REVIEW

Male Gamete-Attracting Substances of Marine Algae

Tadahiko KAJIWARA*

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I. INTRODUCTION

Plants physiologists have observed for a long time that male-reproductive cells are attracted by female cells. In 1845, Thuret\(^1\) reported that eggs of Fucus attract the spermatozoids. Cook et al.\(^2,3\) demonstrated that motile spermatozoids are lured to a volatile substance secreted by mature eggs of brown marine algae, Fucus serratus L. and F. vesiculosus L. However, an attempted search for isolation and identification of this principle from eggs gave inconclusive results. Hlubucek et al.\(^4\) explored extracts from macerated female and male ripe tips of Fucus with helium-gas stream and identified n-hexane specifically in the female plants. In 1973, Müller in co-operation with chemists\(^5\) succeeded in isolation of the volatile attractant of spermatozoids, an isomer of 1,3,5-octatrienes, fucoserratene from eggs and oogonia of F. serratus a dioecious brown alga. This attractant was later identified with \((3E, 5Z)\)-octa-1,3,5-triene \((1)\) by synthesis and biological activities\(^6\).

Earlier, Muller et al.\(^7\) isolated for the first time male-attracting substance from cultures of a brown marine alga Ectocarpus siliculosus and its structure was determined as \((S)-(+)\)-6-(1E-but-1-enyl)-cyclohepta-1,4-diene \((2)\). Since discover of ectocarpene in 1971, five more male gamete-attracting-substances have been identified: multifidene\(^8\) \([cis*\text{-}1\text{-vinyl-2\text{-}(1E\text{-but-1-enyl})\text{-cyclopent-3-ene}}\ (4)\), fucoserratene\(^5\) \([3E,5Z]\text{-octa-1,3,5-triene}\ (1)\), dictyopterene \(C^9\) \([(-)-(R)-6\text{-butyl-cyclohepta-1,4-diene}}\ (3)\), desmarestene\(^10\) \([6\text{-}(1Z\text{-buta-1,3-dienyl})\text{-cyclohepta-1,4-diene}}\ (5)\) and viridiene\(^11\) \([cis\text{-}1\text{-vinyl-2\text{-}(1Z\text{-buta-1,3-dienyl})\text{-cyclopent-3-ene}}\ (6)\), in the marine Phaeophyta, Cutleria, Fucus, Dictyopteris, Desmarestia and Syringoderma, respectively.

II. SYNTHESIS OF MALE GAMETE-ATTRACTING SUBSTANCES

Dictyopterenes \(C'\)\([(-)-(3)]\) and \(D'\) \([\text{ectocarpene: } (+)-(2)]\) have been isolated as "Ocean smell" from the essential oils of brown algae, Dictyopteris plagiogramma (Montagne) Vickers; D. australis Sonder,\(^12-14\) D. prolifera and D. undulata\(^15,16\) together with dictyopterenes A \([(+)-(7)]\) and B \([(-)-(8)]\). The thermal rearrangement of the con-

* Tadahiko KAJIWARA: Department of Agricultural Chemistry, University of Yamaguchi, Yamaguchi 753, Japan.

* cis, trans-notation for stereochemical structure of the cyclopropane ring.
constituents of “Ocean smell” [(+)-7 and (−)-8] to male-gamete attractants [(+)-3 and (−)-2], respectively, stimulated syntheses of 7 and 8 in racemic forms. However, optically active dictyopterenes have not been synthesized so far. Thus, the authors studied on stereoselective syntheses of (+)-dictyopterene A [(+)-7], (−)-dictyopterene B[(−)-8], and the related compounds as shown in Scheme 1.32)

\[
\text{Scheme 1. Synthetic Route of Dictyopterenes A and B, and Their Geometrical Isomers.}
\]

In the first stage of the synthetic route, the key synthon, ethyl trans-2-formyl-cyclopropanecarboxylate (9a) was prepared by condensation of acrolein with the ylid of carboethoxymethyl dimethylsulfonium bromide (the method of Payne) or the sulfonium salt (a modified method) in liquid-solid two-phase systems using crown ethers. With the modified method, to a mixture of the sulfonium halide, bases and crown ether in THF and/or dichloromethane, was added the unsaturated aldehyde at room temperature and 9a was obtained in 60–70% yields after stirring for a while (Table I). From the data in Table I, it was found that the trans-isomer (9a) is selectively produced in THF using 18-crown-6-potassium carbonate and in the absence of crown ethers, little or no cyclopropane is formed. A major advantage of this procedure is the simplicity of the one step reaction to afford selectively the trans-isomer in
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Table I. Crown Ether and Solvent Effects in the Formation of 9a and 7a in Liquid-solid Two-phase Systems.

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Base and Catalyst</th>
<th>trans/cis* (E)/(Z)</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>formation of cyclopropanes</td>
<td>trans/cis* (E)/(Z)</td>
<td>Yield (%)</td>
<td></td>
</tr>
<tr>
<td>THF</td>
<td>K₂CO₃, 18-crown-6</td>
<td>95/5</td>
<td>58⁹</td>
</tr>
<tr>
<td>THF+CH₃Cl₂</td>
<td>K₂CO₃, 18-crown-6</td>
<td>88/12</td>
<td>62⁹</td>
</tr>
<tr>
<td>CH₃Cl₂</td>
<td>K₂CO₃, 18-crown-6</td>
<td>87/13</td>
<td>67⁹</td>
</tr>
<tr>
<td>CH₃Cl₄</td>
<td>NaOH, 18-crown-6</td>
<td>81/19</td>
<td>71⁹</td>
</tr>
</tbody>
</table>

formation of alkenes (E/Z)

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Base and Catalyst</th>
<th>(E/Z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>THF</td>
<td>t-BuOK, 18-crown-6</td>
<td>5/95</td>
</tr>
<tr>
<td>C₅H₅OC₂H₅</td>
<td>t-BuOK, 18-crown-6</td>
<td>7/93</td>
</tr>
<tr>
<td>CH₂Cl₂</td>
<td>t-BuOK, 18-crown-6</td>
<td>10/90</td>
</tr>
<tr>
<td>THF</td>
<td>t-BuOK, 18-crown-6</td>
<td>6/94</td>
</tr>
<tr>
<td>CH₃Cl₄</td>
<td>t-BuOK, Dibenzo-18-crown-6</td>
<td>9/91</td>
</tr>
</tbody>
</table>

a Determined by GLC. b Distilled yield of 9a+9b. c GLC yield of 9a+9b. d Distilled yield of 7+7a. e GLC yield of 7+7a. f THF: CH₂Cl₂/50:50

satisfactory yields. This procedure promises to be a general method for syntheses of functionalized cyclopropanes from S-ylids and α, β-unsaturated aldehydes.

In the next step the Wittig reaction between the trans-aldehyde (9a) and methylidenetriphenylphosphorane afforded ethyl 2-vinylcyclopropanecarboxylate (11) (90%). The ethyl ester (11) was hydrolyzed to 2-vinylcyclopropanecarboxylic acid (12). Chemical resolution of the carboxylic acid (12) with (-)-quinine gave (+)-(12); [α]D⁶+178°. The absolute configuration of (+)-12 was determined to be 1S:2R since the Lemieux oxidation of this (+)-acid, gave (+)-(R, R)-trans-1,2-cyclopropandicarboxylic acid which after Sephadex LH-20 column chromatography and recrystallization from acetonitrile had mp 175-177° and [α]D⁶+201°. The optical purity of (+)-12, [α]D⁶+178°, was evaluated to be 85% from both the rotation value of the derived dicarboxylic acid and the enantiomeric composition on glc analysis of the diastereomeric esters of (+)-12 with (-)-(R)-2-octanol. Thus, the maximum rotation of (+)-(1S, 2R)-12 should be [α]D⁶+210° in ethanol.

Esterification of (+)-12 with diazomethane and the subsequent reduction with LiAlH₄, gave a hydroxy-cyclopropane, [(+)-14] (92%); [α]D⁶+54°. This alcohol [(+)-14] was oxidized with Collins reagent to an aldehyde [(+)-15] (88%), [α]D⁶+161°.

In the final stage of the synthetic route, the Wittig reaction of (+)-15 with a pentylidenetriphenylphosphorane afforded a geometrical mixture of dictyopterene
A [(+)-7] and the (Z)-isomer [(-)-7a] (65%, E/z=40/60) according to the method of Schlosser.28) The glc separation of the mixture [(+)-7 and (-)-7a] allowed the isolation of (+)-7, [alpha]_D^20 +65°, which was found to be identical with the natural (+)-dictyopterene A in D. proliferals,15,16) and D. undulata15) in all respects except the magnitude of optical rotation. The synthetic compound (+)-7 had 87% optical purity on the basis of the reported [alpha]_D^20 +72° (c=6.74, CHCl_3), 96.3% optical purity of naturally occurring dictyopterene A.14)

On the other hands, the geometrical isomer [(-)-7a] is stereoselectively prepared according to the method of Boden25) as indicated in Table I. The Wittig reaction between the aldehyde [(+)-15], [alpha]_D^20 +161°, and amyltriphenylphosphonium bromide in THF using crown ether-t-BuOK at -10°C, gave exclusively the geometrical (Z)-isomer [(-)-7a] of dictyopterene A, (77%), [alpha]_D^20 -123°. The geometrical purity of (-)-7a was found to be 95% by glc analysis.

According to the method of Schlosser,28) a mixture of (-)-8 and (-)-8a was obtained by the Wittig reaction of the aldehyde [(+)-15], [alpha]_D^20 +161°, with (Z)-2-pentenylidenetriphenylphosphorane in a mixed solvent of diethyl ether and THF. The mixture of 8 and 8a was partially rearranged to an enantiomer [(+)-2] of the naturally occurring ectocarpene [(+)-2] during glc analysis. The retention times of the rearranged isomer (-)-2 and the synthetic (-)-8 were identical with those of natural dictyopterene B and ectocarpene, respectively, in the essential oils of D. proliferals,15,16) and D. undulata.16) To discuss the relationship between biological activity and absolute configuration of ectocarpene, highly optical-active ectocarpene [(+)-2] and its antipode [(+)-2] were stereoselectively synthesized via biological and chemical resolution using microorganism and (-)-quinine.33)

As shown in Scheme 2, the copper-catalyzed reaction of ethyl diazoacetate
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1, 3-butadiene gave a mixture of ethyl trans- and cis-2-vinylcyclopropanecarboxylate (16a: 16b = 55: 45) (24%), which were reduced to the alcohols 17 with LiAlH₄.

Oxidation of 17 with PPC gave the aldehydes (18) (57%), which were converted into a mixture of cyclopropane ester 19a and cycloheptadiene ester (±)-20 (55: 45) (97%) by the Wittig reaction between 18 and ethoxycarbonylmethylenetriphenylphosphorane in CH₂Cl₂. The cis-cyclopropane ester 19b produced during the Wittig reaction, rearranged to (±)-20 spontaneously and the trans-isomer 19a was then quantitatively converted into the cycloheptadiene ester (±)-20 by refluxing in xylene or non-sensitized photochemical reaction in benzene. This racemic cycloheptadiene ester (±)-20 was resolved by microbiological asymmetric hydrolysis with Rhodotorula and the corresponding carboxylic acid (±)-21 was resolved with (−)-quinine.

From the result of screening of our stocked forty microorganisms, eight microorganisms in Table II were selected for asymmetric hydrolysis of (±)-20. Rhodotorula minuta var. texensis IFO 1102, Rhodotorula minuta var. texensis IFO 0412, Rhodotorula glutinis var. rebeschens IFO 0413 and Rhodotorula glutinis IFO 0711 were found to have the enzyme activity to hydrolyze enantioselectively the cycloheptadiene ester (±)-20 to the corresponding carboxylic acid. The enantioselectivity on the hydrolysis of (±)-20 was different by used microorganisms.

Table II. Enatioselective Hydrolysis of the Ethyl Ester (±)-20 to the Corresponding Carboxylic Acid with Microorganisms.

<table>
<thead>
<tr>
<th>Microorganism</th>
<th>Shaking time (hr)</th>
<th>Hydrolytic ratio (%)</th>
<th>[α]⁺⁰ (°)</th>
<th>e.e. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhodotorula minuta var. texensis IFO 1102</td>
<td>72</td>
<td>15</td>
<td>+8.9°</td>
<td>89</td>
</tr>
<tr>
<td>Rhodotorula minuta var. texensis IFO 0412</td>
<td>72</td>
<td>18</td>
<td>+6.6°</td>
<td>66</td>
</tr>
<tr>
<td>Rhodotorula glutinis var. rebeschens IFO 0413</td>
<td>72</td>
<td>22</td>
<td>+1.5°</td>
<td>15</td>
</tr>
<tr>
<td>Rhodotorula glutinis IFO 0711</td>
<td>72</td>
<td>29</td>
<td>+1.4°</td>
<td>14</td>
</tr>
<tr>
<td>Rhodotorula rubra IFO 0714</td>
<td>72</td>
<td>24</td>
<td>0°</td>
<td>0</td>
</tr>
<tr>
<td>Enterobacter aerogenes IFO 3317</td>
<td>72</td>
<td>3</td>
<td>0°</td>
<td>0</td>
</tr>
<tr>
<td>Bacillus subtilis IFO 3026</td>
<td>18</td>
<td>100</td>
<td>0°</td>
<td>0</td>
</tr>
<tr>
<td>Baker's yeast</td>
<td>9</td>
<td>28</td>
<td>0°</td>
<td>0</td>
</tr>
</tbody>
</table>

a: Dried cell (0.5 g)/substrate (1.0 g)/potassium phosphate buffer, pH 7.0 (100 ml).

The preparative scale hydrolysis was carried out using Rhodotorula minuta var. texensis IFO 1102 with substrate concentration of 1% as shown in Table III. When hydrolytic ratio was attained to 14%, the optically active carboxylic acid (S)-(−)-21, [α]⁺⁰ +8.9° (ε=1.74, EtOH, 89% optical purity) and the ester (−)-20, [α]⁺⁰ +0.3° (ε=10.1, EtOH) were isolated. This carboxylic acid [(−)-21] was converted to an antipode [(−)-2] of ectocarpene [(+)-2] as shown in Fig. 2. Thus, the absolute configuration of (−)-21 was determined as (S) and the optical purity of (+)-21, [α]⁺⁰ +8.9°, was evaluated to be 89% from the reported maximum rotation value of
Table III. Preparative Asymmetric Hydrolysis by *Rhodotorula minuta* var. *texensis* IFO 1102

<table>
<thead>
<tr>
<th>Substrate [(+)-21]*</th>
<th>Carboxylic Acid [(+)-21]</th>
<th>Ethyl Ester [(+)-20]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[α]_D (g)/dried cells (g)</td>
<td>Hydrolytic ratio (%)</td>
<td>Yield (g)</td>
</tr>
<tr>
<td>0°</td>
<td>14.0/7.0</td>
<td>14</td>
</tr>
<tr>
<td>+0.3°</td>
<td>6.5/3.5</td>
<td>15</td>
</tr>
<tr>
<td>+0.8°</td>
<td>2.7/1.4</td>
<td>55</td>
</tr>
</tbody>
</table>

a: Substrate concentration of 1% (potassium phosphate buffer, pH 7.0).
b: Isolated yield. The total recovery of the carboxylic acid and the ester was generally low (~50%).

ectocarpene ([α]_D^3^+75°) and the enantiomeric composition on GLC analysis of the diastereomeric esters of (+)-21 with (−)-(R)-2-octanol.

To obtain (R)-(−)-20 with high optical purity, the recovered ester (+)-20, [α]_D^3^+0.3°, was again treated with the same microorganism to give a mixture of the carboxylic acid (+)-21, [α]_D^3^+5.6° (c=1.39, EtOH, 56% e.e.), and the ester (+)-20, [α]_D^3^+0.8° (c=1.06, EtOH, 36% e.e.). The further enantioselective hydrolysis of the isolated ester (36% e.e.) gave (R)-(−)-20 with highest optical purity, [α]_D^9^+1.7° (c=1.04, EtOH, 78% e.e.) at 55% hydrolytic ratio.

On the other hand, resolution of (±)-21 with (−)-quinine gave (S)-(−)-21 (95% e.e.) and (R)-(−)-21 (e.e.~38%). (S)-(−)-2,5-Cycloheptadienecarboxylic acid [(+)-21, 95% e.e.] and (R)-(−)-ethyl 2, 5-cycloheptadienecarboxylate [(+)-20, 78% e.e.] thus obtained, were reduced to the corresponding alcohols [(S)-(−)-23: [α]_D^3^+8.5° and (R)-(−)-23: [α]_D^3^−7.0°], respectively. Pilot experiments for oxidation of the alcohol (±)-23 to the aldehyde (±)-24 indicates that Collins reagent is best for oxidation of the 2, 5-cycloheptadiene alcohol because isomerization of the double bond at C-2 of (±)-23 to the conjugated system (1, 5-heptadienylcarbaldehyde) was not observed. Thus, both enantiomers of the alcohol [(+)-23 and (−)-23] were oxidized to the aldehydes [(S)-(−)-24 and (R)-(−)-24] with Collins reagent, respectively.

The Wittig reaction of the aldehydes [(S)-(−)-24 and (R)-(−)-24] with propyltriphenylphosphonium bromide in THF in solid-liquid two phase using 18-crown ether–t-BuOK afforded practically pure (Z)-olefins, (R)-(−)-2; [α]_D^4^−68.4° (e.e. 95%) and (S)-(−)-2; [α]_D^4^+56.2°, ectocarpene (e.e. 78%), respectively.

The synthetic ectocarpene and its enantiomer were identical except the magnitude of optical rotation, with the thermally rearranged isomers [(+)-2 ([α]_D^8^+11.3°) and (−)-2 ([α]_D^8^−11.0°)], respectively, from (S, S)-(−)-1-[(E, Z)-hexa-1', 3'-dienyl]-2-vinylcyclopropane (containing geometrical isomer, [α]_D^8^+77°) and dictyopterene B (partially optical active,[α]_D^8^−37°).14,32) The retention times of the synthesized ectocarpene and its antipode were identical with those of natural ectocarpene in the essential oils of *D. prolifera* and *D. undulata*.16

More recently, the syntheses of other chiral attractants multitifidene* (4),
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desmarestenene* (5) and viridiene* (6)- have aroused keen interest from receptor specificity and threshold concentration in the Phaeophyte.

III. MALE GAMETE-ATTRACTING SUBSTANCE IN HERMAPHRODITE BROWN ALGAE, PELVETIA WRIGHTII AND FUCUS EVANESCENS.

Müller and Jaenicke\(^6\), in 1973, isolated the volatile attractant of spermatozoids, (3E, 5Z)-octa-1,3,5-triene (fucoserratene, 1) from the eggs and oogonia of a dioecious brown alga, Fucus serratus. However, male gamete-attracting substances of hermaphrodite brown algae have not been explored so far.

Hermaphrodite brown algae, Pelvetia wrightii and F. evanescens were collected in the tidal flat along the Charatsunai coast of Muroran, Hokkaido, October and June respectively. The mature receptacles which were detached from the plants, were wiped with gauze and rinsed in filtered sea water to remove diatoms and microorganisms.\(^3\) The cleaned receptacles were kept at 18°C in a growth chamber illuminated with white fluorescent lamps at about 2500 lux for 8 hr and then transferred to Yamaguchi University, in a container at 5°C with dry ice.

When the receptacles cold-treated were soaked in sea water, the ripe female gametes of Fucus attracted male gametes released from antherida as shown in Fig. 1. Thus, the attractant was extracted as follows. The treated receptacles (22.4 kg) emerged the contents of the conceptacles were soaked in MeOH saturated with pentane for 3 days and pentane-soluble portion was chromatographed on an alumina gel and florisil gel with pentane. Early fractions were further separated by AgNO\(_3\)-silica gel column chromatography followed by preparative glc. The structure of the attractant

\[(a)(b)\]

Fig. 1. Chemotaxis of a hermaphrodite brown alga, F. evanescens.

(a) an oogonium containing eight female gametes attracts male gametes. (b) a female gamete attracting male gametes.

* The configurations are still unknown.
was fully substantiated by comparison of UV, MS, $^1$H-NMR and $^{13}$C-NMR data$^{5,37}$ with those of authentic 1 which was prepared by a Wittig reaction between 1, trans-3-pentadienal and propyltriphenyl phosphonium bromide in THF in solid-liquid two phase using 18-crown ether-t-BuOK.$^{33}$ The separated attractant was found to show spermatozoid-attracting activity of spermatozoids like synthetic (3E, 5Z)-octa-1,3,5-triene as shown in Fig. 2. The natural 1 from P. wrightii was shown to contain a small amount ($\sim 5\%$) of (3E, 5E)-octa-1,3,5-triene (1a)$^{38-40}$ by $^{13}$C-NMR. From a hermaphrodite alga, F. evanescens, the male-gamete attractant, 1 ($4 \times 10^{-5}\%$ based on the weight of fresh receptacles), was separated according to the procedure described above.

![Fig. 2. Chemotaxis assay for male gametes of F. evanescens. (a) a spherosil bead containing natural fucoserratene, (b) a capillary tube containing synthetic fucoserratene, both attracting male gametes.](image)

This procedure including fluorescent illumination and cold treatment is an effective method of attractants extraction.$^{41}$

The roles of 1a in the seriated sex behavior of hermaphrodite brown algae, particularly and examination of the synergistic and inhibitory effects and of the species-specificity of sexual chemotaxis, have remained unknown. Thus, the authors examined quantitatively the response of male gametes of Pelvetia wrightii and Fucus evanescens to various concentrations of attractants such as synthetic fucoserratene (1) and (3E, 5E)-octa-1,3,5-triene (1a) which were prepared by the Wittig reaction of (2E, 4Z)- and (2E, 4E)-hepta-2,4-dienals with methyldienetriphenylphosphorane, respectively. The (E)-isomer (1a) of fucoserratene (1) was found to have attractive properties. However, the threshold concentration is ca. 10 times higher than that of synthetic fucoserratene according to the method of Müller.$^{42}$ The addition of (E)-isomer to fucoserratene did not substantially affect to attraction of male-gametes. From these facts and findings, fucoserratene may be considered to be the only intrinsic attractant.$^{43}$
REFERENCES