Received: 2 April 2020 | Revised: 8 May 2020 | Accepted: 9 May 2020

DOI: 10.1002/jhet.4027

WILEY

ARTICLE

Synthesis and optical characterization of new ketocyanine dyes with extended polymethine chaines

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Funding information
Generalitat de Catalunya, Grant/Award Number: 2014SGR837; Ministerio de Economía y Competitividad, Grant/Award Number: CTQ2012-36165; Ministry of Education and Science of the Russian Federation, Grant/Award Number: AAAA-A16-116071450048-3

Abstract

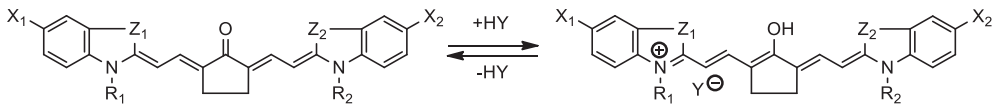
New symmetrical and unsymmetrical near-infrared absorbing ketocyanine-type dyes are synthesized and their optical characterization is done. The relationships between their structure and optical properties are discussed. The synthesized ketocyanine dyes show a positive solvatochromism and are poorly fluorescent. A new procedure for the preparation of *N*,*N*,*N*′,*N*′-tetramethylvinamidinium perchlorate, which was a very useful reagent for the synthesis of various heterocyclic compounds as well as for the preparation of cyanine dyes is developed.

1 | INTRODUCTION

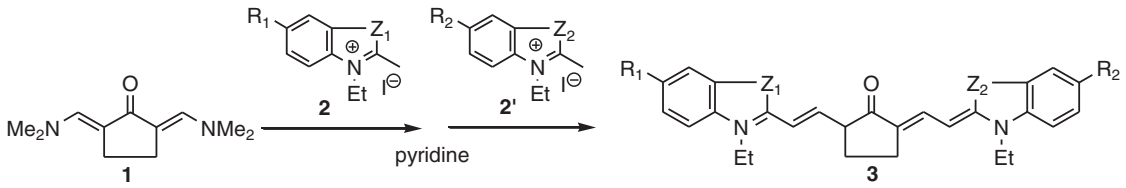
Cyanine dyes are excellent candidates for use as signaling recognition molecules of biological processes in bioassays or as labels, because of their structural variability and because their active absorption and emission wavelengths can be easily shifted depending on their structure. Many biological processes are accompanied by the pH-changes thus the long-wave absorbing acidochromic dyes are of special interest as reporters in analytical devices. Ketocyanines, first described in the works of Patonay,[1–3] appeared one of the most promising dyes for these applications due to high molar absoptivities ($>10^5$ L mol^{-1} cm^{-1}) of their protonated forms lying in NIR-region of the visible spectra (700-750 nm). It was also shown that the neutral forms of ketocyanines are strongly fluorescent.[4] The acid–base equilibrium of ketocyanine dyes is depicted on Scheme 1.

Later on ketocyanines found a wide scope of application such as reporters of biochemical reactions involving a pH variation reaction,[5,6] a change in the matrix polarity[7] or just as labels[8,9] with also proved enhanced properties when used in combination with nanomaterials.[10] They also were successively employed as probes or biomarkers to follow biomedical processes as their cyanine counterparts by locating some specific molecules or ions and transduce the biochemical processes into optical signals.[11–15] Owing to their significant fluorescence ketocyanines can find promising applications in fluorescence microscopy[16] and, especially, in newly developed MINFLUX nanoscopywhich opens new perspectives for imaging of biological objects with highly increased resolution and does not require extremally strong fluorescence of the labels.[17,18]

In course of our research regarding the preparation of NIR-absorbing acidochromic cyanine dyes we developed



SCHEME 1 Acid–base equilibrium for ketocyanines



SCHEME 2 Synthesis of ketocyanines **3**.[16] *Reagents and conditions*: **1** (1 mmol) and **2** (1 mmol) in pyridine (10 mL) 1 hour reflux; **2′** (1 mmol) 1 hour reflux

a general method for synthesis of ketocyanines **3**,[4,19] which were further successfully used for the construction of optical sensors (Scheme 2).[20,21]

This work was aimed on preparation of the vinylogues of ketocyanines 3 in order to obtain the new pH-sensitive chromophores with strong absorptivities shifted to the longer-wave region relative to parent dyes.

2 | RESULTS AND DISCUSSION

2.1 | Synthesis of the dyes

In order to synthesize the target ketocyanines with extended polymethine chains we planned to prepare the vinylogues of the *bis*-enaminoketone **1** (compounds **5a**, **5b**, and **7**) like it is shown on the Scheme 3 and then involve them in condensation with heterocyclic salts just similarly for synthesis of the dyes **3**[19] (Scheme 2).

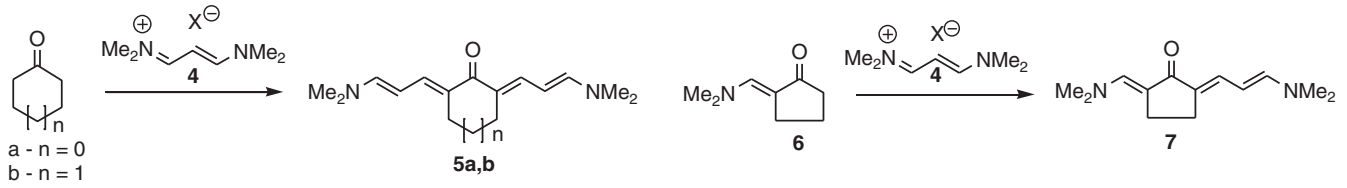
N,*N*,*N*′,*N*′-Tetramethylvinamidinium salt **4** proved to be a versatile reagent in the synthesis of various heterocyclic compounds, such as pyridines,[22–24] pyrimidines,[25,26] and pyrroles.[27,28] The main advantages of **4** over its analogs, substituted with other alkyl or aryl groups, are the minimal steric hindrance of the reaction site for the nucleophilic addition and the ease of the removal of liberating dimethylamine, that simplifies the separation of target product, but the use of this very attractive reagent is greatly limited by the absence of good procedures for its preparation. The existing approaches require utilization of hardly available and expensive dimethylaminoa crolein[29,30] **8** or reduction of 2-chlorosubstituted precursor **9**, which is prepared by laborious Vilsmeier-Haak formylation of chloroacetic acid[31,32] (Scheme 4).

It is well known that *N*,*N*′-diarylvinamidinium salts can be easily produced from 1,1,3,3-tetramethoxypropane **10** and aromatic amines in presence of perchloric acid.[33] Moreover it appeared possible to obtain perchlorate of vinamidinium salt **11** from piperidine and compound **10** in similar conditions (Scheme 5),[34] but the attempt to prepare the salt **4** following directly the same procedure failed.

Using dimethylamine as 4M methanolic solution and acetal **10** we made a series of experiments with different relations of amine to acid and found that when we used 1.4 equiv of perchloric acid (57%) the product **4** ($X = ClO_4^-$) crystallizes directly from the reaction mixture. After the optimization of procedure we formulated a very simple protocol yielding 62%-65% of salt **4** of high purity. Upon controlled heating the product melted at 120°C-122°C and decomposed with flash only above 200°C thus demonstrating sufficient safety for wide use in organic synthesis. The salt **4** can be converted into the piperidine and pyrrolidine analogs (**11** and **12**) in practically quantitative yield by 4-hour boiling in methanol with corresponding amines (Scheme 6).

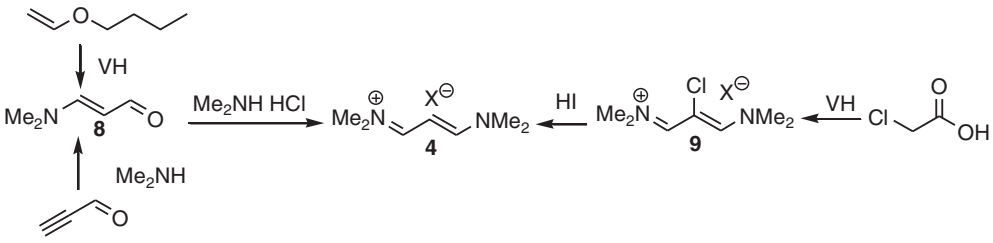
Subsequently the required intermediates **5a**,**b** were successfully obtained from cyclic ketones, 2 equiv of vinamidinium salt **4** and 4 equiv of sodium methylate on boiling in methanol–pyridine mixture for 6 hours in satisfactory yields (**5a**—71%, **5b**—54%). In the same way unsymmetrical precursor **7** was prepared from 2-dimethylaminomethylenecyclopentanone **6** and 1 equiv of vinamidinium salt **4** in 63% yield (Scheme 2). It would be noted that **5a** and **5b** were synthesized earlier from ketones and 1,1,3-trimethoxy-3-dimethylaminopropane even with greater yields (**5a**— 85%, **5b**—87%[35,36]), but the latter reagent was prepared again from dimethylaminoacrolein **8**[37] by laborious procedure that made our protocol more attractive.

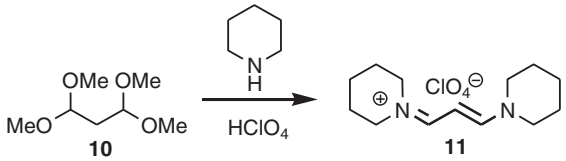
Finally from precursors **5a**,**b** and **7** and corresponding indoleninium salts **2a** and **2b**, following our usual procedure[4,19] we obtained target ketocyanines **13a-d** and **14** in moderate yields (Scheme 7). Yields of the products as well as all the data on their spectral and propolytic properties are listed in Table 1.



SCHEME 3 Proposed scheme for the synthesis of enaminoketones **5a**,**b** and **7**

SCHEME 4 Preparation of *N*,*N*,*N*′,*N*′-tetramethylvinamidinium salt **4**[29–32]





SCHEME 5 Preparation of *N*,*N*,*N*′,*N*′-dipentamethylenevinamidinium salt **11**.[34] *Reagents and conditions*: **10** (85 mmol), 57% $HClO_4$ (18 mL), and piperidine (170 mmol), 2 hours, rt

2.2 | Spectral properties and acid-base behavior of ketocyanines

As it was expected the absorbance maxima of the dyes **13a**-**d** and **14** were shifted to the long-wave region as compared with the unsubstituted indoketocyanine **3a** (Z = $C(CH_3)_3$, $R_1 = R_2 = H$) ($\lambda_{max(base)}$ = 566 nm, $\lambda_{max(acid)}$ = 717 nm), reported earlier.[1,2] The bathochromic shifts caused by introduction of additional vinylene fragment in the structure of the dye **3a** are considerably greater for the protonated form of ketocyanine **14** (94 nm) than for the neutral form (13 nm). Quite the same is observed on comparison of dyes **14** and **13a** also differing by additional vinylene group. In this case the difference in absorbance maxima are 92 nm for protonated forms and 37 nm for neutral ones.

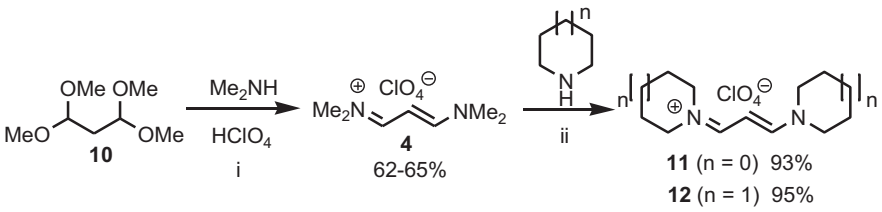
All newly synthesized ketocyanine dyes exhibit a reproducible response in the pH range, where the absorbance changes take place. An illustrative example of the pH-dependence of absorption spectra for dye **14** in ethanol is presented in Figure 1. The clear isosbestic points have been observed as the solution pH has been changed forth and back. It is obvious that the introduction of additional vinylenes does not influence their protolytic properties. Thus pK_a-meanings of the dyes **3a**, **14**, and **13a** bearing two, three, and four vinylene groups are 3.0, 2.9, and 3.0 respectively.

Fluorescence of dyes in 10^{-5} M ethanolic solution was tested for both acidic and basic forms. First, none of the dyes at the acidic form (solution at pH 2) showed any fluorescence in this form and in this medium, as well as the previously examined shorter-chain ketocyanines **3**.[20] In case for the basic forms (solution at pH 7.5) only week emission bonds ($\Phi < 0.07$) were observed on the contrary to the behavior of shorter-chain analogs which demonstrated significant fluorescence ($\Phi > 0.2$).[20] Results are presented in Table 2.

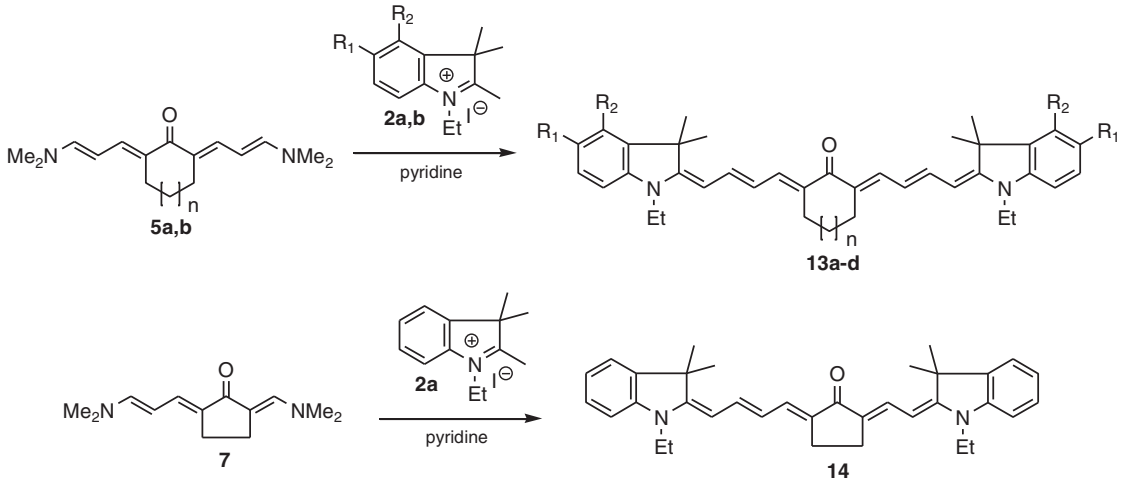
2.3 | Solvent effects on the absorption spectra of ketocyanine dyes

The absorption maxima of the basic form in toluene, dichloromethane (CH_2Cl_2), acetonitrile (CH_3CN), dimethylsulfoxide (DMSO), and ethanol (EtOH) are listed in Table 3. The absorbance of the maximum wavelength shifts to the red as the polarity of the solvent increases. This means that the studied ketocyanine dyes present a positive solvatochromism, as well as shorter-chain ones.[4]

A plot of the absorbance for all the ketocyanine dyes as a function of the Dimroth-Reichart empirical solvent parameter $E_T(30)$[38] is shown in Figure 2. There is a wide range of linear correlation for the absorbance in toluene, dichloromethane, dimethylsulfoxide, acetonitrile, and ethanol. For all dyes, acetonitrile is found to exhibit negative deviations from the common trend like it was observed for earlier examined shorter-chained ketocyanines.[4] This suggests that the nature of the interaction of the dyes with acetonitrile is somewhat different

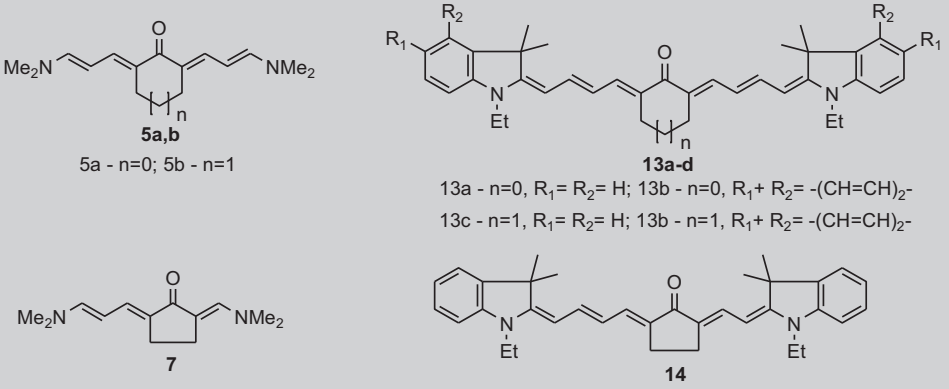


SCHEME 6 Synthesis of vinamidinium salt **4** and its analogs **11** and **12**. *Reagents and conditions*: (i) **10** (17.6 mmol), 57% $HClO_4$ (3.1 mL), and 4 M Me_2NH in MeOH (10 mL), 2d, rt; (ii) **4** (5 mmol), piperidine or pyrrolidine (11 mmol) in MeOH (5 mL), 4 hours reflux



SCHEME 7 Synthesis of ketocyanine dyes **13a-d** and **14**. *Reagents and conditions*: **2a** or **2b** (2 mmol) and **5a**, **5b**, or **7** (1 mmol) in pyridine (10 mL) 2 hours reflux

TABLE 1 Spectral and protolytic properties and yields of ketocyanines



Dye	*n*	R_1	R_2	λ_{max}, nm (base)	ε, L mol^{-1} cm^{-1} (base)	λ_{max} (acid)	ε (acid)	pK_a	Yield, %
5a	0	—	—	503.5	$3.12 \cdot 10^4$	604.5	$>7.0 \cdot 10^4$	—[a]	71
5b	1	—	—	486.0	$6.43 \cdot 10^4$	595.5	$>1.7 \cdot 10^5$	—[a]	54
7	—	—	—	444.0	$4.79 \cdot 10^4$	517.0	$>1.0 \cdot 10^5$	—[a]	63
13a	0	H	H	616.0	$5.49 \cdot 10^4$	903.0	$1.00 \cdot 10^5$	3.0	32
13b	0	—(CH═CH)$_2$—		632.0	$3.94 \cdot 10^4$	938.5	$7.21 \cdot 10^4$	3.1	43
13c	1	H	H	585.0	$5.42 \cdot 10^4$	893.0	$1.14 \cdot 10^5$	3.2	36
13d	1	—(CH═CH)$_2$—		606.0	$4.09 \cdot 10^4$	930.0	$8.08 \cdot 10^4$	3.5	48
14	—	—	—	579.0	$3.30 \cdot 10^4$	811.0	$7.10 \cdot 10^4$	2.9	44

[a]Unstable in acidic media.

from that in the case of the $E_T(30)$ scale. It appears that this solvent goes into a lower interaction with the dyes than it is predicted by the polarity parameters.

The synthesized dyes present very similar regression parameters which are reported in Table 4.

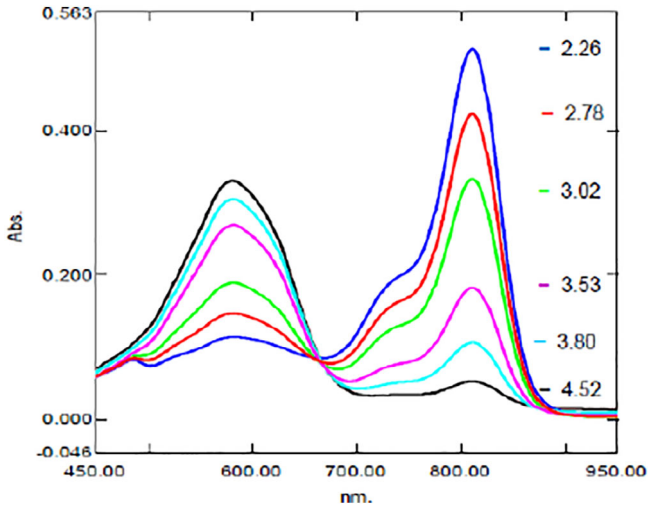


FIGURE 1 Absorbance spectra of dye **14** in ethanol at the indicated pH values

TABLE 2 Excitation wavelengths, emission wavelengths, Stokes' shifts, and quantum yields of the studied ketocyanine dyes in a $1{\cdot}10^{-5}$ M ethanolic solution

Dye	λ_{ex} (nm)	λ_{em} (nm)	$\Delta\lambda$ (nm)	Φ
5a	495.0	556.0	61.0	0.070
5b	480.5	542.5	62.0	0.047
7	433.0	494.0	61.0	0.010
13a	600.0	752.0	152.0	0.013
13b	600.0	760.0	160.0	0.012
13c	584.0	743.0	159.0	0.013
13d	600.0	762.0	162.0	0.012
14	574.5	701.0	126.5	0.028

3 | CONCLUSIONS

To sum up, we have synthesized a set of ketocyanine dyes whose protonated forms represented tetra- and pentacarbocyanines, absorbing in IR region and examined their spectral and acid–base properties. The synthesized ketocyanines probably can be converted to *meso*-chlorinated polymethine dyes capable to nucleophilic substitution thus resulting a library of new functionalized cyanines absorbing in infrared. We also developed a new simple and effective procedure for preparation of vinamidinium perchlorate, which was a very useful reagent in the synthesis of polymethine dyes and various heterocyclic compounds.

4 | EXPERIMENTAL SECTION

All starting materials have been purchased form Aldrich Chemical Co. MS-ES measurements have been made in a Bruker micrOTOF. ^{1}H and ^{13}C NMR spectra have been measured in a Bruker 400 Avance at 400.13 MHz and 100.6 MHz, respectively. Spectrophotometric studies were performed in a UV-Vis-NIR Scanning Spectrophotometer Shimadzu UV-3101PC and Shimadzu UV-1800. The absorption spectra were recorded between 1100 and 400 nm. Fluorescence spectra were obtained using a Fluorolog-3 Fluorometer (Horiba), recording the spectra from 10 nm above its excitation wavelength to 800 nm, and using a concentration in the order of 10^{-6} M of the dye in ethanol. Fluorescence quantum yields (Φ_f) were calculated relative to Rhodamine 6G (Sigma-Aldrich, $\Phi_f = 0.95 \pm 0.01$, $\lambda_{exc} = 490$ nm[39]) as $\Phi_f = \Phi_{f,\,st}\,(F/F_{st})\,(A_{st}/A)$;[40] where $\Phi_{f,\,st}$ is the fluorescence quantum yield of the standard, F the integrated area under the corrected fluorescence emission profile (quanta units), and A the absorbance intensity (always lower than 0.05). In the expression, the subscript st is referred to the standard compound.

Quaternary salts **1a**,**b** were prepared by quaternization of corresponding heterocycles by ethyl iodide.

TABLE 3 Maximum absorbance wavelengths of the ketocyanine dyes in solvents with different polarities and $E_T(30)$ values

No.	Toluene (E_T = 33.9)	CH_2Cl_2 (E_T = 41.1)	DMSO (E_T = 45.0)	CH_3CN (E_T = 46.0)	EtOH (E_T = 51.9)
13a	565	589	599.5	583	616
13b	583	607	616	607	632
13c	543	557	566.5	551	585
13d	559.5	577	586	569	606
14	539.5	557	566	554	579

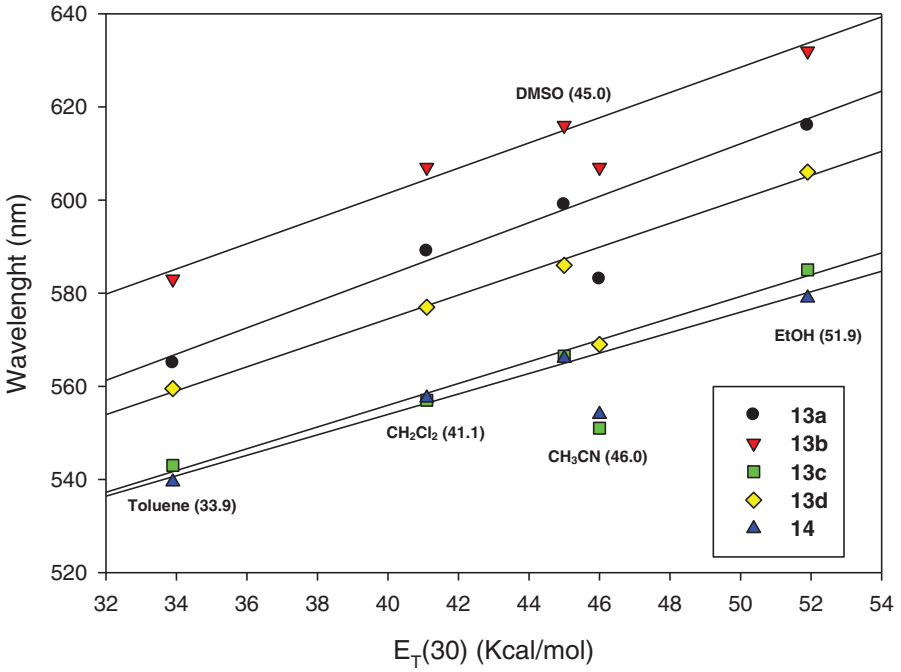


FIGURE 2 The maximum absorbance wavelength of ketocyanine dyes vs $E_T(30)$ solvent polarity values for toluene, dichloromethane, dimethylsulfoxide, acetonitrile, and ethanol

TABLE 4 Parameters resulting of the regression analysis of λ_{max} and $E_T(30)$ of the solvents ($\lambda_{max} = AE_T(30) + B$)

No.	*A*	*B*	*r*
13a	2.83	470.8	0.996
13b	2.83	470.8	0.996
13c	2.71	493.2	0.994
13d	2.57	471.7	0.999
14	2.20	465.8	0.998
3a[2]	3.21	395.6	0.983

Note: Points for acetonitrile are not included.

2-Dimethylaminomethylenecyclopentanone was obtained from cyclopentanone and dimethylformamide dimethylacetal.[41]

5 | PROCEDURES

5.1 | Preparation of vinamidinium salts

5.1.1 | *N,N,N′,N′*-Tetramethylvinamidinium perchlorate (4)

Perchloric acid (0.5 mL, 57%, $d = 1.47$) was added to 1,1,3,3-tetramethoxypropane 10 (2.9 g, 0.176 mmol) and, after staying at rt for 1.5 hours, more perchloric acid (2.6 mL) was added and the resulting solution was added dropwise to 4M solution of dimethylamine in methanol (10 mL) at cooling, keeping $t < 15°C$. The mixture was kept at rt for **2** days (partial crystallization occurred), diluted with 25 mL of ether and kept at −20°C for 3 hours. The resulting crystals were filtered, washed with cold methanol and ether, and dried on air. Light-yellow solid; m.p.: 120°C-122°C. Yield 2.55 g (62%); ^{1}H NMR (DMSO-d_6): δ 3.08 (s, 6H), 3.26 (s, 6H), 5.43 (t, $J = 11.5$ Hz, 1H), 7.73 (d, $J = 11.5$ Hz, 2H). ^{13}C NMR (DMSO-d_6): δ 38.31, 46.11, 90.42, 163.26. The experiment was repeated twice yielding 65% and 63% of 4. Scaling up to 100 mmol of 10 furnished 12.4 g of 4 (54%).

5.1.2 | 3-(1-Pyrrolidinyl)-2-propenylidene] pyrrolidinium perchlorate (11)

Vinamidinium salt **4** (1.14 g, 5 mmol) and pyrrolidine (780 mg, 11 mmol) were refluxed together in methanol (5 mL) for 4 hours. Then the volatiles were removed in vacuo and the residue was washed with ether. Yield of **11** 1.30 g (93%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 1.86-1.95 (m, 4H), 1.95-2.06 (m, 4H), 3.42 (t, $J = 7$ Hz, 4H), 3.70 (t, $J = 7$ Hz, 4H), 5.18 (t, $J = 12$ Hz, 1H), 7.91 (d, $J = 12$ Hz, 2H). ^{13}C NMR (100 MHz, DMSO-d_6): δ 24.82, 24.99, 48.49, 53.69, 92.24, 158.60.

5.1.3 | 3-(1-Piperidinyl)-2-propenylidene] piperidinium perchlorate (12)

In the same way from **4**, piperidine **12** was prepared. Yield 1.46 g (95%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 1.53-1.71 (m, 12H), 3.51-3.63 (m, 8H), 5.79 (t, $J = 11.5$ Hz, 1H), 7.69 (d, $J = 11.5$ Hz, 2H). ^{13}C NMR

(100 MHz, DMSO-d_6): δ 23.51, 25.51, 26.81, 47.20, 55.99, 89.32, 161.58.

5.2 | Preparation of enaminoketones

5.2.1 | *bis*-2,5-[3-(Dimethylamino)-2-propene-1-ylidene]-cyclopentanone (5a)

Cyclopentanone (420 mg, 5 mmol), viamidinium salt **4** (2.26 g, 10 mmol), 2M solution of sodium methylate in methanol (7 mL) and pyridine (3 mL) were kept for 6 hours at reflux. After cooling, the mixture was poured on ice (50 g). The resulting crystals were filtered, washed with water and dried on air. Brown solid; m.p.: 210°C-212°C (Lit.[42] m.p.: 215°C); Yield of **5a** 873 mg (71%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.59 (s, 4H), 2.88 (s, 12H), 4.97 (m, 2H), 6.68(d, J = 13 Hz, 2H), 7.11 (d, J = 12 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 23.96, 40.66, 96.02, 129.58, 133.72, 150.33, 192.88. ES-MS$^+$ $[M + H]^+$ 247.1832 (cal. 247.1810 $[M + H]^+$ for $C_{15}H_{23}N_2O$). λ_{max} (EtOH) = 503.5 nm (ε 3.12·10^4 L mol^{-1} cm^{-1}). λ_{max} (EtOH + HCl) = 604.5 nm.

5.2.2 | *bis*-2,6-[3-(Dimethylamino)-2-propene-1-ylidene]-cyclohexanone (5b)

In the same way from **4** and cyclohexanone **5b** was prepared. Brown solid; m.p.: 178°C-182°C (Lit.[42] m.p.: 185°C); Yield 702 mg (54%). ^{1}H NMR (DMSO-d_6): δ 1.63 (m, 2H), 2.39 (m, 4H), 2.89 (s, 12H), 5.01 (m, 2H), 6.92 (d, J = 13 Hz, 2H), 7.20 (d, J = 12 Hz, 2H). ^{13}C NMR ($CDCl_3$): δ 26.52, 40.63, 95.25, 124.44, 137.94, 150.21, 186.88. ES-MS$^+$ $[M + H]^+$ 261.1951 (cal. 261.1967 $[M + H]^+$ for $C_{16}H_{25}N_2O$). λ_{max} (EtOH) = 486.0 nm (ε 6.43·10^4 L mol^{-1} cm^{-1}). λ_{max} (EtOH + HCl) = 595.5 nm.

5.2.3 | 2-[3-(Dimethylamino)-2-propene-1-ylidene]-5-(dimethylaminomethylene)-cyclopentanone (7)

2-(Dimethylaminomethylene)-cyclopentanone **6** (700 mg, 5 mmol), **4** (1.13 g, 5 mmol) 2M sodium methylate in methanol (5 mL) were kept for 6 hours at reflux. After cooling, the mixture was poured on ice (100 g). The resulting crystals were filtered, washed with water, and dried on air. Dark-red solid; m.p.: 149°C-151°C. Yield of 7690 mg (63%); ^{1}H NMR ($CDCl_3$): δ 2.52 (m, 2H), 2.84 (br.s, 8H), 3.01 (s, 6H), 4.91 (m, 1H), 6.57 (d, J = 13 Hz, 1H), 7.09 (d, J = 12 Hz, 1H), 7.23 (br.s, 1H). ^{13}C NMR ($CDCl_3$) δ (ppm): 24.20, 24.45, 40.57, 42.16, 95.73, 107.81, 128.30, 131.94, 146.00, 149.47, 193.02. ES-MS$^+$ $[M + H]^+$ 221.1639 (cal. 221.1653 $[M + H]^+$ for $C_{13}H_{21}N_2O$). λ_{max} (EtOH) = 444.0 nm (ε 4.79·10^4 L mol^{-1} cm^{-1}). λ_{max} (EtOH + HCl) = 517.0 nm.

5.3 | Preparation of ketocyanine dyes

5.3.1 | *bis*-2,5-[2-(1-Ethyl-1,3-dihydro-3,3-dimethyl-2*H*-indol-2-ylidene) butadienyl-1,3-idene]-cyclopentanone (13a)

Salt **2a** (630 mg, 2 mmol) and *bis*-2,5-[2-(1-ethyl-1,3-dihydro-3,3-dimethyl-2*H*-indol-2-ylidene)butadienyl-1,3-idene]-cyclopentanone **5a** (246 mg, 1 mmol) in pyridine (10 mL) were kept at reflux for 2 hours. After cooling, the mixture was poured on ice (100 g). The resulting crystals were filtered, washed with water, recrystallized from methanol, and dried on air. Dark-brown solid; m.p.: 154°C-157°C. Yield 170 mg (32%). ^{1}H NMR ($CDCl_3$): δ 1.27 (m, 6H), 1.61 (s, 12 H), 2.77 (s, 4H), 3.70 (m, 4H), 5.56 (d, J = 12 Hz, 2H), 6.17 (dd, J_1 = 14 Hz, J_2 = 12 Hz, 2H), 6.67 (d, J = 8 Hz, 2H), 6.91 (t, J = 8 Hz, 2H), 7.14-7.34 (m, 8H). ^{13}C NMR ($CDCl_3$): δ 11.39, 23.96, 28.21, 36.90, 46.22, 96.88, 106.37, 120.28, 120.79, 121.75, 127.78, 133.80, 135.35, 139.10, 139.39, 143.78, 158.99, 193.93. ES-MS$^+$ $[M + H]^+$ 531.3396 (cal. $[M + H]^+$ = 5 313 375 for $C_{37}H_{43}N_2O$). $\lambda_{max\ (base)}$ (EtOH) = 616.0 nm (ε 5.49·10^4 L mol^{-1} cm^{-1}). $\lambda_{max\ (acid)}$ (EtOH + HCl) = 903.0 nm (ε 1.00·10^5 L mol^{-1} cm^{-1}).

Ketocyanines **13b-d** and **14** were synthesized following the same procedure from salts **2a** and **2b** and *bis*-enaminoketones **5a**, **5b**, and **7**.

5.3.2 | *bis*-2,5-[2-(3-Ethyl-1,3-dihydro-1,1-dimethyl-2*H*-benz[e]indol-2-ylidene) butadienyl-1,3-idene]-cyclopentanone (13b)

Dark-brown solid; m.p.: 172°C-174°C. From **2b** and **5a** yield 271 mg (43%). ^{1}H NMR ($CDCl_3$): δ 1.32 (m, 6H), 1.95 (s, 12 H), 2.81 (s, 4H), 3.81 (m, 4H), 5.60 (d, J = 12.0 Hz, 2H), 6.21 (m, 2H), 7.06 (d, J = 8.5 Hz, 2H), 7.25-7.53 (m, 8H), 7.77 (d, J = 8.5 Hz, 2H), 7.82 (d, J = 8.5 Hz, 2H), 8.05 (d, J = 8.5 Hz, 2H). ^{13}C NMR ($CDCl_3$): δ 11.79, 24.02, 27.39, 37.03, 48.22, 96.56, 109.01, 120.67, 121.72, 122.44, 126.84, 129.05, 129.40, 129.54, 129.80, 129.87, 133.88, 135.33, 139.09, 141.18, 160.97, 193.87. ES-MS$^+$ $[M + H]^+$ 6 313 706 (cal. $[M + H]^+$ = 6 313 688 for $C_{45}H_{47}N_2O$). $\lambda_{max\ (base)}$ (EtOH) = 632 nm (ε 3.94·10^4 L mol^{-1} cm^{-1}). $\lambda_{max\ (acid)}$ (EtOH) = 938.5 nm (ε 7.21·10^4 L mol^{-1} cm^{-1}).

5.3.3 | *bis*-2,5-[2-(1-Ethyl-1,3-dihydro-3,3-dimethyl-2*H*-indol-2-ylidene) butadienyl-1,3-idene]-cyclohexanone (13c)

Dark-brown solid; m.p.: 127°C-131°C. From **2a** and **5b** yield 195 mg (36%). ^{1}H NMR ($CDCl_3$): δ 1.26 (m, 6H), 1.62 (s, 12 H), 1.83 (m, 2H), 2.68 (m, 4H), 3.69 (m, 4H), 5.54 (d, J = 12.0 Hz, 2H), 6.27 (m, 2H), 6.66 (d, J = 8 Hz, 2H), 6.90 (m, 2H), 7.13-7.24 (m, 4H), 7.31 (m, 2H), 7.55 (d, J = 12.0 Hz, 2H). ^{13}C NMR ($CDCl_3$): δ 11.38, 22.54, 26.56, 28.24, 36.86, 46.14, 96.86, 106.25, 120.00, 120.11, 121.74, 127.76, 130.32, 137.84, 138.74, 139.39, 143.87, 158.68, 188.00. ES-MS$^+$ $[M + H]^+$ 5 453 519 (cal. $[M + H]^+$ = 5 453 532 for $C_{38}H_{45}N_2O$). $\lambda_{max\ (base)}$ (EtOH) = 585.0 nm (ε 5.42·10^4 L mol^{-1} cm^{-1}). $\lambda_{max\ (acid)}$ (EtOH) = 893 nm (ε 1.14·10^5 L mol^{-1} cm^{-1}).

5.3.4 | *bis*-2,5-[2-(3-Ethyl-1,3-dihydro-1,1-dimethyl-2*H*-benz[*e*]indol-2-ylidene) butadienyl-1,3-idene]-cyclohexanone (13d)

Dark-brown solid; m.p.: 160°C-164°C. From **2b** and **5b** yield 309 mg (48%). ^{1}H NMR ($CDCl_3$): δ 1.31 (m, 6H), 1.86 (m, 2H), 1.95 (s, 12 H), 2.71 (m, 4H), 3.80 (m, 4H), 5.58 (d, J = 12.0 Hz, 2H), 6.30 (m, 2H), 7.06 (d, J = 8.5 Hz, 2H), 7.28 (m, 2H), 7.3-7.53 (m, 4H), 7.62 (d, J = 12.0 Hz, 2H), 7.77 (d, J = 8.5 Hz, 2H), 7.82 (d, J = 8 Hz, 2H), 8.04 (d, J = 8.5 Hz, 2H). ^{13}C NMR ($CDCl_3$): δ 11.75, 22.59, 26.61, 27.40, 36.98, 48.13, 96.54, 108.98, 119.90, 121.72, 122.34, 126.79, 129.08, 129.32, 129.49, 129.80, 130.28, 137.92, 138.71, 141.27, 160.64, 187.92. ES-MS$^+$ $[M + H]^+$ 6 453 837 (cal. $[M + H]^+$ = 6 453 845 for $C_{46}H_{49}N_2O$). $\lambda_{max\ (base)}$ (EtOH) = 606.0 nm (ε 4.09s·10^4 L mol^{-1} cm^{-1}). $\lambda_{max\ (acid)}$ (EtOH) = 930.0 nm (ε 8.08·10^4 L mol^{-1} cm^{-1}).

5.3.5 | 2-[2-(1-Ethyl-1,3-dihydro-3,3-dimethyl-2*H*-indol-2-ylidene) butadienyl-1,3-idene]-5-[2-(1-ethyl-1,3-dihydro-3,3-dimethyl-2*H*-indol-2-ylidene)ethyliden]-cyclopentanone (14)

Dark-brown solid; m.p.: 142°C-144°C. From **2a** and **7** yield 221 mg (44%). ^{1}H NMR ($CDCl_3$): δ 1.22 (m, 3H), 1.34 (m, 3H), 1.62 (s, 6 H), 1.68 (s, 6 H), 2.77 (s, 4H), 3.69 (m, 2H), 3.77 (m, 2H), 5.39 (d, J = 13.0 Hz, 1H), 5.55 (d, J = 12.0 Hz, 1H), 6.18 (dd, J_1 = 14.0 Hz, J_2 = 12.0 Hz, 1H), 6.67 (d, J = 8.0 Hz, 1H), 6.72 (d, J = 8.0 Hz, 1H), 6.90 (m, 1H), 6.96 (m, 1H), 7.12-7.34 (m, 6H), 7.79 (d, J = 13.0 Hz, 1H). ^{13}C NMR ($CDCl_3$): δ 11.11, 11.37, 23.82, 23.88, 28.24, 28.52, 36.85, 37.13, 46.11, 46.71, 93.16, 96.82, 106.22, 106.65, 120.09, 120.80, 121.11, 127.73, 127.84, 127.75, 129.38, 132.01, 132.53, 136.13, 137.94, 139.36, 139.83, 143.55, 143.91, 158.35, 162.57, 192.97. ES-MS$^+$ $[M + H]^+$ 505.3210 (cal. $[M + H]^+$ = 5 053 219 for $C_{35}H_{41}N_2O$). $\lambda_{max\ (base)}$ (EtOH) = 579.0 nm (ε 3.30·10^4 L mol^{-1} cm^{-1}). $\lambda_{max\ (acid)}$ (EtOH) = 811.0 nm (ε 7.10·10^4 L mol^{-1} cm^{-1}).

ACKNOWLEDGMENTS

We acknowledge the Center for Magnetic Resonance and the Center for Chemical Analysis and Materials Research of Saint Petersburg State University for performing the NMR and ES-MS studies. The work is carried out according to the State Assignment from the Ministry of Education and Science of the Russian Federation (Reg. no. AAAA-A16-116071450048-3) and funded by Ministerio de Economía y Competitividad (Project CTQ2012-36165) and Generalitat de Catalunya (2014SGR837).

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How to cite this article: Miltsov S, Alonso-Chamarro J, Puyol M. Synthesis and optical characterization of new ketocyanine dyes with extended polymethine chaines. *J Heterocyclic Chem*. 2020;1–9. https://doi.org/10.1002/jhet.4027