

# Cannabinoids Inhibit Cellular Respiration of Human Oral Cancer Cells

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## Key Words

Cannabinoids · Respiration · Mitochondria · Oral cancer

## Abstract

**Background and Purpose:** The primary cannabinoids,  $\Delta^9$ -tetrahydrocannabinol ( $\Delta^9$ -THC) and  $\Delta^8$ -tetrahydrocannabinol ( $\Delta^8$ -THC) are known to disturb the mitochondrial function and possess antitumor activities. These observations prompted us to investigate their effects on the mitochondrial  $O_2$  consumption in human oral cancer cells (Tu183). This epithelial cell line overexpresses *bcl-2* and is highly resistant to anticancer drugs. **Experimental Approach:** A phosphorescence analyzer that measures the time-dependence of  $O_2$  concentration in cellular or mitochondrial suspensions was used for this purpose. **Key Results:** A rapid decline in the rate of respiration was observed when  $\Delta^9$ -THC or  $\Delta^8$ -THC was added to the cells. The inhibition was concentration-dependent, and  $\Delta^9$ -THC was the more potent of the two compounds. Anandamide (an endocannabinoid) was ineffective; suggesting the effects of  $\Delta^9$ -THC and  $\Delta^8$ -THC were not mediated by the cannabinoid receptors. Inhibition of  $O_2$  consumption by cyanide confirmed the oxidations occurred in the mitochondrial respiratory chain.  $\Delta^9$ -THC inhibited the respiration of isolated mitochondria from beef heart. **Con-**

**clusions and Implications:** These results show the cannabinoids are potent inhibitors of Tu183 cellular respiration and are toxic to this highly malignant tumor.

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## Introduction

The primary cannabinoids  $\Delta^9$ -tetrahydrocannabinol ( $\Delta^9$ -THC) and  $\Delta^8$ -tetrahydrocannabinol ( $\Delta^8$ -THC) [1] are known to have antitumor activities [2–8] and to induce apoptosis [3]. The latter cytotoxic process [9] is initiated by cell-surface receptors (e.g. Fas/APO-1) or intracellular targets (e.g., the pro-apoptotic Bcl-2 family member Bid). The resulting signals permeabilize the outer mitochondrial membrane, releasing low-molecular-weight soluble proteins (e.g., cytochrome c) from the mitochondrial intermembrane space. In the cytosol, cytochrome c binds to Apaf-1 (apoptotic protease-activating factor 1), forming oligomers (apoptosomes) that activate caspases (cysteine aspartate-directed proteases). Caspase activation leads to opening of the permeability transition pores (located at contact sites between the inner and outer mitochondrial membranes), collapse of the inner mitochondrial membrane potential ( $\Delta\mu_{H^+}$ ) and impair-

ment of cellular respiration. These findings have been described in tumor cells treated with  $\Delta^9$ -THC [10].

Tu183 cells are derived from a squamous cell carcinoma of the tonsil [11]. This epithelial cell line overexpresses *bcl-2* and is highly resistant to cytotoxic drugs [12–15].

The term cellular respiration implies delivery of  $O_2$  and metabolic fuels to the mitochondria, oxidations of reduced fuels with passage of electrons to  $O_2$ , and synthesis of ATP. Impaired respiration thus entails an interference with any of these processes. We recently used a sensitive phosphorescence oxygen analyzer to investigate the toxic effects of doxorubicin on respiration of HL-60 (myeloid) and Jurkat (lymphoid) cells [16]. This anticancer agent inhibits mitochondrial oxygen consumption in both cell lines. We present here similar measurements for the cannabinoids on Tu183 cells.

Studies have shown that cannabinoids inhibit tumor cell proliferation, induce apoptosis and collapse  $\Delta\mu_{H^+}$  [2–8]. In addition, activities of cannabinoids against oral cancer cells [4] and other tumors [5] are well documented. Furthermore, the polycyclic structure of  $\Delta^9$ -THC has potent effects on the inner mitochondrial membrane [17]. Therefore, we hypothesized that  $\Delta^9$ -THC and  $\Delta^8$ -THC impair the ‘cellular bioenergetics’ (oxidative phosphorylation and accompanying ATP synthesis) of Tu183 cell line. The results show for the first time that cannabinoids are potent inhibitors of respiration and ATP content in this highly malignant cell line. Moreover, light microscopy and TUNEL assay further confirmed the toxic effects of  $\Delta^9$ -THC and  $\Delta^8$ -THC on Tu183 cells.

## Materials and Methods

### Reagents

$\Delta^9$ -THC (63.7 mmol/l = 20 mg/ml 95% EtOH; MW 314.47; stored at  $-4^\circ\text{C}$  under argon) and  $\Delta^8$ -THC (127.4 mmol/l = 40 mg/ml 99% EtOH; MW 314.47; stored at  $-4^\circ\text{C}$  under argon) were provided by the National Institute of Drug Abuse (NIDA). Laboratory standards of  $\Delta^9$ -THC (1.0 mg/ml in MeOH) and  $\Delta^8$ -THC (1.0 mg/ml in MeOH) were prepared by Cerilliant Corp. (Round Rock, Tex., USA) and purchased from Cambridge Isotope Laboratories, Andover, Mass., USA. Anandamide (*N*-arachidonoyl-ethanolamine, MW 347.6) was purchased from Biomol International, LP (Plymouth Meeting, Pa., USA).

Pd (II) complex of *meso*-tetra-(4-sulfonatophenyl)-tetrabenzoporphyrin (Pd phosphor sodium salt) was purchased from Porphyrin Products (Logan, Utah, USA). Luciferin-luciferase mixture (0.2 mg luciferin and 22,000 units luciferase per vial, stored at  $-20^\circ\text{C}$ ) and ATP (2  $\mu\text{mol}$  per vial, stored at  $-20^\circ\text{C}$ ) were purchased from Chrono-Log (Havertown, Pa., USA). The remaining reagents were purchased from Sigma-Aldrich.

Pd phosphor (2.0 mmol/l) was made by dissolving the powder at 2.5 mg/ml in  $\text{dH}_2\text{O}$  and stored at  $-20^\circ\text{C}$  in small aliquots. Anandamide (25 mg) was suspended in 1.0 ml of 100% EtOH (71.9 mmol/l) and stored at  $-80^\circ\text{C}$  under argon. NaCN (1.0 mol/l) was made in  $\text{dH}_2\text{O}$  and pH was adjusted to 7.0 with 12 N HCl. Aqueous solution of ATP (0.4 mmol/l) was made fresh in 10 mmol/l Tris-HEPES (pH 7.5); its final concentration was determined by absorbance at 259 nm, using an extinction coefficient of 15,400  $\text{mol}^{-1}\cdot\text{cm}^{-1}$ . A working solution of ATP (8  $\mu\text{mol}$ /l) was prepared immediately prior to use in 0.1 mol/l Tris-HEPES (pH 7.5), 5 mmol/l  $\text{MgCl}_2$  and 0.1% fat-free bovine serum albumin. A lyophilized powder containing luciferin (0.2 mg, MW 280) and luciferase (22,000 units) was freshly dissolved in 1.25 ml phosphate-buffered saline (PBS), protected from light and placed on ice. The final concentration of luciferin (570  $\mu\text{mol}$ /l) was determined by absorbance at 327 nm, using an extinction coefficient of 18,000  $\text{mol}^{-1}\cdot\text{cm}^{-1}$ .

### Cells

Tu183 cells were obtained from Professor Edward J. Shillitoe (SUNY Upstate Medical University, Syracuse, N.Y., USA). The cells were cultured in Dulbecco’s Modified Eagle Medium Nutrient Mixture F-12 (Invitrogen, Carlsbad, Calif., USA) plus 10% fetal bovine serum, 1% penicillin/streptomycin and 0.2% primosin. For harvesting, the cells were incubated at  $37^\circ\text{C}$  in 2.5 ml of 0.05% (w/v) trypsin plus 0.53 mmol/l EDTA solution for 5 min and then collected. Each flask was carefully inspected and remaining cells were gently scraped and retrieved. The cell count was determined by light microscopy, using a hemocytometer under standard trypan blue staining conditions.

### High-Performance Liquid Chromatography

Samples of the NIDA  $\Delta^9$ -THC and  $\Delta^8$ -THC solutions were run on high-performance liquid chromatography (HPLC), and compared to runs of the laboratory standard cerilliant  $\Delta^9$ -THC and  $\Delta^8$ -THC on the same system (Beckman reversed-phase HPLC with wavelength at 228 nm,  $4.6 \times 250$  mmol/l Beckman Ultrasphere IP column at  $25^\circ\text{C}$ ). The running solvent was acetonitrile: 0.1% phosphoric acid (75:25), isocratic at 1.5 ml/min. In all cases, the resulting chromatograms for NIDA  $\Delta^9$ -THC and cerilliant  $\Delta^9$ -THC were identical to one another, as were the resulting chromatograms for NIDA  $\Delta^8$ -THC and cerilliant  $\Delta^8$ -THC.

### Cellular Respiration

$[O_2]$  in the cell suspensions was determined as a function of time, using the Pd phosphor. Samples were exposed to light flashes (10/s) from a pulsed light-emitting diode array with peak output at 625 nm (OTL630A-5-10-66-E, Opto Technology, Inc., Wheeling, Ill., USA). Emitted light was detected by a Hamamatsu photomultiplier tube after passing through a wide-band interference filter centered at 800 nm. The amplified phosphorescence decay was digitized at 1 MHz by an A/D converter (Computer Boards, Inc., Norton, Mass., USA). The phosphorescence decay of the probe was exponential, with decay rate  $(1/\tau)$  theoretically linear in  $[O_2]$ , according to  $\tau^0/\tau = 1 + \tau^0 k_q [O_2]$ ;  $\tau$ , lifetime in the presence of  $O_2$ ;  $\tau^0$ , lifetime in the absence of  $O_2$ ; and  $k_q$ , second-order  $O_2$  quenching constant. Values of  $\tau$  associated with known  $[O_2]$  were determined in a series of ascorbate plus ascorbate oxidase solutions, simultaneously with electrochemical  $O_2$  measurements on the same solutions. A plot of  $1/\tau$  vs.  $[O_2]$  was linear. The

quenching constant ( $k_q$ ) calculated from the linear fit was  $96.1 \pm 1.2 \mu\text{m}^{-1}\cdot\text{s}^{-1}$  and  $1/\tau^0$  was  $10,087 \pm 156 \text{ s}^{-1}$  [16].

Respiration was measured at 37°C. For each run, 1.0 ml of the cell suspension was placed in a 1.0-ml glass vial. The vial was sealed with a crimp top aluminum seal. Mixing was accomplished with the aid of a parylene-coated stirring bar. The rate of respiration (zero-order rate constant,  $k$ , in  $\mu\text{mol/l O}_2 \text{ min}^{-1}$ ) was the negative of the slope of a plot of  $[\text{O}_2]$  vs.  $t$ . The addition of 10 mmol/l NaCN caused  $-k = d[\text{O}_2]/dt$  to decrease almost to 0, demonstrating that the decline in  $[\text{O}_2]$  with time was mainly due to mitochondrial  $\text{O}_2$  consumption.

#### Mitochondrial Respiration

Measurements with mitochondria were included to demonstrate a direct effect of  $\Delta^9$ -THC on the mitochondrial respiratory chain [17]. Mitochondria were prepared from beef heart as described [18]. Mitochondria were suspended in 1.0 ml of 10 mmol/l Tris-Cl (pH 8.2), 250 mmol/l sucrose, 2.0  $\mu\text{mol/l}$  Pd phosphor and 0.5% albumin. The mixture was transferred to a 1.0-ml glass vial and placed in the instrument for  $\text{O}_2$  measurement.  $\text{O}_2$  consumption was initiated by the addition of 50 mmol/l succinate. Where shown, other additions were 2  $\mu\text{l}$  EtOH (control), 120  $\mu\text{mol/l}$   $\Delta^9$ -THC, 10 mmol/l NaCN and glucose (1.0 mmol/l) plus glucose oxidase (7.0 units). Glucose oxidase catalyzes the reaction:  $\beta$ -D-glucose +  $\text{O}_2 \rightarrow$  D-glucono-1,5-lactone +  $\text{H}_2\text{O}_2$ .

#### Cellular ATP

ATP was measured in Tu183 cell acid extracts that were prepared by adding 400  $\mu\text{l}$  of 10% perchloric acid to pellets containing  $2.4 \times 10^5$  cells. The mixtures were sonicated on ice for 30 s and the supernatants were neutralized with 400  $\mu\text{l}$  of 2.0 mol/l KOH. The samples were incubated on ice for 15 min and the precipitated  $\text{KClO}_4$  was removed by centrifugation.

The luciferin-luciferase bioluminescence system was used to determine cellular ATP. Luminescence was measured at 37°C using a luminometer (Chrono-Log Corporation, Havertown, Pa., USA) connected to Chrono-log AGGRO/LINK™ interface and analyzed as described [16]. The reaction (final volume, 0.4 ml) contained 0.1 mol/l Tris-HEPES (pH 7.6), 5 mmol/l  $\text{MgCl}_2$ , 0.1% albumin and ATP (5–40 pmol) or cellular acid extracts (25  $\mu\text{l}$ ). The reaction was started by injecting 10  $\mu\text{l}$  of luciferin/luciferase mixture (5 nmol luciferin plus 176 units luciferase). The luminometer was calibrated with known amounts of ATP (5–40 pmol). The intensity was measured every 0.5 s out to 600 s. Plots of luminescence intensity  $I$  vs.  $t$  were obtained and fitted to:  $I = a + b e^{-ct}$  ( $r > 0.9556$ ). Cellular ATP content was calculated as described [16].

#### TUNEL Assay

DNA fragmentation was visualized using the terminal deoxynucleotidyl transferase-mediated dUTP nick end labeling (TUNEL) technique (In situ Cell Death Detection Kit, Fluorescein; Roche Applied Science, Mannheim, Germany). Cells were plated at  $2.0 \times 10^5$  per well in chamber slides overnight. On the day of treatment, media with EtOH (control) or  $\Delta^9$ -THC (120  $\mu\text{mol/l}$ ) were added and the cells were incubated at 37°C for 60 min. The slides were air dried, fixed in 4% (v/v) paraformaldehyde (in PBS, pH 7.4) and rinsed in PBS. The slides were then incubated on ice in the permeabilisation solution (0.1% (v/v) Triton X-100 in 0.1% (v/v) sodium citrate) for 2 min and rinsed twice in PBS. 50  $\mu\text{l}$  of

the TUNEL reaction mixture was added. The slides were covered with coverslips, incubated at 37°C in the dark for 1 h, and rinsed 3 times with PBS. Vectashield (Vector Laboratories, Inc., Burlingame, Calif., USA) and coverslips were placed before viewing under a Nikon fluorescence microscope, with an exciter filter at 465–495 nm and a barrier filter at 515–555 nm.

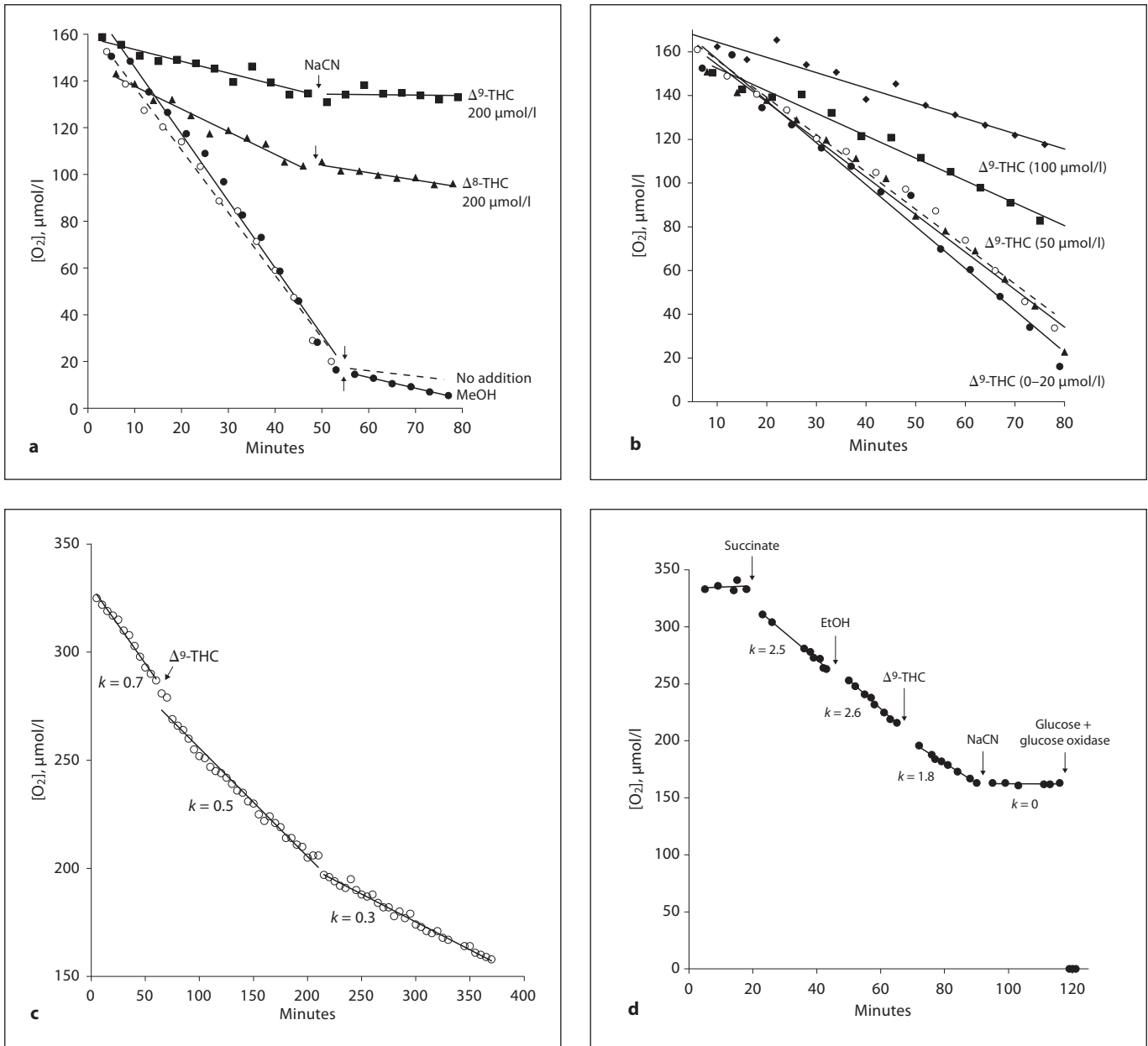
## Results

### Cannabinoids Inhibited Tu183 Cellular Respiration

Cells ( $0.5 \times 10^6/\text{ml}$ ) were suspended in media containing 2  $\mu\text{mol/l}$  Pd phosphor and 0.5% albumin with and without 200  $\mu\text{mol/l}$   $\Delta^9$ -THC or  $\Delta^8$ -THC. The plots of  $[\text{O}_2]$  as function of time are shown in figure 1a. The rate of cellular mitochondrial  $\text{O}_2$  consumption ( $k$ , in  $\mu\text{mol/l O}_2/\text{min}$ ) for untreated cells was 2.6 ( $r^2 = 0.991$ ), for cells treated with MeOH 2.8 ( $r^2 = 0.988$ ; added as a control for the cannabinoids' vehicle), for cells treated with  $\Delta^9$ -THC 0.5 ( $r^2 = 0.903$ , 81% inhibition), and for cells treated with  $\Delta^8$ -THC 0.9 ( $r^2 = 0.973$ , 65% inhibition). Cyanide (10 mmol/l) gave almost complete inhibition ( $\geq 84\%$ ); confirming the decline in  $[\text{O}_2]$  was mainly due to mitochondrial  $\text{O}_2$  consumption. The  $k$  values for media (without cells) plus  $\Delta^9$ -THC or  $\Delta^8$ -THC were very similar to the instrument drift (0.03  $\mu\text{mol/l O}_2 \text{ min}^{-1}$ ). Thus, potential interactions between cannabinoids and  $\text{O}_2$  or Pd phosphor are negligible.

Dependence of the inhibition on  $\Delta^9$ -THC dosing is shown in figure 1b.  $\text{O}_2$  consumption was measured in Tu183 cells ( $0.5 \times 10^6/\text{ml}$ ) in the presence of 0–100  $\mu\text{mol/l}$   $\Delta^9$ -THC. The value of  $k$  ( $\mu\text{mol/l O}_2 \text{ min}^{-1}$ ) for untreated cells was 1.7, for cells treated with 10  $\mu\text{mol/l}$   $\Delta^9$ -THC 1.9, for cells treated with 20  $\mu\text{mol/l}$   $\Delta^9$ -THC 1.7, for cells treated with 50  $\mu\text{mol/l}$   $\Delta^9$ -THC 1.0 (41% inhibition), and for cells treated with 100  $\mu\text{mol/l}$   $\Delta^9$ -THC 0.8 (53% inhibition). The same experiment was repeated with  $\Delta^8$ -THC (not shown). The value of  $k$  for untreated cells was 1.9, for cells treated with 10  $\mu\text{mol/l}$   $\Delta^8$ -THC 2.0, for cells treated with 20  $\mu\text{mol/l}$   $\Delta^8$ -THC 2.0, for cells treated with 50  $\mu\text{mol/l}$   $\Delta^8$ -THC 1.8, and for cells treated with 100  $\mu\text{mol/l}$   $\Delta^8$ -THC 1.3 (32% inhibition). In other experiments, the inhibition with 120  $\mu\text{mol/l}$   $\Delta^9$ -THC was 48%, with 150  $\mu\text{mol/l}$   $\Delta^9$ -THC 76%, and with 100  $\mu\text{mol/l}$   $\Delta^8$ -THC 39%. Thus, the cannabinoids produced dose-dependent inhibition of Tu183 cellular respiration.

In another experiment, cells ( $0.5 \times 10^6/\text{ml}$ ) were treated at 37°C with 4  $\mu\text{l}$  MeOH or 25  $\mu\text{mol/l}$   $\Delta^8$ -THC (both added to 5-ml cell suspensions at minute zero). The cells were then harvested at 0 and 108 min, respectively for  $\text{O}_2$  measurement. The value of  $k$  ( $\mu\text{mol/l O}_2 \text{ min}^{-1}$ ) for un-



**Fig. 1.** Cannabinoids inhibit Tu183 cellular respiration. **a** TU183 cells ( $1.0 \times 10^6$ /ml) were suspended in media containing  $2 \mu\text{mol/l}$  Pd phosphor and  $0.5\%$  albumin with no addition (open circles and dashed line,  $r^2 > 0.991$ ) or with the addition of MeOH (closed circles and solid line,  $r^2 > 0.988$ ),  $200 \mu\text{mol/l}$   $\Delta^9$ -THC (squares and solid line,  $r^2 > 0.903$ ), or  $200 \mu\text{mol/l}$   $\Delta^8$ -THC (triangles and solid line,  $r^2 > 0.973$ ). Rates of respiration ( $k$ ,  $\mu\text{mol/l O}_2 \text{ min}^{-1}$ ) were set as the negative of the slopes. The lines are linear fits. The addition of  $10 \text{ mmol/l}$  NaCN (arrows) is shown. **b** Respiration of TU183 cells ( $0.5 \times 10^6$ /ml) were measured in the presence of  $0$ – $100 \mu\text{mol/l}$   $\Delta^9$ -THC. Open circles and dotted lines ( $r^2 > 0.987$ ), un-

treated; closed circles and solid lines ( $r^2 > 0.980$ ),  $10 \mu\text{mol/l}$ ; tri-angles and solid lines ( $r^2 > 0.988$ ),  $20 \mu\text{mol/l}$ ; squares and solid lines ( $r^2 > 0.980$ ),  $50 \mu\text{mol/l}$ ; diamonds and solid line ( $r^2 > 0.960$ ),  $100 \mu\text{mol/l}$ . **c** Respiration of TU183 cells ( $0.8 \times 10^6$  cells/ml) with injection of  $120 \mu\text{mol/l}$   $\Delta^9$ -THC. Best-fit curves ( $r > 0.977$ ) and values of  $k$  ( $\mu\text{mol/l O}_2 \text{ min}^{-1}$ ) are shown. **d**  $\Delta^9$ -THC inhibited  $\text{O}_2$  consumption by isolated mitochondria ( $12.5 \mu\text{g}$ ) from beef heart.  $\text{O}_2$  consumption was initiated with  $50 \text{ mmol/l}$  succinate. Other additions were  $2 \mu\text{l}$  EtOH,  $120 \mu\text{mol/l}$   $\Delta^9$ -THC,  $10 \text{ mmol/l}$  NaCN, and glucose ( $1.0 \text{ mmol/l}$ ) + glucose oxidase ( $7.0 \text{ units}$ ). Best-fit curves ( $r > 0.994$ ) and values of  $k$  ( $\mu\text{mol/l O}_2 \text{ min}^{-1}$ ) are shown.

treated cells was 1.5 and for  $\Delta^8$ -THC-treated cells 1.6. Thus,  $\Delta^8$ -THC at  $\leq 25 \mu\text{mol/l}$  was ineffective, even with 2 h exposure. The same experiment was then repeated with  $100 \mu\text{mol/l}$   $\Delta^8$ -THC. Cells ( $2.0 \times 10^6/\text{ml}$ ) were treated at  $37^\circ\text{C}$  without or with  $100 \mu\text{mol/l}$   $\Delta^8$ -THC. The cells were harvested at minutes 260 and 290, respectively, for  $\text{O}_2$  measurement. The value of  $k$  ( $\mu\text{mol/l O}_2 \text{ min}^{-1}$ ) for MeOH-treated cells was 9.5 and for  $\Delta^8$ -THC-treated cells 1.9 (80% inhibition). Thus, a prolonged exposure to  $100 \mu\text{mol/l}$   $\Delta^8$ -THC augmented the inhibition. The experiment was also repeated with  $40 \mu\text{mol/l}$   $\Delta^9$ -THC. Cells ( $0.5 \times 10^6/\text{ml}$ ) were treated at  $37^\circ\text{C}$  with  $3 \mu\text{l}$  EtOH or  $40 \mu\text{mol/l}$   $\Delta^9$ -THC (both added to 5-ml cell suspensions at zero minutes). The cells were harvested at minutes 124 and 227, respectively, for  $\text{O}_2$  measurement. The value of  $k$  for EtOH-treated cells was  $1.8 \mu\text{mol/l O}_2 \text{ min}^{-1}$  and for  $\Delta^9$ -THC-treated cells  $1.7 \mu\text{mol/l O}_2 \text{ min}^{-1}$ . Thus,  $\Delta^9$ -THC at  $\leq 40 \mu\text{mol/l}$  was ineffective, even with a long exposure.

To precisely determine the onset of respiratory inhibition,  $\Delta^9$ -THC ( $120 \mu\text{mol/l}$ ) was injected into the cell suspension during  $\text{O}_2$  measurement. The value of  $k$  ( $\mu\text{mol/l O}_2 \text{ min}^{-1}$ ) before any injection was 1.1 ( $4 \text{ min} < t < 30 \text{ min}$ ), after injecting  $2 \mu\text{l}$  EtOH 1.3 ( $35 \text{ min} < t < 60 \text{ min}$ ), after injecting  $120 \mu\text{mol/l}$   $\Delta^9$ -THC 1.0 ( $69 \text{ min} < t < 96 \text{ min}$ ; 23% inhibition) and 0.6 ( $99 \text{ min} < t < 126 \text{ min}$ ; 54% inhibition), and after injecting  $10 \text{ mmol/l}$  NaCN 0.4 ( $130 \text{ min} < t < 155 \text{ min}$ ; 69% inhibition). The remaining  $\text{O}_2$  was rapidly consumed when glucose oxidase was injected. The same experiment was repeated (fig. 1c). The value of  $k$  before the injection was 0.7 ( $0 \text{ min} < t < 60 \text{ min}$ ) and after injecting  $120 \mu\text{mol/l}$   $\Delta^9$ -THC 0.5 ( $65 \text{ min} < t < 215 \text{ min}$ ; 29% inhibition) and 0.3 ( $215 \text{ min} < t < 370 \text{ min}$ ; 57% inhibition). Thus,  $\Delta^9$ -THC caused immediate inhibition of respiration followed by further inhibition after  $\sim 150 \text{ min}$ . Rapid inhibition was also observed with injecting  $174 \mu\text{mol/l}$   $\Delta^8$ -THC (not shown).

Anandamide ( $120 \mu\text{mol/l}$ ), an endocannabinoid, did not inhibit cellular mitochondrial  $\text{O}_2$  consumption, suggesting the effect on respiration was not mediated by cannabinoid receptors.

ATP content was measured in Tu183 cells following incubation at  $37^\circ\text{C}$  for 60 min with  $12 \mu\text{l}$  EtOH or  $150 \mu\text{mol/l}$   $\Delta^9$ -THC (both added to 5-ml cell suspensions). For EtOH-treated cells, the average  $\pm$  SD of ATP level ( $n = 3$ ) was  $1.28 \pm 0.09 \text{ nmol}$  for  $2.4 \times 10^5$  cells. The presence of  $\Delta^9$ -THC led to  $\sim 64\%$  decrease in the ATP level,  $0.46 \pm 0.04 \text{ nmol}$  for  $2.4 \times 10^5$  cells. Addition of  $10 \text{ mmol/l}$  NaCN to the cells resulted in 22% decrease in the ATP level at 1 h, suggesting  $\Delta^9$ -THC treatment caused cellular ATP leak.

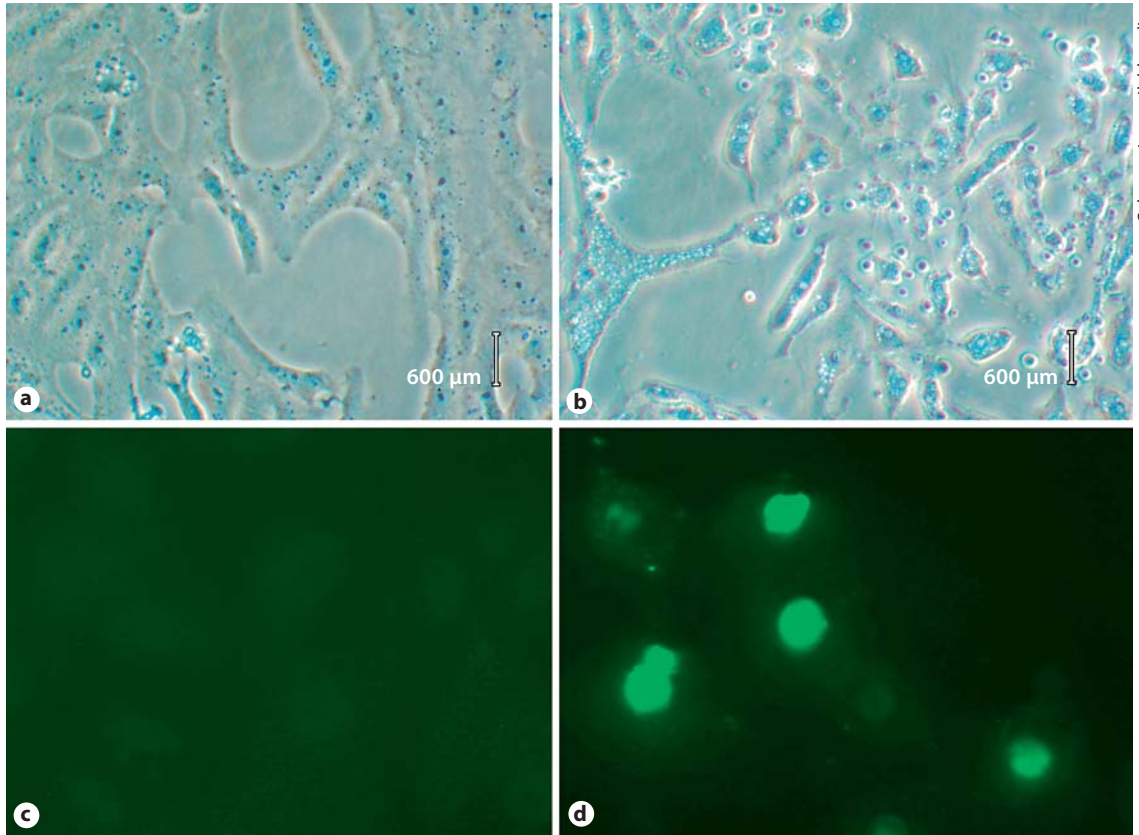
Figure 1d shows the effect of  $\Delta^9$ -THC on the respiration of isolated mitochondria from beef heart. In the presence of  $120 \mu\text{mol/l}$   $\Delta^9$ -THC, the value of  $k$  decreased from 2.6 to  $1.8 \mu\text{mol/l O}_2 \text{ min}^{-1}$  (30% inhibition). Complete inhibition of the respiration was observed with  $10 \text{ mmol/l}$  NaCN;  $\text{O}_2$  depletion was then observed with glucose plus glucose oxidase.

Figure 2a, b shows the morphologic effects of  $\Delta^9$ -THC treatment ( $120 \mu\text{mol/l}$  for 60 min) on Tu183 cells. Loss of cell-to-cell contact, nuclear condensation, membrane blebbing, cytoplasmic condensation and cytoplasmic vacuolization are evident. Some of these features were present as early as 25 min into the drug treatment. The ability of  $\Delta^9$ -THC to induce DNA fragmentation was then investigated by the TUNEL assay (fig. 2c, d). The cells were incubated at  $37^\circ\text{C}$  with EtOH (fig. 2c) or  $120 \mu\text{mol/l}$   $\Delta^9$ -THC (fig. 2d) for 60 min. Positive cells were noted with  $\Delta^9$ -THC (fig. 2d). No positive cells were seen when the cells were treated with  $120 \mu\text{mol/l}$   $\Delta^9$ -THC for  $\leq 30 \text{ min}$  (data not shown). In the viability test, the percentage (mean  $\pm$  SD,  $n = 12$ ) of trypan blue-positive cells for EtOH-treated cells was  $1.8 \pm 1.0$  and for  $\Delta^9$ -THC-treated cells ( $120 \mu\text{mol/l}$  for 60 min)  $6.5 \pm 4.3$  ( $p < 0.003$ ).

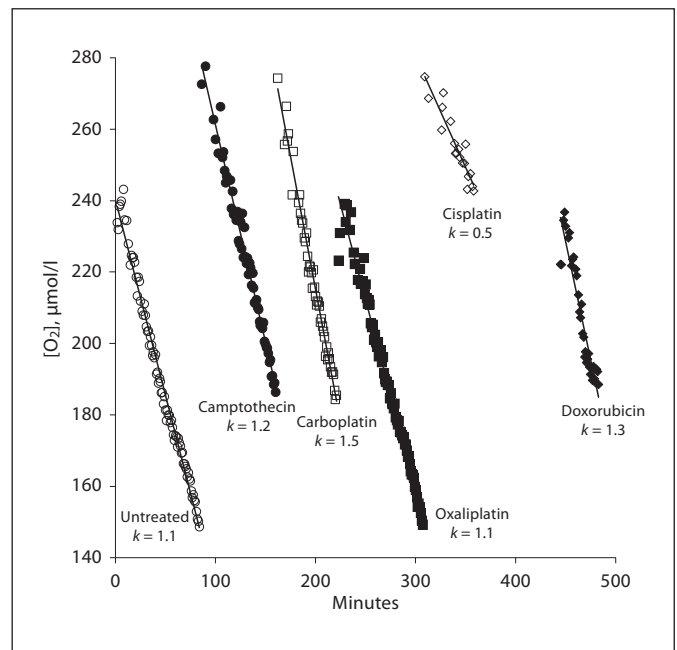
The effects of cannabinoids were then compared with that of other anticancer drugs. Tu183 cells are known to be resistant to chemotherapeutic agents. Therefore, a longer exposure to the drugs was used. The cells were treated at  $37^\circ\text{C}$  with  $2 \mu\text{l}$  dimethyl sulfoxide (control) or  $10 \mu\text{mol/l}$  camptothecin for 5 h. The rates of respiration for the two conditions were the same ( $1.1 \mu\text{mol/l O}_2 \text{ min}^{-1}$ ). In another experiment, the cells were treated at  $37^\circ\text{C}$  with  $25 \mu\text{mol/l}$  camptothecin, carboplatin, oxaliplatin, cisplatin or doxorubicin for 20 h. Inhibition of respiration (55%) was observed only in the cisplatin-treated cells (fig. 3).

## Discussion

Oral squamous cell carcinoma is the 6th most common malignancy. This cancer is responsible for the death of over 8,000 patients per year in the US [20]. The tumor remains one of the hardest to treat, not only because of its poor response to therapy, but also due to physical complications posed by the surgery [21]. Moreover, oral cancer cells (e.g., Tu183 cells) are known to adapt genetic changes that block cell death. Examples of such adaptations include mutations of *p53* and upregulation of *bcl-2* expression [12].



**Fig. 2.** Bright-field microscopy of Tu183 cells.  $\times 20$ . **a, b** Cells at 85% confluence in 5-ml media were treated at  $37^{\circ}\text{C}$  with  $10\ \mu\text{l}$  EtOH (**a**) or  $120\ \mu\text{mol/l}$   $\Delta^9$ -THC (**b**) for 60 min. TUNEL assay.  $\times 100$ . **c, d** Cells were grown in chamber slides ( $500\ \mu\text{l/well}$ ) overnight, and then treated at  $37^{\circ}\text{C}$  with  $1.0\ \mu\text{l}$  EtOH (**c**) or  $120\ \mu\text{mol/l}$   $\Delta^9$ -THC (**d**) for 60 min.



**Fig. 3.** Effects of anticancer drugs on Tu183 cellular respiration. Cells were treated at  $37^{\circ}\text{C}$  with  $25\ \mu\text{mol/l}$  camptothecin, carboplatin, oxaliplatin, cisplatin or doxorubicin for 20 h. The cells were then harvested, suspended in media plus  $2.0\ \mu\text{mol/l}$  Pd phosphor plus 0.5% albumin, and analyzed for  $\text{O}_2$  consumption. Best-fit curves ( $r > 0.939$ ) and values of  $k$  ( $\mu\text{mol/l O}_2\ \text{min}^{-1}$ ) are shown.

The Tu183 cells are derived from a squamous cell carcinoma of the tonsil [11]. This cell line, as shown in figure 3, is highly resistant to chemotherapeutic drugs [13]. We report here on the inhibitory effects of  $\Delta^9$ -THC and  $\Delta^8$ -THC on Tu183 cellular respiration (fig. 1). As early as 1975,  $\Delta^9$ -THC was shown to reduce growth of lung tumors in mice [22]. Studies have also shown that cannabinoids inhibit tumor cell proliferation, induce apoptosis and collapse  $\Delta\mu_{H^+}$  [2–8, 23]. These effects are functions of drug concentration and exposure time. For example, loss of  $\Delta\mu_{H^+}$  was observed in cultured pulmonary cells exposed to 40  $\mu\text{mol/l}$   $\Delta^9$ -THC for 1 h [10]. Moreover, in mice, in vivo treatment with  $\Delta^9$ -THC produced lymphocyte atrophy (apoptosis) at about 6 h [3], presumably due to release of the pro-apoptotic immune modulator interleukin-1 and block of the anti-apoptotic protein Bcl-2 [8]. In addition, activities of cannabinoids against oral cancer cells [4] and other tumors [5] have been reported.

Our results show that cannabinoids (especially  $\Delta^9$ -THC) are potent inhibitors of Tu183 cell respiration (fig. 1). Furthermore, the effect of  $\Delta^9$ -THC is immediate (fig. 1c) and more potent than that observed with commonly used anticancer drugs (fig. 3). On the other hand, anandamide (an endocannabinoid) is ineffective, suggesting that the effects of  $\Delta^9$ -THC and  $\Delta^8$ -THC are not mediated via the cannabinoid receptors.

The mechanism of cannabinoid-mediated impairment of cellular respiration (inhibition of mitochondrial  $\text{O}_2$  consumption and accompanying ATP synthesis) remains unknown.  $\Delta^9$ -THC is known to interfere with

components of the mitochondrial respiratory chain [17]. In addition to a direct inhibition of oxidative phosphorylation [17],  $\Delta^9$ -THC-induced proteases may impair other processes in ATP synthesis or hydrolysis [19]. Attempts to block the effect of  $\Delta^9$ -THC on respiration by using the pan-caspase inhibitor N-acetyl-asp-glu-val-asp-7-amino-4-trifluoromethyl coumarin were complicated by the fact that dimethyl sulfoxide (the vehicle) itself increased respiration in Tu183 cells. Since the inhibition of respiration is immediate (fig. 1c), it is unlikely that caspase activation (a timed process) is involved in the beginning. However, caspases could be activated later, as a consequence of decreased respiration or drug-induced apoptosis. These possibilities need further investigation.

The fact that  $\Delta^9$ -THC inhibits the respiration of isolated mitochondria from beef heart (fig. 1d) suggests a direct toxic interaction of the compound with mitochondria. It has been argued [17] that the polycyclic structure of  $\Delta^9$ -THC can have strong effects on membrane-dependent processes such as those of the inner mitochondrial membrane. Future studies are necessary to determine whether the cannabinoids can be used to treat patients with oral cancer.

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