J = 9.7, 8.2, 2.8 Hz), 6.84 (2H, td, J = 2.2, 1.3 Hz), 6.38−6.29 (2H, m), 4.55 (1H, q, J = 6.6 Hz), 2.00 (1H, s), 1.39 (3H, d, J = 6.6 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 160.6 (CF, dd, J = 250, 13 Hz), 157.3 (CF, dd, J = 253, 13 Hz), 127.5 (C, dd, J = 13, 4 Hz), 123.3 (C, dd, J = 12, 3 Hz), 122.6 (2CH, d, J = 2 Hz), 115.0 (CH, dd, J = 24, 4 Hz), 109.2 (2CH), 105.4 (CH, dd, J = 26, 25 Hz), 97.5 (C), 78.7 (C, dd, J = 5, 3 Hz), 58.5 (CH), 23.6 (CH_3). ^{19}F NMR ($CDCl_3$, 367 MHz) δ −110.14 (d, J = 7.4 Hz), −117.79 (d, J = 7.4 Hz). IR (neat, cm^{-1}) 3329 (broad), 2985 (w), 1616 (m), 15944 (m), 1508 (s), 1439 (m), 1308 (m), 1138 (s), 1118 (s), 1068 (s), 1009 (s), 859 (m), 724 (s), 617 (m), 598 (m). LC-MS (ESI) m/z = 248.0 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{14}H_{12}NOF_2$ 248.0887, found 248.0911 (Δ = 4.7 ppm).

4-(3,5-Difluoro-2-(1*H*-pyrrol-1-yl)phenyl)-2-phenylbut-3-yn-ol, (3j): brown oil, 84% yield (2.7 g on 10 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45−7.41 (2H, m), 7.36−7.27 (3H, m), 7.09 (1H, ddd, J = 8.4, 2.8, 1.7 Hz), 6.97 (1H, ddd, J = 9.6, 8.2, 2.8 Hz), 6.85 (2H, dt, J = 2.2, 1.1 Hz), 6.37−6.34 (2H, m), 2.46 (1H, s), 1.72 (3H, s). ^{13}C NMR (101 MHz, $CDCl_3$) δ 160.8 (CF, dd, J = 250, 13 Hz), 157.5 (CF, dd, J = 253, 13 Hz), 144.5 (C), 128.3 (2CH), 127.8 (CH), 127.6 (C, dd, J = 13, 5 Hz), 124.9 (2CH), 123.6 (C, dd, J = 12, 3 Hz), 122.6 (2CH, d, J = 1 Hz), 115.0 (CH, dd, J = 24, 4 Hz), 109.4 (2CH), 105.5 (CH, dd, J = 26, 25 Hz), 98.8 (C), 79.5 (C, dd, J = 5, 3 Hz), 70.2 (C), 32.6 (CH_3). ^{19}F NMR ($CDCl_3$, 367 MHz) δ −109.81 (d, J = 7.4 Hz), −117.60 (d, J = 7.4 Hz). IR (neat, cm^{-1}) 3384 (broad), 1591 (m), 1508 (s), 1438 (m), 1310 (m), 1128 (s), 1069 (s), 1016 (s), 997 (m), 850 (m), 764 (m), 725 (s), 6998 (s), 610 (m). LC-MS (ESI) m/z = 346.1 (M+Na). HR-MS (TOF-ES$^+$) calculated for $C_{20}H_{15}NOF_2Na$ 346.1019, found 346.1010 (Δ = −2.6 ppm).

In a general batch procedure, propargylic alcohol **3a−j** (1 mmol, 1.0 equiv) was dissolved in chloroform (2 mL, 0.5 M) and combined with triethylamine (1.3 mmol, 1.3 equiv). To this mixture either chlorodiphenylphosphine or diethyl chlorophosphite (1.3 mmol, 1.3 equiv) was added carefully at room temperature avoiding temperature increase above 30 °C. The crude reaction mixture was stirred at room temperature and reaction progress was monitored by tlc. In case of primary propargylic alcohols (R_1 = H) full conversion of the substrate to the desired product **1** was realized within 3−8 h, whereas for substrates with R_1 = Me conversion of the intermediate allene **2** to **1** did not occur at room temperature within 24 h. In either case the crude reaction mixture was quenched by adding excess aqueous K_2CO_3 solution followed by aqueous extraction (3× 10 mL water). The combined organic layers were dried over anhydrous Na_2SO_4, filtered and evaporated to dryness using a rotary evaporator. Purification of the crude products was accomplished by silica column chromatography using EtOAc (10−20%) and hexanes as solvent system allowing to isolate clean pyrrolo[1,2-*a*]quinolines (**1**) or allenes (**2**).

In order to convert tetrasubstituted allenes **2** into the corresponding pyrrolo[1,2-*a*]quinolines, the crude reaction mixtures were transferred into a microwave vial (typically 5 mL volume), capped and heated at 110 °C in a Biotage microwave reactor for 90 min. Following the same workup and purification procedure outlined above allowed isolation of the pure cyclization products.

For the continuous flow procedure, two stock solutions containing the propargylic alcohol **3a,c,h** (1 equiv, 1.0 M) and NEt_3 (1.3 equiv) in chloroform (stock solution A) and the chlorodiphenylphosphine or diethyl chlorophosphite reagent (1.3 equiv, 1.0 M in chloroform, stock solution B) were prepared. Using a Vaportec MedChem flow system streams of these two stock solutions were pumped at individual flow rates of 0.3 mL/min. After mixing in a T-piece the combined stream was directed into two subsequent reactor coils (PTFE, 10 mL volume each) maintained at 80 °C. After exiting these flow reactor coils a stream containing saturated aqueous K_2CO_3 solution was mixed with the crude reaction stream in order to quench the reaction prior to passing through a back-pressure regulator (75 psi). The product was collected in a separating funnel and workup and purification was accomplished as described in the above batch scenario.

This setup was used to prepare **1f** (from **3a**), **1b** (from **3c**) and **2h** (from **3h**) with a total flow path length (reactor coils and tubing) of 25 mL at a combined flow rate of 0.6 mL/min corresponding to a residence time of 41.7 min and a general throughput of 18 mmol substrate per hour. Starting from 30 mmol **3a** yielded 23.7 mmol of purified **1f** (79% yield, 8.32 g), 10 mmol **3c** yielded 8.5 mmol purified **1b** (85%, 3.54 g) and at a reactor temperature of 50 °C 10 mmol **3h** yielded 9.0 mmol purified **2h** (90% yield, 3.70 g).

Upon increasing the temperature of the second reactor coil to 120 °C while leaving the first one at 50 °C substrate **3h** was converted into ∼35% **1o** together with 40% **2h** and several side products (10 mmol scale experiment). Additionally, when using a first reactor coil at 50 °C followed by a subsequent UV-photoreactor coil (75 W power, 75−80 °C temperature) substrate **3h** was converted to 60% **1o**, 20% **2h** as well as ∼15% side products (10 mmol scale experiment).

(7-Chloro-4-methylpyrrolo[1,2-*a*]quinolin-5-yl)-diphenylphosphine oxide, (1a):3.2 g (78%, 10 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.36 (1H, d, J = 2.4 Hz), 7.90 (1H, dd, J = 1.2, 2.8 Hz), 7.70−7.79 (5H, m), 7.48−7.53 (2H, m), 7.41−7.47 (4H, m), 7.30 (1H, dd, J = 2.0, 8.8 Hz), 6.82 (1H, dd, J = 3.2, 4.0 Hz), 6.75 (1H, dd, J = 0.8, 4.0 Hz), 2.30 (3H, d, J = 1.6 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.1 (C, d, J = 9 Hz), 135.1 (2C, d, J = 104 Hz), 131.8 (2CH, d, J = 3 Hz), 131.5 (2 × 2CH, d, J = 10 Hz), 131.3 (C, d, J = 13 Hz), 130.5 (C, d, J = 9 Hz), 128.9 (2 × 2CH, J = 12 Hz), 128.8 (C), 128.5 (CH, d, J = 4 Hz), 127.3 (CH), 125.2 (C, d, J = 10 Hz), 115.5 (CH), 114.8 (CH), 113.9 (CH), 113.8 (C, d, J = 105 Hz), 106.3 (CH), 19.1 (CH_3, d, J = 7 Hz). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 30.00 (s). IR (neat, cm^{-1}) 3057 (w), 1478 (m), 1437 (m), 1406 (m), 1171 (m), 1116 (m), 721 (s), 693 (s), 516 (s). LC-MS (ESI) m/z = 416.0 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{25}H_{20}NOPCl$ 416.0971, found 416.0973 (Δ = 0.5 ppm).

(7,9-Difluoro-4-methylpyrrolo[1,2-*a*]quinolin-5-yl)-diphenylphosphine oxide, (1b): 3.4 g (81%, 10 mmol scale). ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.29 (1H, s), 8.14 (1H, d, J = 11.4 Hz), 7.70−7.78 (4H, m), 7.49−7.55 (2H, m), 7.43−7.47 (4H, m), 6.94 (1H, ddd, J = 2.4, 7.2, 13.2 Hz), 6.82 (1H, m), 6.80 (1H, m), 2.23 (3H, d, J = 1.8 Hz). ^{13}C NMR (150 MHz, $CDCl_3$) δ 156.8 (CF, dd, J = 243, 13 Hz), 152.5 (CF, ddd, J = 249, 13, 2 Hz), 139.7 (C, d, J = 9 Hz), 134.8 (2CP, d, J = 105 Hz), 131.9 (2CH, d, J = 3 Hz), 131.5 (C, d, J = 12 Hz), 131.4 (2 × 2CH, d, J = 10 Hz), 128.9 (2 × 2CH, d, J = 12 Hz), 127.6 (C, td, J = 11, 3 Hz), 121.0 (CH, d, J = 23 Hz), 119.0 (C, td, J = 9, 3 Hz), 113.6 (CH, d, J = 5 Hz), 113.4 (CP, d, J = 106 Hz), 110.4 (CH, dt, J = 26, 4 Hz), 106.1 (CH, d, J = 1 Hz), 103.0 (CH, dd, J = 28, 25 Hz), 19.3 (CH_3, d, J = 6 Hz). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 30.30 (s). ^{19}F NMR ($CDCl_3$, 367 MHz) δ −115.0 (d, J = 18 Hz), −118.6 (d, J = 18 Hz). IR (neat, cm^{-1}) 3057 (w), 1629 (m), 1593 (m), 1472 (m), 1436 (m), 1415 (m), 1363 (m), 1172 (m), 1116 (s), 1045 (s), 721 (s), 694 (s), 541 (s). LC-MS (ESI) m/z = 417.7 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{25}H_{19}NOPF_2$ 418.1172, found 418.1166 (Δ = −1.4 ppm).

(8-Chloro-7-fluoro-4-methylpyrrolo[1,2-*a*]quinolin-5-yl)-diphenylphosphine oxide, (1c): 3.6 g (84%, 10 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.48 (1H, d, J = 12.0 Hz), 7.90 (1H, dd, J = 1.2, 6.8 Hz), 7.85−7.87 (1H, m), 7.70−7.78 (4H, m), 7.55−7.59 (2H, m), 7.44−7.51 (4H, m), 6.85 (1H, dd, J = 2.8, 3.6 Hz), 6.75 (1H, dd, J = 1.2, 4.0 Hz), 2.20 (3H, d, J = 1.6 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 153.7 (CF, d, J = 244 Hz), 138.5 (C, d, J = 9 Hz), 134.7 (2CP, d, J = 105 Hz), 132.0 (2CH, d, J = 3 Hz), 131.5 (2 × 2CH, d, J = 10 Hz), 131.2 (C, d, J = 14 Hz), 129.0 (2 × 2CH, d, J = 12 Hz), 124.1 (C, d, J = 8 Hz), 124.0 (C, d, J = 10 Hz), 120.4 (C, d, J = 21 Hz), 116.1 (C, dd, J = 26, 4 Hz), 115.8 (CH), 114.9 (CH), 114.1

DOI: 10.1021/acs.joc.5b01982
J. Org. Chem. 2015, 80, 10806−10816

(CH), 113.6 (CP, dd, J = 3, 101 Hz), 106.5 (CH), 19.2 (CH_3, d, J = 6 Hz). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 30.58 (s). ^{19}F NMR ($CDCl_3$, 367 MHz) δ −120.0 (s). IR (neat, cm^{-1}) 2932 (w), 1436 (m), 1410 (m), 1165 (m), 1116 (m), 844 (m), 715 (s), 690 (s), 622 (s), 545 (s), 526 (s), 513 (s). LC-MS (ESI) m/z = 434.3 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{25}H_{19}NOPClF$ 434.0877, found 434.0872 (Δ = 1.2 ppm).

(7-Chloro-4-methyl-9-nitropyrrolo[1,2-*a*]quinolin-5-yl)-diphenylphosphine oxide, (1d): 2.0 g (86%, 5 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.81 (1H, d, J = 2.0 Hz), 7.70−7.80 (4H, m), 7.54−7.60 (3H, m), 7.46−7.53 (4H, m), 7.40−7.44 (1H, m), 6.82−6.89 (2H, m), 2.24 (3H, d, J = 1.2 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.8 (C), 140.5 (C, d, J = 11 Hz), 134.4 (2C, d, J = 104 Hz), 132.3 (C, d, J = 13 Hz), 132.2 (2CH, d, J = 3 Hz), 131.7 (CH, d, J = 4 Hz), 131.4 (2 × 2CH, d, J = 10 Hz), 129.1 (2 × 2CH, d, J = 13 Hz), 128.2 (C, d, J = 11 Hz), 128.0 (C), 122.5 (CH), 122.0 (C, d, J = 8 Hz), 119.2 (CH), 115.3 (CH), 113.5 (C, d, J = 104 Hz), 107.6 (CH), 19.5 (CH_3, d, J = 6 Hz). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 30.06 (s). IR (neat, cm^{-1}) 3055 (w), 1529 (m), 1438 (m), 1364 (m), 1172 (s), 1114 (m), 948 (m), 751 (m), 719 (s), 691 (s), 519 (s). LC-MS (ESI) m/z = 460.9 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{25}H_{19}N_2O_3PCl$ 461.0822, found 461.0814 (Δ = 1.7 ppm).

(2-Bromo-6-methylpyrrolo[1,2-*a*][1,5]naphthyridin-5-yl)-diphenyl phosphine oxide, (1e): 1.8 g (79%, 5 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.13 (1H, app t, J = 2.0 Hz), 8.11 (1H, d, J = 2.0 Hz), 7.75−7.85 (5H, m), 7.40−7.46 (2H, m), 7.33−7.38 (4H, m), 6.93 (1H, dd, J = 0.8, 4.0 Hz), 6.86 (1H, dd, J = 2.8, 4.0 Hz), 3.17 (3H, d, J = 2.0 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 144.4 (C, d, J = 7 Hz), 144.0 (CH), 139.9 (C, d, J = 8 Hz), 135.7 (2C, d, J = 109 Hz), 132.3 (C, d, J = 5 Hz), 131.8 (2 × 2CH, d, J = 10 Hz), 130.9 (2CH, d, J = 3 Hz), 128.1 (C, d, J = 6 Hz), 127.8 (2 × 2CH, d, J = 13 Hz), 123.3 (CH), 117.2 (C), 116.0 (C, d, J = 108 Hz), 114.9 (CH), 113.7 (CH), 107.3 (CH), 16.2 (CH_3, d, J = 4 Hz). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 33.54 (s). IR (neat, cm^{-1}) 3148 (w), 2968 (w), 1581 (w), 1468 (m), 1434 (m), 1409 (m), 1159 (m), 1100 (m), 873 (m), 730 (s), 722 (s), 696 (s), 537 (s), 518 (s). LC-MS (ESI) m/z = 460.9 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{24}H_{19}N_2OPBr$ 461.0418, found 461.0407 (Δ = −2.4 ppm). Single crystal X-ray data: CCDC 1411501; $P2_1/n$; a = 11.8026(2) Å, b = 11.7519(2) Å, c = 17.7173(3) Å; α = 90°, β = 98.8047(17)°, γ = 90°.

Diethyl (7-chloro-4-methylpyrrolo[1,2-*a*]quinolin-5-yl)-phosphonate, (1f): 1.3 g (73%, 5 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.77 (1H, d, J = 2.4 Hz), 7.89 (1H, dd, J = 1.2, 2.4 Hz), 7.79 (1H, dd, J = 1.6, 8.8 Hz), 7.43 (1H, dd, J = 2.4, 8.8 Hz), 6.86 (1H, dd, J = 0.8, 3.6 Hz), 6.85 (1H, dd, J = 2.8, 4.0 Hz), 4.23 (2H, ddq, J = 7.1, 7.9, 10.1 Hz), 4.08 (2H, ddq, J = 7.1, 7.9, 10.1 Hz), 2.91 (3H, d, J = 2.4 Hz), 1.33 (6H, t, J = 7.2 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.5 (C, d, J = 11 Hz), 131.2 (C, d, J = 19 Hz), 130.4 (C, d, J = 12 Hz), 129.3 (C), 128.2 (CH), 127.3 (CH), 124.5 (C, d, J = 13 Hz), 115.3 (CH), 114.6 (CH), 113.9 (CH), 110.7 (C, d, J = 187 Hz), 106.8 (CH), 61.8 ($2CH_2$, d, J = 5 Hz), 17.8 (CH_3, d, J = 4 Hz), 16.3 ($2CH_3$, d, J = 7 Hz). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 18.55 (s). IR (neat, cm^{-1})2981 (w), 1480 (m), 1408 (m), 1226 (s), 1014 (s), 946 (s), 799 (s), 739 (m), 701 (m), 593 (s), 542 (s). LC-MS (ESI) m/z = 352.2 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{17}H_{20}NO_3PCl$ 352.0869, found 352.0862 (Δ = −2.0 ppm).

Diethyl (7,9-difluoro-4-methylpyrrolo[1,2-*a*]quinolin-5-yl)-phosphonate, (1g): 1.4 g (79%, 5 mmol scale). ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.40 (1H, dt, J = 11.8, 2.2 Hz), 8.31−8.26 (1H, m), 7.03 (1H, ddd, J = 13.3, 7.7, 2.8 Hz), 6.92 (1H, d, J = 3.9 Hz), 6.83 (1H, dd, J = 4.1, 2.9 Hz), 4.20 (2H, ddq, J = 10.2, 8.4, 7.1 Hz), 4.08 (2H, ddq, J = 10.2, 8.4, 7.1 Hz), 2.91 (3H, d, J = 2.4 Hz), 1.32 (6H, t, J = 7.1 Hz). ^{13}C NMR (150 MHz, $CDCl_3$) δ 157.3 (CF, dd, J = 242, 13 Hz), 152.5 (CF, ddd, J = 249, 13, 3 Hz), 141.5 (C, d, J = 11 Hz), 131.4 (C, d, J = 19 Hz), 126.8 (C, ddd, J = 14, 11, 3 Hz), 121.0 (CH, d, J = 24 Hz), 118.8 (C, ddd, J = 12, 9, 3 Hz), 113.6 (CH, dd, J = 5, 1 Hz), 110.4 (CP, d, J = 181 Hz), 109.7 (CH, ddd, J = 26, 4, 2 Hz), 106.6 (CH, d, J = 1 Hz), 102.9 (CH, dd, J = 28, 26 Hz), 61.8 ($2CH_2$, d, J = 5 Hz), 17.9 (CH_3, d, J = 4 Hz), 16.3 ($2CH_3$, d, J = 7 Hz). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 18.4 (s). ^{19}F NMR ($CDCl_3$, 367 MHz) δ −115.3 (d, J = 8 Hz), −118.8 (d, J = 8 Hz). IR (neat) (v) 2985 (w), 1628 (m), 1595 (m), 1439 (m), 1365 (m), 1245 (s), 1122 (m), 1016 (s), 952 (s), 795 (m), 714 (m), 559 (s). LC-MS (ESI) m/z = 354.9 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{17}H_{19}NO_3PF_2$ 354.1071, found 354.1065 (Δ = −1.7 ppm).

Diethyl (8-chloro-7-fluoro-4-methylpyrrolo[1,2-*a*]quinolin-5-yl)phosphonate, (1h): 1.4 g (77%, 5 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.70 (1H, d, J = 12.4 Hz), 7.91 (1H, dd, J = 1.8, 6.7 Hz), 7.86 (1H, dd, J = 1.5, 2.5 Hz), 6.90 (1H, dd, J = 1.2, 4.0 Hz), 6.88 (1H, dd, J = 2.8, 4.0 Hz), 4.24 (2H, ddq, J = 7.2, 8.0, 10.1 Hz), 4.10 (2H, ddq, J = 7.2, 8.2, 10.2 Hz), 2.91 (3H, d, J = 2.4 Hz), 1.35 (6H, t, J = 7.2 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 154.2 (CF, d, J = 241 Hz), 140.5 (C, d, J = 11 Hz), 131.2 (C, d, J = 19 Hz), 128.8 (C, dd, J = 2, 12 Hz), 123.2 (C, dd, J = 8, 14 Hz), 120.2 (C, d, J = 20 Hz), 115.7 (CH), 115.6 (CH, m), 114.8 (CH), 114.1 (CH), 110.5 (CP, d, J = 210 Hz), 107.1 (CH), 61.9 ($2CH_2$, d, J = 5 Hz), 17.7 (CH_3, d, J = 4 Hz), 16.3 ($2CH_3$, d, J = 6 Hz). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 18.27 (s). ^{19}F NMR ($CDCl_3$, 367 MHz) δ −120.4 (s). IR (neat, cm^{-1}) 2985 (w), 1487 (m), 1410 (m), 1256 (s), 1222 (s), 1015 (s), 960 (s), 728 (s), 700 (s), 626 (m), 556 (s). LC-MS (ESI) m/z = 369.9 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{17}H_{19}NO_3PFCl$ 370.0775, found 370.0765 (Δ = −2.7 ppm).

Diethyl (7-chloro-4-methyl-9-nitropyrrolo[1,2-*a*]quinolin-5-yl)phosphonate, (1i): 1.4 g (70%, 5 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.13 (1H, d, J = 2.4 Hz), 7.64 (1H, d, J = 2.4 Hz), 7.39 (1H, dd, J = 0.4, 2.8 Hz), 6.99 (1H, d, J = 4.0 Hz), 6.87 (1H, dd, J = 2.8, 4.0 Hz), 4.25 (2H, ddq, J = 10.1, 8.0, 7.1 Hz), 4.11 (2H, ddq, J = 10.1, 8.0, 7.1 Hz), 2.92 (3H, d, J = 1.6 Hz), 1.34 (6H, t, J = 7.1 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 142.1 (C, d, J = 11 Hz), 140.8 (C), 132.2 (C, d, J = 9 Hz), 131.3 (CH, d, J = 2 Hz), 128.3 (C), 127.5 (C, d, J = 16 Hz), 122.4 (CH), 121.7 (C, d, J = 13 Hz), 119.2 (CH), 115.3 (CH), 110.5 (CP, d, J = 190 Hz), 108.2 (CH), 62.2 ($2CH_2$, d, J = 5 Hz), 18.1 (CH_3, d, J = 4 Hz), 16.3 ($2CH_3$, d, J = 6 Hz). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 17.25 (s). IR (neat, cm^{-1}) 2980 (w), 1533 (s), 1466 (m), 1408 (m), 1365 (m), 1258 (s), 1230 (s), 1006 (s), 959 (s), 790 (s), 698 (m), 557 (s), 537 (s). LC-MS (ESI) m/z = 397.0 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{17}H_{19}N_2O_5PCl$ 397.0720, found 397.0725 (Δ = 1.3 ppm).

Diethyl (2-bromo-6-methylpyrrolo[1,2-*a*][1,5]naphthyridin-5-yl)phosphonate, (1j): 1.4 g (71%, 5 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.73 (1H, d, J = 2.0 Hz), 8.26 (1H, app t, J = 2.0 Hz), 7.85 (1H, dd, J = 1.6, 2.4 Hz), 6.90 (1H, dd, J = 1.2, 4.0 Hz), 6.88 (1H, dd, J = 2.8, 4.0 Hz), 4.27 (2H, m), 4.19 (2H, m), 2.95 (3H, d, J = 2.8 Hz), 1.32 (6H, t, J = 7.2 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 145.8 (CH), 142.9 (C, d, J = 11 Hz), 140.3 (C, d, J = 8 Hz), 131.5 (C, d, J = 19 Hz), 128.3 (C, d, J = 10 Hz), 123.5 (CH), 117.5 (C), 115.8 (CH), 115.2 (CH), 114.8 (C, d, J = 190 Hz), 107.7 (CH), 62.1 ($2CH_2$, d, J = 6 Hz), 17.7 (CH_3, d, J = 4 Hz), 16.4 ($2CH_3$, d, J = 7 Hz). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 17.49 (s). IR (neat, cm^{-1}) 2979 (w), 1584 (w), 1471 (m), 1305 (m), 1224 (m), 1102 (m), 1021 (s), 960 (s), 717 (s), 602 (s), 555 (s). LC-MS (ESI) m/z = 396.9 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{16}H_{19}N_2O_3PBr$ 397.0317, found 397.0321 (Δ = 1.0 ppm).

Diethyl (1-(3,5-difluoro-2-(1*H*-pyrrol-1-yl)phenyl)-3-methylbuta-1,2-dien-1-yl)phosphonate, (2f): 1.8 g (83%, 5 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.21 (1H, ddt, J = 8.9, 3.0, 1.6 Hz), 6.90−6.82 (1H, m), 6.75 (2H, td, J = 2.1, 1.1 Hz), 6.25 (2H, t, J = 2.1 Hz), 4.14−3.96 (4H, m), 1.48 (6H, d, J = 6.7 Hz), 1.28 (6H, td, J = 7.1, 0.7 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 208.0 (C, d, J = 3 Hz), 161.0 (CF, ddd, J = 251, 13, 2 Hz), 158.3 (CF, dd, J = 252, 13 Hz), 134.5 (C, t, J = 10.1 Hz), 124.9 (C, ddd, J = 12, 8, 4 Hz), 123.0 (2CH), 112.9 (CH, dt, J = 23, 3 Hz), 109.1 (2CH), 103.8 (CH, ddd, J = 26, 25, 2 Hz), 99.0 (C, d, J = 15 Hz), 89.3 (CP, d, J = 199 Hz), 62.8 ($2CH_2$, d, J = 7 Hz), 19.1 ($2CH_3$, d, J = 7 Hz), 16.3 ($2CH_3$, d, J = 7 Hz). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 14.63 (s). ^{19}F NMR ($CDCl_3$, 367 MHz) δ −109.7 (d, J = 8 Hz), −117.5 (d, J = 8 Hz). IR (neat, cm^{-1}) 2989 (w), 1963 (w), 1597 (m), 1509 (s), 1440 (m), 1299 (m), 1234 (s), 1140 (m), 1015 (s), 973 (s), 955 (s), 735 (s), 611 (s), 600 (s), 565 (s). LC-MS (ESI) m/z = 382.0 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{19}H_{23}NO_3PF_2$ 382.1384, found 382.1376 (Δ = −2.1

DOI: 10.1021/acs.joc.5b01982
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ppm). mp 90 °C (decomposition). Single crystal X-ray data: CCDC 1411502; $P2_1/n$; a = 8.01820(10) Å, b = 14.4498(2) Å, c = 16.8318(2) Å; α = 90°, β = 100.2909(17)°, γ = 90°.

(1-(3,5-Difluoro-2-(1*H*-pyrrol-1-yl)phenyl)-3-methylbuta-1,2-dien-1-yl)diphenylphosphine oxide, (2f′): 2.0 g (90%, 5 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.71−7.62 (4H, m), 7.54−7.47 (2H, m), 7.47−7.39 (4H, m), 7.09 (1H, ddt, J = 9.1, 3.0, 1.5 Hz), 6.79 (1H, dddd, J = 9.1, 8.1, 2.9, 0.8 Hz), 6.73 (2H, td, J = 2.1, 0.7 Hz), 6.28 (2H, t, J = 2.1 Hz), 1.18 (6H, d, J = 6.1 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 209.6 (C, d, J = 5 Hz), 161.1 (CF, ddd, J = 251, 13, 2 Hz), 158.8 (CF, dd, J = 252, 13 Hz), 134.8−134.5 (C, m), 131.9 (2CH, d, J = 3 Hz), 131.9 (2CP, d, J = 106 Hz), 131.7 (2 × 2CH, d, J = 10 Hz), 128.3 (2 × 2CH, d, J = 12 Hz), 125.1 (C, m), 123.3 (2CH), 112.8 (CH, dt, J = 24, 3 Hz), 109.2 (2CH), 103.7 (CH, t, J = 26 Hz), 99.5 (C, d, J = 13 Hz), 93.3 (CP, d, J = 103 Hz), 18.9 ($2CH_3$, d, J = 6 Hz). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 30.59 (s). ^{19}F NMR ($CDCl_3$, 367 MHz) δ −108.8 (d, J = 8 Hz), −117.3 (d, J = 8 Hz). IR (neat, cm^{-1}) 3019 (w), 1956 (w), 1592 (w), 1510 (m), 1437 (m), 1294 (m), 1184 (s), 1140 (m), 893 (m), 739 (s), 696 (s), 593 (s), 535 (s), 520 (s). LC-MS (ESI) m/z = 446.1 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{27}H_{23}NOPF_2$ 446.1485, found 446.1482 (Δ = −0.7 ppm). mp 145 °C (decomposition).

Diethyl (7,9-difluoro-4-isopropylpyrrolo[1,2-*a*]quinolin-5-yl)phosphonate, (1k): 1.6 g (83%, 5 mmol scale). ^{1}H NMR (700 MHz, $CDCl_3$) δ 8.63 (1H, td, J = 2.8, 11.9 Hz), 8.29 (1H, dt, J = 2.7, 1.1 Hz), 7.12 (1H, dt, J = 4.1, 1.2 Hz), 7.03 (1H, ddd, J = 13.3, 7.6, 2.8 Hz), 6.85 (1H, dd, J = 4.1, 2.9 Hz), 4.60 (1H, dsept, J = 7.1, 0.6 Hz), 4.22 (2H, ddq, J = 10.2, 8.0, 7.1 Hz), 4.10 (2H, ddq, J = 10.2, 8.0, 7.1 Hz), 1.55 (6H, d, J = 7.1 Hz), 1.33 6H, (td, J = 7.1, 0.6 Hz). ^{13}C NMR (175 MHz, $CDCl_3$) δ 157.2 (CF, dd, J = 13, 242 Hz), 152.4 (CF, ddd, J = 3, 13, 247 Hz), 151.8 (C, d, J = 12 Hz), 128.2 (C, d, J = 18 Hz), 127.2 (C, ddd, J = 16, 11, 3 Hz), 119.8 (CH, d, J = 25 Hz), 119.2−118.4 (C, m), 113.2 (CH, dd, J = 5, 1 Hz), 110.3 (CP, td, J = 3, 190 Hz), 110.2 (CH, ddd, J = 26, 4, 2 Hz), 108.9 (CH, d, J = 1 Hz), 103.0 (CH, dd, J = 28, 26 Hz), 62.0 ($2CH_2$, d, J = 5 Hz), 31.4 (CH, d, J = 5 Hz), 21.8 ($2CH_3$), 16.3 ($2CH_3$, d, J = 7 Hz). ^{31}P NMR ($CDCl_3$, 283 MHz) δ 18.90 (s). ^{19}F NMR ($CDCl_3$, 367 MHz) δ −115.4 (d, J = 7 Hz), −118.6 (m). IR (neat, cm^{-1}) 2981 (w), 1628 (w), 1595 (m), 1442 (m), 1339 (m), 1247 (s), 1128 (m), 1044 (s), 1016 (s), 958 (s), 716 (s), 558 (s). LC-MS (ESI) m/z = 381.4 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{19}H_{23}NO_3PF_2$ 382.1384, found 382.1379 (Δ = −1.3 ppm).

(7,9-Difluoro-4-isopropylpyrrolo[1,2-*a*]quinolin-5-yl)-diphenylphosphine oxide, (1l): 0.9 g (41%, 5 mmol scale). ^{1}H NMR (700 MHz, $CDCl_3$) δ 8.31 (1H, dt, J = 2.8, 1.2 Hz), 8.14 (1H, dddd, J = 11.7, 2.8, 1.8, 0.8 Hz), 7.75 (4H, ddd, J = 12.3, 8.3, 1.3 Hz), 7.57−7.51 (2H, m), 7.50−7.44 (4H, m), 6.98−6.94 (2H, m,), 6.84 (1H, dd, J = 4.1, 2.9 Hz), 3.62 (1H, dsept, J = 7.0, 1.4 Hz), 1.07 (6H, d, J = 7.0 Hz). ^{13}C NMR (175 MHz, $CDCl_3$) δ 156.7 (CF, dd, J = 243, 13 Hz), 152.4 (CF, ddd, J = 249, 13, 2 Hz), 150.2 (C, d, J = 9 Hz), 135.1 (2CP, d, J = 105 Hz), 131.8 (2CH, d, J = 3 Hz), 131.6 (2 × 2CH, d, J = 10 Hz), 128.8 (2 × 2CH, d, J = 13 Hz), 128.3 (C, d, J = 12 Hz), 127.9 (C, td, J = 11, 3 Hz), 120.0 (CH, d, J = 24 Hz), 119.2−118.7 (C, m), 113.2 (CH, d, J = 4 Hz), 113.1 (CP, d, J = 107 Hz), 110.8 (CH, dt, J = 26, 4 Hz), 108.4 (CH, d, J = 1 Hz), 103.0 (CH, dd, J = 28, 26 Hz), 33.4 (CH, d, J = 8 Hz), 21.0 ($2CH_3$). ^{31}P NMR ($CDCl_3$, 283 MHz) δ 32.06 (s). ^{19}F NMR ($CDCl_3$, 367 MHz) δ −115.4 (d, J = 7 Hz), −118.6 (m). IR (neat, cm^{-1}) 2959 (w), 1597 (m), 1473 (m), 1436 (s), 1179 (s), 1115 (m), 998 (m), 769 (m), 720 (s), 690 (s), 592 (m), 527 (s). LC-MS (ESI) m/z = 445.4 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{27}H_{23}NOPF_2$ 446.1485, found 446.1492 (Δ = 1.6 ppm).

(7,9-Difluoro-4-(propan-2-ylidene)-4,5-dihydropyrrolo[1,2-*a*]quinolin-5-yl)diphenylphosphine oxide, (1l′): 0.8 g (37%, 5 mmol scale). ^{1}H NMR (700 MHz, $CDCl_3$) δ 7.89−7.83 (2H, m), 7.58−7.52 (1H, m), 7.49−7.44 (2H, m), 7.31 (1H, tt, J = 7.0, 1.6 Hz), 7.22−7.14 (4H, m), 7.01 (1H, dq, J = 8.4, 2.0 Hz), 6.85 (1H, dq, J = 4.0, 1.4 Hz), 6.79 (1H, ddt, J = 13.0, 8.3, 2.4 Hz), 6.30 (1H, dd, J = 3.8, 1.4 Hz), 6.23 (1H, t, J = 3.3 Hz), 4.75 (1H, d, J = 20.2 Hz), 1.97 (3H, d, J = 5.7 Hz), 1.41 (3H, d, J = 3.7 Hz). ^{13}C NMR (175 MHz, $CDCl_3$) δ 157.9 (CF, ddd, J = 247, 12, 4 Hz), 151.9 (CF, ddd, J = 250, 12, 4 Hz), 132.9 (C, d, J = 11 Hz), 132.2 (2CH, d, J = 8 Hz), 132.0 (CH, d, J = 3 Hz), 131.2 (CH, d, J = 3 Hz), 130.7 (2CH, d, J = 9 Hz), 129.8 (CP, d, J = 161 Hz), 129.2 (CP, d, J = 159 Hz), 128.3 (C, d, J = 2 Hz), 127.9 (2CH, d, J = 11 Hz), 127.8 (2CH, d, J = 12 Hz), 127.6 (C, ddd, J = 9, 6, 3 Hz), 121.6 (C, dt, J = 9, 4 Hz), 119.4 (CH, d, J = 15 Hz), 115.2 (C, d, J = 7 Hz), 112.8 (CH, dt, J = 23, 4 Hz), 110.4 (CH, d, J = 3 Hz), 110.0 (CH), 104.3 (CH, ddd, J = 26, 25, 3 Hz), 49.9 (CH, d, J = 58 Hz), 23.4 (CH_3, d, J = 3 Hz), 21.0 (CH_3, d, J = 3 Hz). ^{31}P NMR ($CDCl_3$, 283 MHz) δ 27.48 (s). ^{19}F NMR ($CDCl_3$, 367 MHz) δ −115.4 (m), −122.5 (m). IR (neat, cm^{-1}) 2956 (w), 1625 (w), 1507 (s), 1437 (s), 1302 (m), 1185 (s), 1125 (s), 831 (m), 716 (s), 695 (s), 519 (s). LC-MS (ESI) m/z = 446.0 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{27}H_{23}NOPF_2$ 446.1485, found 446.1483 (Δ = −0.4 ppm).

Diethyl (1-(5-cyano-2-(1*H*-pyrrol-1-yl)phenyl)3-methylbuta-1,2-dien-1-yl)phosphonate, (2g): 1.7 g (90%, 5 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (1H, t, J = 1.7 Hz), 7.58 (1H, ddd, J = 8.2, 1.9, 1.0 Hz), 7.31 (1H, d, J = 8.0 Hz), 6.93 (2H, t, J = 2.2 Hz), 6.28−6.22 (2H, t, J = 2.2 Hz), 4.16−4.00 (4H, m), 1.44 (6H, d, J = 6.7 Hz), 1.28 (6H, td, J = 7.1, 0.7 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 208.1 (C, d, J = 4 Hz), 143.8 (C, d, J = 7 Hz), 135.0 (CH, d, J = 2 Hz), 132.0 (CH, d, J = 1 Hz), 130.5 (C, d, J = 10 Hz), 127.4 (CH), 122.0 (2CH), 118.1 (CN), 110.5 (C, d, J = 2 Hz), 110.3 (2CH), 99.2 (C, d, J = 16 Hz), 89.6 (CP, d, J = 201 Hz), 62.9 (2CH, d, J = 7 Hz), 18.6 ($2CH_3$, d, J = 7 Hz), 16.3 ($2CH_3$, d, J = 7 Hz). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 14.47 (s). IR (neat, cm^{-1}) 2978 (w), 2230 (m), 1955 (w), 1601 (w), 1504 (s), 1333 (m), 1238 (s), 1113 (m), 1049 (m), 1018 (s), 964 (s), 724 (s), 571 (m). LC-MS (ESI) m/z = 371.0 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{20}H_{24}N_2O_3P$ 371.1525, found 371.1517 (Δ = −2.2 ppm).

3-(1-(Diphenylphosphoryl)-3-methylbuta-1,2-dien-1-yl)-4-(1*H*-pyrrol-1-yl)benzonitrile, (2g′): 1.9 g (88%, 5 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.74−7.64 (4H, m), 7.59−7.52 (4H, m), 7.50−7.43 (4H, m), 7.32 (1H, d, J = 8.0 Hz), 6.96−6.89 (2H, t, J = 2.1 Hz), 6.29 (2H, t, J = 2.1 Hz,), 1.22 (6H, d, J = 6.0 Hz,). ^{13}C NMR (101 MHz, $CDCl_3$) δ 209.3 (C, d, J = 6 Hz), 144.5 (C, d, J = 5 Hz), 134.6 (CH, d, J = 2 Hz), 132.1 (2CH, d, J = 3 Hz), 132.0 (CH), 131.8 (2CP, d, J = 106 Hz), 131.7 (2 × 2CH, d, J = 10 Hz), 131.2 (C, d, J = 8 Hz), 128.4 (2 × 2CH, d, J = 12 Hz), 128.1 (CH), 122.5 (2CH), 118.0 (CN), 111.0 (C), 110.0 (2CH), 99.4 (C, d, J = 13 Hz), 93.6 (CP, d, J = 103 Hz), 18.6 ($2CH_3$, d, J = 5 Hz). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 29.71 (s). IR (neat, cm^{-1}) 3058 (w), 2230 (m), 1956 (w), 1500 (m), 1436 (m), 1329 (m), 1182 (m), 1117 (m), 1100 (m), 916 (m), 723 (s), 693 (s), 546 (s), 533 (s). LC-MS (ESI) m/z = 435.1 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{28}H_{24}N_2OP$ 435.1626, found 435.1622 (Δ = −0.9 ppm).

Diethyl (7-cyano-4-isopropylpyrrolo[1,2-*a*]quinolin-5-yl)-phosphonate, (1m): 1.4 g (78%, 5 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.38 (1H, d, J = 1.7 Hz), 7.93−7.86 (2H, m), 7.70 (1H, dd, J = 8.6, 1.8 Hz), 7.11 (1H, d, J = 3.6 Hz), 6.91 (1H, dd, J = 4.1, 2.9 Hz), 4.64 (1H, pd, J = 7.1, 1.0 Hz), 4.25 (2H, ddq, J = 10.1, 7.9, 7.1 Hz), 4.12 (2H, ddq, J = 10.1, 8.0, 7.1 Hz), 1.54 (6H, d, J = 7.1 Hz), 1.34 (6H, td, J = 7.0, 0.6 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 151.4 (C, d, J = 12 Hz), 134.4 (CH), 134.2 (C, d, J = 13 Hz), 129.9 (CH), 128.2 (C, d, J = 18 Hz), 123.8 (C, d, J = 15 Hz), 119.2 (CN), 115.0 (CH, d, J = 1 Hz), 114.6 (CH, d, J = 1 Hz), 114.2 (CH), 110.7 (CP, d, J = 190 Hz), 110.2 (CH), 107.2 (C), 62.2 ($2CH_2$, d, J = 5 Hz), 31.3 (CH, d, J = 5 Hz), 21.7 ($2CH_3$), 16.3 ($2CH_3$, d, J = 7 Hz). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 18.38 (s). IR (neat, cm^{-1}) 2933 (w), 2224 (m), 1606 (m), 1512 (s), 1436 (s), 1346 (s), 1179 (s), 1119 (m), 822 (m), 700 (s), 596 (m), 524 (s), 504 (s). LC-MS (ESI) m/z = 371.0 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{20}H_{24}N_2O_3P$ 371.1525, found 371.1516 (Δ = −2.4 ppm).

5-(Diphenylphosphoryl)-4-isopropylpyrrolo[1,2-*a*]-quinoline-7-carbonitrile, (1n): 0.8 g (38%, 5 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.92 (1H, d, J = 1.7 Hz), 7.96 (1H, dd, J = 3.1, 1.2 Hz), 7.91 (1H, dd, J = 8.7, 1.5 Hz), 7.78−7.71 (4H, m), 7.62 (1H, dd, J = 8.7, 1.8 Hz), 7.59−7.54 (2H, m), 7.52−7.46 (4H, m), 6.95 (1H, dd, J = 4.1, 1.2 Hz), 6.90 (1H, dd, J = 4.0, 2.9 Hz), 3.62 (1H,

DOI: 10.1021/acs.joc.5b01982
J. Org. Chem. 2015, 80, 10806−10816

pd, J = 7.0, 1.5 Hz), 1.07 (6H, d, J = 6.9 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 149.7 (C, d, J = 9 Hz), 134.9 (2CP, d, J = 105 Hz), 134.5 (CH, d, J = 4 Hz), 134.4 (C, d, J = 9 Hz), 132.1 (2CH, d, J = 3 Hz), 131.6 (2 × 2CH, d, J = 10 Hz), 129.9 (CH), 128.9 (2 × 2CH,d, J = 12 Hz), 128.3 (C, d, J = 12 Hz), 124.6 (C, d, J = 11 Hz), 118.7 (CN), 115.2 (CH), 114.6 (CH), 114.4 (CH), 113.7 (CP, d, J = 105 Hz), 109.7 (CH), 106.7 (C), 33.4 (CH, d, J = 8 Hz), 20.8 ($2CH_3$). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 31.96 (s). IR (neat, cm^{-1}) 2935 (w), 2227 (m), 1604 (w), 1482 (m), 1438 (m), 1166 (m), 1116 (m), 1099 (m), 908 (m), 725 (s), 691 (s), 524 (s). LC-MS (ESI) m/z = 434.7 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{28}H_{24}N_2OP$ 435.1626, found 435.1619 (Δ = −1.6 ppm).

5-(Diphenylphosphoryl)-4-(propan-2-ylidene)-4,5dihydropyrrolo[1,2-*a*]quinoline-7-carbonitrile, (1n′): 0.7 g (32%, 5 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.88−7.80 (2H, m), 7.63 (1H, t, J = 2.2 Hz), 7.60−7.53 (1H, m), 7.52−7.44 (3H, m), 7.35−7.29 (1H, m), 7.25−7.21 (2H, m), 7.20−7.13 (2H, m), 7.08 (1H, d, J = 8.4 Hz), 6.64 (1H, dd, J = 3.1, 1.4 Hz), 6.34 (1H, dd, J = 3.7, 1.4 Hz), 6.31 (1H, t, J = 3.3 Hz), 4.76 (1H, d, J = 19.4 Hz), 1.97 (3H, d, J = 5.7 Hz), 1.44 (3H, d, J = 3.8 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.5 (C, d, J = 4 Hz), 134.0 (C, d, J = 11 Hz), 133.8 (CH, d, J = 5 Hz), 132.4 (CH, d, J = 3 Hz), 132.2 (2CH, d, J = 7.9 Hz), 132.1 (CH), 131.4 (CH, d, J = 3 Hz), 130.8 (2CH, d, J = 9 Hz), 130.0 (CP, d, J = 95 Hz), 128.9 (CP, d, J = 95 Hz), 128.9 (C, d, J = 2 Hz), 128.1 (2CH, d, J = 11 Hz), 127.9 (2CH, d, J = 12 Hz), 124.3 (C, d, J = 7 Hz), 118.5 (CN), 115.7 (CH, d, J = 3 Hz), 115.3 (CH), 114.7 (C, d, J = 7 Hz), 112.3 (CH), 111.6 (CH), 107.1 (C, d, J = 3 Hz), 48.6 (CH, d, J = 58 Hz), 23.6 (CH_3), 21.3 (CH_3). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 27.45 (s). IR (neat, cm^{-1}) 2977 (w), 2224 (m), 1602 (w), 1428 (m), 1354 (m), 1229 (m), 1164 (m), 1014 (s), 935 (s), 818 (s), 714 (s), 612 (s), 547 (s). LC-MS (ESI) m/z = 435.1 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{28}H_{24}N_2OP$ 435.1626, found 435.1611 (Δ = −3.4 ppm).

Diethyl (1-(5-bromo-2-(1*H*-pyrrol-1-yl)phenyl)-3-methylbuta-1,2-dien-1-yl)phosphonate, (2h): 1.9 g (90%, 5 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.79−7.73 (1H, m), 7.45 (1H, ddd, J = 8.4, 2.3, 1.2 Hz), 7.12 (1H, dd, J = 8.4, 0.9 Hz), 6.89 (2H, t, J = 2.2 Hz), 6.24 (2H, t, J = 2.2 Hz), 4.19−4.00 (4H, m,), 1.47 (6H, d, J = 6.7 Hz), 1.30 (6H, t, J = 7.1 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 208.1 (C, d, J = 4 Hz), 139.3 (C, d, J = 7 Hz), 133.6 (CH, d, J = 3 Hz), 131.5 (C), 131.4 (CH, d, J = 2 Hz), 128.5 (CH), 122.3 (2CH), 120.5 (C, d, J = 2 Hz), 109.3 (2CH), 98.5 (C, d, J = 16 Hz), 89.7 (CP, d, J = 199 Hz), 62.8 ($2CH_2$, d, J = 7 Hz), 18.8 ($2CH_3$, d, J = 7 Hz), 16.3 ($2CH_3$, d, J = 7 Hz). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 14.92 (s). IR (neat, cm^{-1}) 3109 (w), 2978 (w), 1965 (w), 1499 (s), 1327 (m), 1238 (s), 1113 (m), 1013 (s), 966 (s), 831 (m), 721 (s), 582 (s), 565 (s). LC-MS (ESI) m/z = 423.9 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{19}H_{24}NO_3PBr$ 424.0677, found 424.0684 (Δ = 1.7 ppm). mp 95 °C (decomposition).

(1-(5-Bromo-2-(1*H*-pyrrol-1-yl)phenyl)-3-methylbuta-1,2-dien-1-yl)diphenylphosphine oxide, (2h′): 2.1 g (87%, 5 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.72−7.64 (4H, m), 7.56−7.49 (2H, m), 7.45 (5H, m), 7.39 (1H, ddd, J = 8.4, 2.3, 0.9 Hz), 7.09 (1H, dd, J = 8.4, 0.7 Hz), 6.83 (2H, t, J = 2.1 Hz), 6.24 (2H, t, J = 2.1 Hz), 1.21 (6H, d, J = 6.0 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 209.3 (C, d, J = 6 Hz), 139.8 (C, d, J = 5 Hz), 133.4 (CH, d, J = 3 Hz), 132.1 (2CP, d, J = 106 Hz), 131.9 (C), 131.8 (2CH, m), 131.7 (2 × 2CH, d, J = 10 Hz), 131.3 (CH, d, J = 1 Hz), 129.1 (CH), 128.3 (2 × 2CH, d, J = 12 Hz), 122.8 (2CH), 120.9 (C, d, J = 2 Hz), 109.1 (2CH), 99 (C, d, J = 13 Hz), 93.9 (CP, d, J = 103 Hz), 18.7 ($2CH_3$, d, J = 6 Hz). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 29.78 (s). IR (neat, cm^{-1}) 3059 (w), 1955 (w), 1589 (m), 1437 (m), 1181 (s), 1117 (m), 1068 (m), 913 (m), 722 (s), 693 (s), 558 (s). LC-MS (ESI) m/z = 487.9 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{27}H_{24}NOPBr$ 488.0779, found 488.0767 (Δ = −2.5 ppm). mp 145 °C (decomposition).

Diethyl (7-bromo-4-isopropylpyrrolo[1,2-*a*]quinolin-5-yl)-phosphonate, (1o): 1.7 g (79%, 5 mmol scale). ^{1}H NMR (700 MHz, $CDCl_3$) δ 9.14 (1H, d, J = 2.1 Hz), 7.87 (1H, dd, J = 3.0, 1.3 Hz), 7.72 (1H, dd, J = 8.8, 2.0 Hz), 7.55 (1H, dd, J = 8.8, 2.2 Hz), 7.05 (1H, m), 6.85 (1H, dd, J = 4.0, 2.8 Hz), 4.64 (1H, sept., J = 7.1 Hz), 4.24 (2H, ddq, J = 10.1, 7.9, 7.1 Hz), 4.10 (2H, ddq, J = 10.1, 7.9, 7.1 Hz), 1.53 (6H, d, J = 7.1 Hz), 1.34 (6H, t, J = 7.1 Hz). ^{13}C NMR (175 MHz, $CDCl_3$) δ 150.7 (C, d, J = 12 Hz), 131.7 (CH, d, J = 2 Hz), 130.7 (C, d, J = 13 Hz), 130.1 (CH), 127.9 (C, d, J = 18 Hz), 125.1 (C, d, J = 15 Hz), 116.9 (C), 115.5 (CH), 113.5 (2CH, m), 110.4 (C, d, J = 188 Hz), 109.3 (CH), 61.9 ($2CH_2$, d, J = 5 Hz), 31.2 (CH, d, J = 5 Hz), 21.7 ($2CH_3$, d, J = 1 Hz), 16.3 ($2CH_3$, d, J = 7 Hz). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 19.01 (s). IR (neat, cm^{-1}) 2979 (w), 1475 (m), 1426 (m), 1224 (m), 1042 (s), 1015 (s), 957 (s), 804 (s), 730 (s), 550 (s). LC-MS (ESI) m/z = 424.0 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{19}H_{24}NO_3PBr$ 424.0677, found 424.0671 (Δ = −1.4 ppm).

7-Bromo-4-isopropylpyrrolo[1,2-*a*]quinolin-5-yldiphenylphosphine oxide, (1p): 0.9 g (36%, 5 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.48 (1H, dd, J = 2.1, 0.7 Hz), 7.90 (1H, dd, J = 2.9, 1.3 Hz), 7.81−7.68 (5H, m), 7.53 (2H, ddt, J = 8.3, 4.7, 1.5 Hz), 7.50−7.44 (5H, m), 6.92 (1H, dd, J = 4.1, 1.3 Hz), 6.84 (1H, dd, J = 4.1, 2.9 Hz), 3.77 (1H, dtd, J = 13.9, 6.9, 1.6 Hz), 1.11 (6H, d, J = 6.9 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 149.7 (C, d, J = 9 Hz), 135.4 (2CP, d, J = 105 Hz), 132.0 (CH, d, J = 4 Hz), 131.7 (2CH, d, J = 3 Hz), 131.6 (2 × 2CH, d, J = 10 Hz), 130.9 (C, d, J = 9.1 Hz), 130.1 (CH), 128.8 (2 × 2CH, d, J = 12 Hz), 128.1 (C, d, J = 12 Hz), 125.7 (C, d, J = 11 Hz), 116.2 (C), 115.7 (CH), 113.7 (CH), 113.6 (CH), 113.4 (CP, d, J = 107 Hz), 108.8 (CH), 33.2 (CH, d, J = 8 Hz), 21.0 ($2CH_3$). ^{31}P NMR ($CDCl_3$, 162 MHz) δ 31.23 (s). IR (neat, cm^{-1}) 2968 (w), 1476 (w), 1437 (w), 1326 (m), 1171 (m), 1115 (m), 1099 (m), 906 (m), 747 (s), 722 (s), 691 (s), 519 (s). LC-MS (ESI) m/z = 487.9 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{27}H_{24}NOPBr$ 488.0779, found 488.0782 (Δ = 0.6 ppm).

7-Bromo-4-(propan-2-ylidene)-4,5-dihydropyrrolo[1,2-*a*]-quinolin-5-yl)diphenylphosphine oxide, (1p′): 1.0 g (40%, 5 mmol scale). ^{1}H NMR (700 MHz, $CDCl_3$) δ 7.87−7.80 (2H, m), 7.54 (1H, td, J = 7.4, 1.4 Hz), 7.52 (1H, t, J = 2.4 Hz), 7.47−7.43 (2H, m), 7.33 (1H, dt, J = 8.5, 2.2 Hz), 7.30 (1H, tt, J = 7.3, 1.4 Hz), 7.23 (2H, ddd, J = 11.2, 8.1, 1.4 Hz), 7.17−7.12 (2H, m), 6.89 (1H, d, J = 8.5 Hz), 6.55 (1H, dd, J = 3.0, 1.4 Hz), 6.28 (1H, dd, J = 3.6, 1.4 Hz), 6.22 (1H, t, J = 3.3 Hz), 4.72 (1H, d, J = 20.4 Hz), 1.97 (3H, d, J = 5.7 Hz), 1.44 (3H, d, J = 3.7 Hz). ^{13}C NMR (175 MHz, $CDCl_3$) δ 135.3 (C, d, J = 5 Hz), 133.1 (C, d, J = 11 Hz), 132.9 (CH, d, J = 4 Hz), 132.3 (2CH, d, J = 8 Hz), 131.8 (CH, d, J = 3 Hz), 131.2 (CH, d, J = 3 Hz), 131.1 (CH, d, J = 3 Hz), 130.8 (2CH, d, J = 9 Hz), 130.2 (CP, d, J = 95 Hz), 129.2 (CP, d, J = 94 Hz), 128.3 (C, d, J = 2 Hz), 127.8 (2CH, d, J = 11 Hz), 127.7 (2CH, d, J = 12 Hz), 125.1 (C, d, J = 6 Hz), 116.6 (C, d, J = 4 Hz), 116.6 (CH, d, J = 3 Hz), 115.4 (C, d, J = 7 Hz), 114.9 (CH), 111.0 (CH), 110.7 (CH, d, J = 1 Hz), 48.8 (CH, d, J = 58 Hz), 23.5 (CH3, d, J = 3 Hz), 21.2 (CH_3, d, J = 3 Hz). ^{31}P NMR ($CDCl_3$, 283 MHz) δ 27.47 (s). IR (neat, cm^{-1}) 2933 (w), 2847 (w), 1499 (s), 1436 (s), 1342 (s), 1179 (s), 1107 (s), 901 (s), 806 (s), 697 (s), 592 (s), 524 (s), 508 (s). LC-MS (ESI) m/z = 487.9 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{27}H_{24}NOPBr$ 488.0779, found 488.0789 (Δ = −1.6 ppm).

Diethyl (1-(3,5-difluoro-2-(1*H*-pyrrol-1-yl)phenyl)-3-phenylbuta-1,2-dien-1-yl)phosphonate, (2r): 1.2 g (89%, 3 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37−7.27 (m, 3H), 7.25−7.16 (m, 3H), 6.95−6.86 (1H, m), 6.80 (2H, td, J = 2.1, 1.1 Hz), 6.29 (2H, t, J = 2.1 Hz), 4.19−3.94 (4H, m), 1.76 (3H, d, J = 6.7 Hz), 1.27 (3H, td, J = 7.2, 0.4 Hz), 1.25 (3H, td, J = 7.2, 0.4 Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 210.7 (C, d, J = 2 Hz), 161.0 (CF, ddd, J = 242, 12, 2 Hz), 158.4 (CF, dd, J = 253, 13 Hz), 134.0 (C, d, J = 8 Hz), 133.6 (C, t, J = 10 Hz), 128.6 (2CH, d, J = 1 Hz), 127.9 (CH, d, J = 2 Hz), 126.1 (2CH, d, J = 2 Hz), 125.0 (C, m), 123.1 (2CH), 112.9 (CH, dt, J = 23, 3 Hz), 109.4 (2CH), 104.2 (CH, t, J = 25 Hz), 104.1 (C, m), 93.8 (C, d, J = 197 Hz), 63.1 ($2CH_2$, t, J = 7 Hz), 16.3 (CH_3, d, J = 3 Hz), 16.3 (CH_3, d, J = 3 Hz), 15.4 (CH_3, d, J = 7 Hz). ^{31}P NMR ($CDCl_3$, 283 MHz) δ 13.99 (s). ^{19}F NMR ($CDCl_3$, 367 MHz) δ −109.3 (d, J = 7.4 Hz), −117.0 (d, J = 7.4 Hz). IR (neat, cm^{-1}) 2971 (m), 1945 (w), 1739 (s), 1597 (w), 1508 (m), 1438 (m), 1366 (s), 1230 (s), 1218 (s), 1047 (s), 1018 (s), 970 (m), 761 (m), 728 (m). LC-MS (ESI) m/z = 444.0 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{24}H_{25}NO_3PF_2$ 444.1540, found 444.1527 (Δ = −2.9 ppm).

DOI: 10.1021/acs.joc.5b01982
J. Org. Chem. 2015, 80, 10806−10816

Diethyl (4-ethyl-7,9-difluoropyrrolo[1,2-*a*]quinolin-5-yl)-phosphonate, (1q): 0.9 g (50%, 5 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.30 (1H, dt, J = 1.7, 0.7 Hz), 8.28−8.21 (1H, m), 7.05 (1H, ddd, J = 13.3, 7.7, 2.8 Hz), 6.96 (1H, dd, J = 3.3, 2.0 Hz), 6.86 (1H, dd, J = 4.1, 2.9 Hz), 4.22 (2H, ddq, J = 10.1, 7.9, 7.1 Hz), 4.08 (2H, ddq, J = 10.1, 8.3, 7.1 Hz), 3.51 (2H, qd, J = 7.4, 1.6 Hz), 1.40 (3H, t, J = 7.5 Hz), 1.32 (6H, td, J = 7.1, 0.5 Hz). ^{13}C NMR (175 MHz, $CDCl_3$) δ 157.2 (CF, dd, J = 242, 13 Hz), 152.6 (CF, ddd, J = 249, 13, 3 Hz), 148.2 (C, d, J = 13 Hz), 130.7 (C, d, J = 19 Hz), 127.0−126.5 (C, m), 120.8 (CH, d, J = 24 Hz), 118.9 (C, td, J = 9, 5 Hz), 114.0−113.4 (CH, m), 109.9 (CH, dt, J = 26, 3 Hz), 109.4 (CP, d, J = 192 Hz), 106.6 (CH), 102.9 (CH, dd, J = 28, 26 Hz), 61.8 ($2CH_2$, d, J = 5 Hz), 24.6 (CH_2, d, J = 4 Hz), 16.3 ($2CH_3$, d, J = 7 Hz), 15.9 (CH_3, d, J = 2 Hz). ^{31}P NMR ($CDCl_3$, 283 MHz) δ 17.85 (s). ^{19}F NMR ($CDCl_3$, 367 MHz) δ −115.6 (m), −118.6 (m). IR (neat, cm^{-1}) 2981 (w), 1630 (m), 1596 (s), 1508 (m), 1473 (m), 1441 (s), 1272 (s), 1250 (s), 1129 (m), 1018 (s), 959 (s), 786 (m), 720 (m), 559 (m). LC-MS (ESI) m/z = 368.5 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{18}H_{21}NO_3PF_2$ 368.1227, found 368.1230 (Δ = 0.8 ppm).

(*Z*)-Diethyl (4-ethylidene-7,9-difluoro-4,5-dihydropyrrolo-[1,2-*a*]quinolin-5-yl)phosphonate, (1q′): 0.6 g (35%, 5 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44 (1H, td, J = 3.4, 1.5 Hz), 6.98−6.91 (1H, m), 6.87 (1H, ddt, J = 12.4, 8.3, 2.6 Hz), 6.40−6.33 (1H, m), 6.28 (1H, dd, J = 3.6, 3.0 Hz), 6.14 (1H, pd, J = 7.1, 0.9 Hz), 4.38 (1H, d, J = 26.3 Hz), 3.99−3.84 (3H, m), 3.71 (1H, ddq, J = 10.0, 8.7, 7.0 Hz), 1.90 (3H, dd, J = 7.2, 6.2 Hz), 1.14 (3H, td, J = 7.1, 0.5 Hz), 1.10 (3H, t, J = 7.1 Hz).^{13}C NMR (101 MHz, $CDCl_3$) δ 159.1−156.3 (CF, m), 153.5−150.5 (CF, m), 131.0 (C, d, J = 3 Hz), 126.7−126.2 (C, m), 122.4 (CH, d, J = 13 Hz), 121.5 (C, m), 121.2 (C, d, J = 12 Hz), 119.6 (CH, d, J = 17 Hz), 113.2 (CH, ddd, J = 23, 5, 4 Hz), 111.0 (CH, d, J = 4 Hz), 104.9 (CH), 104.5 (CH, td, J = 26, 4 Hz), 63.0 (CH_2, d, J = 7 Hz), 62.8 (CH_2, d, J = 8 Hz), 41.4 (CHP, d, J = 135 Hz), 16.3 (CH_3, d, J = 6 Hz), 16.2 (CH_3, d, J = 6 Hz), 14.0 (CH_3, d, J = 3 Hz). ^{31}P NMR ($CDCl_3$, 283 MHz) δ 20.62 (s). ^{19}F NMR ($CDCl_3$, 367 MHz) δ −116.3 (m), −121.3 (m). IR (neat, cm^{-1}) 2981 (w), 1603 (w), 1505 (s), 1304 (m), 1247 (m), 1124 (m), 1019 (s), 968 (m), 710 (m), 582 (m). LC-MS (ESI) m/z = 368.5 (M+H). HR-MS (TOF-ESI$^+$) calculated for $C_{18}H_{21}NO_3PF_2$ 368.1227, found 368.1226 (Δ = −0.3 ppm).

Diethyl (7,9-difluoro-4-(1-phenylethyl)pyrrolo[1,2a]-quinolin-5-yl)phosphonate, (1r): 0.1 g (10%, 3 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.64 (1H, dt, J = 12.1, 2.3 Hz), 8.18 (1H, dd, J = 2.8, 1.5 Hz), 7.38−7.26 (4H, m), 7.22−7.14 (1H, m), 7.07 (1H, ddd, J = 13.3, 7.6, 2.8 Hz), 6.60 (1H, dd, J = 4.2, 2.9 Hz), 6.38 (1H, d, J = 4.2 Hz), 6.06 (1H, q, J = 7.0 Hz), 4.39−4.00 (4H, m), 1.88 (3H, d, J = 7.1 Hz), 1.37 (3H, t, J = 7.1 Hz), 1.27 (3H, t, J = 7.0 Hz). ^{13}C NMR (175 MHz, $CDCl_3$) δ 157.2 (CF, dd, J = 242, 14 Hz), 153.5−151.5 (CF, m), 149.7 (C, d, J = 12 Hz), 144.2 (C), 128.2 (2CH), 126.7 (2CH), 125.7 (CH), 119.6 (CH, d, J = 25 Hz), 119.1 (C, m), 113.5 (CH, d, J = 5 Hz), 111.6 (CP, d, J = 190 Hz), 110.3 (CH, dt, J = 26, 3 Hz), 110.2 (CH), 103.2 (CH, dd, J = 28, 26 Hz), 62.2 (CH_2, d, J = 3 Hz), 62.2 (CH_2, d, J = 3 Hz), 39.6 (CH, d, J = 5 Hz), 18.5 (CH_3, d, J = 1 Hz), 16.3 (CH_3, d, J = 7 Hz), 16.2 (CH_3, d, J = 7 Hz), 2 C resonances not found. ^{31}P NMR ($CDCl_3$, 283 MHz) δ 18.56 (s). ^{19}F NMR ($CDCl_3$, 367 MHz) δ −115.4 (m), −118.4 (m). IR (neat, cm^{-1}) 2981 (w), 1606 (w), 1508 (s), 1248 (m), 1049 (m), 1020 (s), 964 (m), 725 (s), 700 (s), 602 (m), 571 (m). LC-MS (ESI) m/z = 444.5 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{24}H_{25}NO_3PF_2$ 444.1540, found 444.1542 (Δ = 0.5 ppm).

(*E*)-Diethyl (7,9-difluoro-4-(1-phenylethylidene)-4,5-dihydropyrrolo[1,2-*a*]quinolin-5-yl)phosphonate, (1r′): 0.9 g (64%, 3 mmol scale). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35−7.27 (4H, m), 7.22−7.17 (2H, m), 7.03−6.96 (1H, m), 6.90 (1H, ddt, J = 12.2, 8.4, 2.6 Hz), 6.00 (1H, dd, J = 3.8, 3.0 Hz), 5.26−5.18 (1H, m), 4.52 (1H, d, J = 25.6 Hz,), 4.01−3.84 (3H, m), 3.70 (1H, ddq, J = 10.1, 8.7, 7.1 Hz), 2.26 (3H, d, J = 5.3 Hz), 1.17 (3H, t, J = 7.1 Hz), 1.14 (3H, t, J = 7.1 Hz). ^{13}C NMR (175 MHz, $CDCl_3$) δ 158.8−157.0 (CF, m), 153.0−150.9 (CF, m), 144.5 (C, d, J = 4 Hz), 135.4 (C, d, J = 13 Hz), 128.7 (C, d, J = 3 Hz), 128.5 (2CH), 128.2 (2CH, d, J = 4 Hz), 127.2 (C, t, J = 9 Hz), 126.9 (CH), 121.7 (C, d, J = 10 Hz), 118.6 (CH, d, J = 16 Hz), 116.6 (C, d, J = 11 Hz), 113.3−112.6 (CH, m), 111.0 (CH), 110.6 (CH), 104.9−104.1 (CH, m), 62.8 ($2CH_2$, app t, J = 8 Hz), 43.7 (CHP, d, J = 135 Hz), 22.2 (CH_3, d, J = 3 Hz), 16.4 (CH_3, d, J = 6 Hz), 16.3 (CH_3, d, J = 6 Hz). ^{31}P NMR ($CDCl_3$, 283 MHz) δ 20.91 (s). ^{19}F NMR ($CDCl_3$, 367 MHz) δ −116.0 (m), −121.9 (m). IR (neat, cm^{-1}) 2983 (w), 1609 (w), 1508 (s), 1250 (m), 1120 (m), 1022 (s), 966 (m), 700 (m), 602 (m). LC-MS (ESI) m/z = 444.7 (M+H). HR-MS (TOF-ES$^+$) calculated for $C_{24}H_{25}NO_3PF_2$ 444.1540, found 444.1527 (Δ = −2.9 ppm).

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.5b01982.

Crystallographic data (CCDC-1411501 and CCDC-1141502). (CIF)

General experimental methods, emission spectra from flow reactions, and spectra. (PDF)

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

Financial support from the Royal Society (to MB and IRB; UF130576) is gratefully acknowledged. Furthermore, we are grateful to Dr Dmitry Yufit (Durham University, Department of Chemistry) for solving the X-ray structures and Duncan Guthrie as well as Stacey Crane (Vapourtec) for lending the photospectrometer and helpful discussions.

■ REFERENCES

(1) (a) Leeson, P.; Springthorpe, B. *Nat. Rev. Drug Discovery* **2007**, *6*, 881. (b) Wess, G.; Urmann, M.; Stickenberger, B. *Angew. Chem., Int. Ed.* **2001**, *40*, 3341. (c) Hulme, C.; Gore, V. *Curr. Med. Chem.* **2003**, *10*, 51. (d) Wild, H.; Heimbach, D.; Huwe, C. *Angew. Chem., Int. Ed.* **2011**, *50*, 7452. (e) Silverman, R. B. *The Organic Chemistry of Drug Design and Drug Action*; Elsevier Academic Press: Burlington, MA, 2004. (f) Li, J. J. *Heterocyclic Chemistry in Drug Discovery*; Wiley: New York, 2013.

(2) (a) Manane, V.; Hannen, P.; Fürstner, A. *Chem. - Eur. J.* **2004**, *10*, 4556. (b) Hulcoop, D. G.; Lautens, M. *Org. Lett.* **2007**, *9*, 1761. (c) Chai, D. I.; Lautens, M. *J. Org. Chem.* **2009**, *74*, 3054. (d) Fürstner, A.; Mamane, V. *J. Org. Chem.* **2002**, *67*, 6264. (e) Kobayashi, K.; Takanohashi, A.; Himei, Y.; Sano, T.; Fukamachi, S.; Morikawa, O.; Konishi, H. *Heterocycles* **2007**, *71*, 2717.

(3) (a) Kumar, S.; Bawa, S.; Gupta, H. *Mini-Rev. Med. Chem.* **2009**, *9*, 1648. (b) Mukharjee, S.; Pal, M. *Curr. Med. Chem.* **2013**, *20*, 4386. (c) Sharma, V.; Kumar, V. *Med. Chem. Res.* **2014**, *23*, 3593. (d) Baumann, M.; Baxendale, I. R. *Beilstein J. Org. Chem.* **2013**, *9*, 2265.

(4) (a) Moonen, K.; Laureyn, I.; Stevens, C. V. *Chem. Rev.* **2004**, *104*, 6177. (b) McGrath, J. W.; Chin, J. P.; Quinn, J. P. *Nat. Rev. Microbiol.* **2013**, *11*, 412. (c) Eto, M. *Biosci., Biotechnol., Biochem.* **1997**, *61*, 1.

(5) (a) Ivanova, J. G. *Synth. Commun.* **2006**, *36*, 2231. (b) Altenbach, H. J.; Korff, R. *Tetrahedron Lett.* **1981**, *22*, 5175. (c) Yu, F.; Lian, X.; Zhao, J.; Yu, Y.; Ma, S. *J. Org. Chem.* **2009**, *74*, 1130. (d) He, G.; Yu, Y.; Fu, C.; Ma, S. *Eur. J. Org. Chem.* **2010**, *1*, 101. (e) Guo, H.; Qian, R.; Guo, Y.; Ma, S. *J. Org. Chem.* **2008**, *73*, 7934.

(6) (a) Gangadhararao, G.; Kotikalapudi, R.; Nagarjuna Reddy, M.; Kumara Swamy, C. K. *Beilstein J. Org. Chem.* **2014**, *10*, 996. (b) Phani

DOI: 10.1021/acs.joc.5b01982
J. Org. Chem. 2015, 80, 10806−10816

Pavan, M.; Kumara Swamy, C. K. *Synlett* **2011**, *2011*, 1288. (c) Rama Suresh, R.; Kumara Swamy, C. K. *J. Org. Chem.* **2012**, *77*, 6959.
(7) (a) Chakratvarty, M.; Kumara Swamy, C. K. *J. Org. Chem.* **2006**, *71*, 9128. (b) Sajina, K. V.; Kumara Swamy, C. K. *J. Org. Chem.* **2012**, *77*, 5345.
(8) Sajina, K. V.; Kumara Swamy, C. K. *J. Org. Chem.* **2012**, *77*, 8712.
(9) Chakratvarty, M.; Bhuvan; Kumar, N. N.; Sajina, K. V.; Kumara Swamy, C. K. *Eur. J. Org. Chem.* **2008**, *2008*, 4500.
(10) (a) Bhuvan Kumar, N. N.; Nagarjuna; Reddy, M.; Kumara Swamy, C. K. *J. Org. Chem.* **2009**, *74*, 5395. (b) Phani Pavan, M.; Nagarjuna Reddy, M.; Bhuvan; Kumar, N. N.; Kumara Swamy, C. K. *Org. Biomol. Chem.* **2012**, *10*, 8113.
(11) Similar exo- and endocyclic product distributions are reported in related cases (e.g., indoles and isocoumarines): see reference 6a.
(12) (a) Ley, S. V.; Fitzpatrick, D. E.; Ingham, R. J.; Myers, R. M. *Angew. Chem., Int. Ed.* **2015**, *54*, 3449. (b) Wegner, J.; Ceylan, S.; Kirschning, A. *Adv. Synth. Catal.* **2012**, *354*, 17. (c) Yoshida, J.; Takahasi, Y.; Nagaki, A. *Chem. Commun.* **2013**, *49*, 9896. (d) Webb, D.; Jamison, J. T. *Chem. Sci.* **2010**, *1*, 675. (e) Baumann, M.; Baxendale, I. R.; Ley, S. V. *Mol. Diversity* **2011**, *15*, 613.
(13) (a) Ingham, R. J.; Battilocchio, C.; Fitzpatrick, D. E.; Sliwinski, E.; Hawkins, J. M.; Ley, S. V. *Angew. Chem., Int. Ed.* **2015**, *54*, 144. (b) Jensen, K. F.; Reizman, B. J.; Newman, S. G. *Lab Chip* **2014**, *14*, 3206. (c) Hessel, V.; Kralisch, D.; Kockmann, N.; Noel, T.; Wang, Q. *ChemSusChem* **2013**, *6*, 746. (d) Yoshida, J.; Kim, H.; Nagaki, A. *ChemSusChem* **2011**, *4*, 331.
(14) (a) Gutmann, B.; Cantillo, D.; Kappe, C. O. *Angew. Chem., Int. Ed.* **2015**, *54*, 6688. (b) Baxendale, I. R. *J. Chem. Technol. Biotechnol.* **2013**, *88*, 519. (c) Pastre, J. C.; Browne, D. L.; Ley, S. V. *Chem. Soc. Rev.* **2013**, *42*, 8849. (d) McQuade, D. T.; Seeberger, P. H. *J. Org. Chem.* **2013**, *78*, 6384. (e) Wiles, C.; Watts, P. *Green Chem.* **2012**, *14*, 38.
(15) By passing clean product **1o** through the flow reactor both under thermal and photochemical conditions significant decomposition of 10−20% was observed.
(16) In parallel to these experiments, a number of common Lewis acids was screened as additives for challenging cyclisation reactions; however, the preliminary data obtained was not promising and hence not followed further.
(17) Shimizu, T. *Photochemistry of Allenes, CRC Handbook of Organic Photochemistry and Photobiology*, 2nd ed.; CRC Press LLC: Boca Raton, FL, 2004.

DOI: 10.1021/acs.joc.5b01982
J. Org. Chem. 2015, 80, 10806−10816