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# *TRAIL-R3*-related apoptosis: Epigenetic and expression analyses in women with ovarian neoplasia

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ABSTRACT

*Objective.* To assess the expression of *TRAIL-R3* and the methylation of a CpG island within the *TRAIL-R3* promoter both in cystadenoma tumors and primary and metastatic epithelial ovarian carcinoma (EOC).

*Methods.* RNA was obtained from women with normal ovarian (NO) tissues (n = 18), ovarian serous cystadenoma tumors (n = 11) and EOC (n = 16) using Trizol®. Quantitative PCR (qRT-PCR) was performed to quantify the relative levels of *TRAIL-R3*. The methylation frequency of the CpG island in the *TRAIL-R3* promoter was assessed using the methylation-specific PCR (MSP) assay after DNA bisulfite conversion. The differences between the groups were evaluated using the chi-square, Student's t, ANOVA, Mann–Whitney U, Wilcoxon or Kruskal–Wallis tests as indicated. The survival rates were calculated using the Kaplan–Meier method.

*Results.* Cystadenoma and metastatic EOC tumors expressed significantly more *TRAIL-R3* mRNA than primary EOC tumors. Methylation of the *TRAIL-R3* promoter was absent in NO tissues, while hemimethylation of the *TRAIL-R3* promoter was frequently found in the neoplasia samples with 45.4% of the cystadenoma tumors, 8.3% of the primary EOC samples and 11.1% of the metastatic EOC samples showing at least partial methylation ($p = 0.018$). Neither the expression of *TRAIL-R3* nor alterations in the methylation profile were associated to cumulative progression-free survival or the overall survival in EOC patients.

*Conclusions.* Primary EOC is associated to a lower TRAIL-R3 expression, which leads to a better understanding of the complex disease and highlighting potential therapeutic targets. Promoter DNA methylation was not related to this finding, suggesting the presence of other mechanisms to transcriptional control.



## Introduction

Epithelial ovarian cancer (EOC) is the seventh most common cancer in women with an estimated 225,500 new cases and 140,200 deaths reported worldwide in 2008 [1]. Despite improvements in surgical management and advances in cytotoxic therapies, EOC still is the most common cause of death among women with gynecologic malignancies. This high death rate is mainly due to late-stage diagnoses (stage III or IV) and a poor prognosis with the present therapies [2,3]. The poor prognosis is commonly due to drug resistance caused by alterations in the cellular factors that regulate cell survival, differentiation, immunity, DNA repair and apoptosis [4,5].

Apoptosis, also known as programmed cell death, is fundamental for the development and homeostatic maintenance of complex biological systems [6,7]. The apoptotic process can be executed intracellularly by the release of a number of factors from the mitochondria (intrinsic pathways) or through the transmembrane death receptors (DRs), which are activated upon binding their cognate ligands (extrinsic pathway) such as TRAIL, a TNF-related apoptosis-inducing ligand that is a type II transmembrane protein. Apoptosis can also be induced by a pathway that involves T-cell mediated cytotoxicity and is dependent on the perforin granzyme [7–10].

Four homologous human receptors for TRAIL have been identified. TRAIL receptor 1 (TRAIL-R1/DR4/TNFRSF10A) [11] and TRAIL receptor 2 (TRAIL-R2/DR5/TRICK2/TNFRSF10B) [11–13] are capable of mediating apoptosis. Both TRAIL-R1 and TRAIL-R2 contain an extracellular cysteine-rich domain, a transmembrane domain and an intracellular death domain that can activate classic death signaling and lead to the activation of caspase 8 and caspase 10 [14,15]. In contrast, neither the decoy receptor (TRAIL-R3/TRID/DcR1/TNFRSF10C), which lacks a cytoplasmic domain [11,12,16], nor TRAIL receptor 4 (TRAIL-R4/DcR2/TNFRSF10D), which contains a truncated cytoplasmic death domain [17], transduces an apoptotic signal directly. In this report, the TRAIL receptors are called TRAIL-R1, TRAIL-R2, TRAIL-R3 and TRAIL-R4.

Alternatively, TRAIL can also activate the intrinsic pathway by cleaving the BH3-interacting domain death agonist (BID) that binds to the Bcl-2-associated X protein (BAX) and the Bcl-2 homologous

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antagonist killer (BAK) [18,19]. Intriguingly, TRAIL signaling can also induce the activation of NF-κB by phosphorylating of the inhibitor of κB (IκB), which leads to its degradation [20].

Targeted cancer therapies are emerging from investigations examining basic signaling mechanisms and molecular targets capable of inducing apoptosis in tumor cells. Although the activation of the apoptotic machinery by the DR ligands such as TRAIL represents a novel therapeutic strategy, little is known about the relevance of these receptors in ovarian neoplasia. Therefore, the aim of this study was to describe the genetic expression and epigenetic variation of *TRAIL-R3* in normal ovarian (NO) tissue, cystadenoma tumors, primary EOC and metastatic EOC. These analyses were performed to evaluate the prognostic significance of *TRAIL-R3* for patient survival.

## Materials and methods

### *Patients and histology*

This study included prospectively 45 women divided into the following three groups: EOC (n = 16), ovarian serous cystadenoma (n = 11) and normal ovary (n = 18). The study was performed in accordance with the Ethical Committee for Research in Human Beings guidelines of the Institution. An informed consent from all patients involved was also obtained. The tumor staging was performed according to the International Federation of Gynecology and Obstetrics (FIGO) recommendations [21]. In the EOC patients the samples were collected from primary tumor and a sample of metastatic tumor was collected when extra pelvic disease above 1 cm was observed. Normal ovarian epithelial tissue samples were taken from postmenopausal women who required a bilateral oophorectomy. After excision, the samples were immediately frozen in liquid nitrogen and stored at −80 °C until use.

### *The isolation of RNA and genomic DNA*

For RNA extraction, the preserved tissue samples (50–100 mg) were homogenized in 1 mL of TRIzol® (Life Technologies, Carlsbad, California, USA), and RNA from the tissues was isolated according to the manufacturer's instructions. The recovered RNA was then treated with an RNase-free DNase Set (Qiagen, Hilden, Germany). Genomic DNA (gDNA) was isolated from the inter-organic phase of the TRIzol®-chloroform mixture and then combined with 0.7 mL of back extraction buffer (4 mol/L guanidine isothiocyanate, 50 mmol/L sodium citrate and 1 mol/L Tris pH 8.0). After vigorous mixing by inversion, phase separation was achieved by centrifugation at 14,000×*g* for 15 min at 4 °C. The gDNA was then precipitated from the upper aqueous phase using 0.7 mL of isopropanol. The isolated gDNA from each fraction was dissolved in 20 μL of Milli-Q water and stored at −20 °C until use. The concentrations of RNA or gDNA along with the 260/280 absorbance ratio were measured using a NanoVue Pathlength Calibration Fluid Kit (GE Healthcare, Little Chalfont, Buckinghamshire, UK).

### *cDNA synthesis*

cDNA was generated from 2 mg of total RNA using Illustra Ready-to-Go RT-PCR Beads (GE Healthcare, Little Chalfont, Buckinghamshire, UK) in a total volume of 50 μL according to the manufacturer's instructions.

### *Quantitative PCR analysis*

The qRT-PCR was performed using an Agilent MX 3005P detection system (Stratagene, Cedar Creek, TX, USA) with duplicate 10 μL reactions containing 1× Brilliant II SYBR® Green QPCR Master Mix (Stratagene, Cedar Creek, TX, USA), 0.2 μL of Rox (1:500), 0.2 μM of each primer, and 40 ng/μL cDNA (RNA equivalent) for each experiment.

Glyceraldehyde 3-phosphate dehydrogenase (*GAPDH)* and TATA Binding Protein (*Tbp*) were used as reference loci for normalization. The sequences of the specific primers used in this study for *GAPDH* (GenBank ID: NM_002046), *Tbp* (GenBank ID: NM_003194) [22] and *TRAIL-R3* (GenBank ID: NM_003841.3) [23] have been previously reported.

The PCR cycling conditions were performed as follows: 95 °C for 10 min and 40 cycles of 95 °C for 30 s, annealing at 60 °C for 60 s (for *TRAIL-R3* and *Tbp)* or 62 °C for 60 s (for *GAPDH*) and extension at 72 °C for 30 s. Each 40-cycle reaction was performed in duplicate.

The optimization of the qRT-PCR reaction was performed according to the manufacturer's instructions. A sample without a template (no cDNA in the PCR) was included as a control in each assay. A melting curve was constructed for each primer pair to confirm product specificity. The efficiency-corrected comparative quantitation method was used to calculate the relative quantities of *TRAIL-R3*.

### *Bisulfite conversion*

gDNA was modified with sodium bisulfite using a Bisulfite Conversion Kit (Applied Biosystems, Foster City, USA) according to the manufacturer's instructions.

### *Methylation-specific polymerase chain reaction (MSP)*

The *TRAIL-R3* primers used to amplify the bisulfite-modified DNA were obtained from the DNA methylation analysis PCR primer

**Table 1**
Clinicopathologic characteristics in ovarian sample.

| | Normal ovary | Cystadenoma | EOC | p value |
|---|---|---|---|---|
| | n = 18 | n = 11 | n = 16 | |
| Age (years) | 50.61 ± 2.13 | 54.3 ± 5.1 | 59.1 ± 2.7 | 0.128 |
| Parity (births) | 2.83 ± 0.44 | 2.3 ± 0.8 | 1.9 ± 0.3 | 0.356 |
| CA-125 (U/mL) | | | | |
| CA < 330 (U/mL) | | 11 (100%) | 8 (50%) | |
| CA > 330 (U/mL) | | 0 | 8 (50%) | |
| Tumor differentiation degree | | | | |
| G2 | | | 6 (37.5%) | |
| G3 | | | 10 (62.5%) | |
| Cytoreduction | | | | |
| Optimal (<1 cm) | | | 7 (43.8%) | |
| Suboptimal (>1 cm) | | | 9 (56.3%) | |
| Stage | | | | |
| Stages I and II | | | 5 (31.8%) | |
| Stages III and IV | | | 11 (68.8%) | |
| Ascites | | | | |
| Yes | | | 10 (64.3%) | |
| No | | | 6 (35.7%) | |
| Recurrence | | | | |
| Yes | | | 6 (37.5%) | |
| No | | | 10 (62.5%) | |
| Mortality | | | | |
| Yes | | | 6 (37.5%) | |
| No | | | 10 (62.5%) | |
| Menarche | | 12.8 ± 0.4 | 12.8 ± 3.4 | 0.991 |
| Menopause | | | | |
| Yes | 18 (100%) | 6 (54.5%) | 13 (81.3%) | 0.008 |
| No | 0 | 5 (45.5%) | 3 (18.8%) | |

EOC: epithelial ovarian carcinoma. The values represent the mean ± standard error or n (percentage). The comparison between groups was performed by a chi-square test or an ANOVA as indicated. The median serum level of CA-125 was considered to determine the cut-off point. The tumor differentiation degree was classified as moderately differentiated (G2) or poorly differentiated (G3). Cytoreduction was considered optimal for a residual tumor of <1 cm after tumor resection surgery. The tumor was staged according to the 2009 recommendations of FIGO (International Federation of Gynecology and Obstetrics). A p value ≤ 0.05 was considered to be statistically significant.

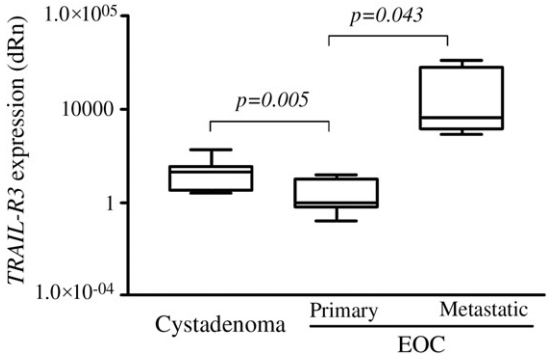


**Fig. 1.** The association of TRAIL-R3 expression in ovarian tumors. The values shown represent the TRAIL-R3 expression levels. The horizontal line indicates the median expression ratio, and the box plots demonstrate the interquartile range (25–75%). The 10th to 90th percentile ranges are also shown. The differences between groups were evaluated using a Mann–Whitney *U* test and a Wilcoxon test. EOC: epithelial ovarian carcinoma.

database [24]. MSP was performed in a total volume of 15 μL containing 10 ng of bisulfite-treated DNA, 1× Brilliant II Master Mix (Stratagene, Cedar Creek, TX, USA) and 1 μM of each primer. Reactions containing unmethylated DNA, methylated DNA or unmethylated bisulfite-converted DNA (Epitech Control DNA Set — Qiagen, Hilden, Germany) were performed as controls. The amplification was performed with the following conditions: 95 °C for 10 min; 30 cycles of 95 °C for 1 min, 55 °C for 1 min, and 72 °C for 30 s; and a final extension step for 10 min at 72 °C. The amplified MSP products (3 μL) were separated by electrophoresis on 4–15% PhastGels (GE Healthcare, Little Chalfont, Buckinghamshire, UK) and visualized by silver nitrate staining.

### *Statistics*

All statistical analyses were performed with the SPSS 18.0 software package (SPSS Inc., Chicago, IL, USA). The data were expressed as a percentage, the mean ± standard error, or the median with the interquartile range. The differences between the groups were evaluated using the chi-square, Student's t, ANOVA, Mann–Whitney U or Wilcoxon tests as indicated. The associations between the methylation level, clinical parameters and gene expression levels were compared using the Kruskal–Wallis test. The survival rates were calculated using the Kaplan–Meier method. A p value less than 0.05 was considered to be statistically significant.

## Results

### *Individuals*

The general sample characteristics are listed in Table 1. The patients included in this study were between 32 and 81 years old with a mean age of 54 ± 5 years ($p = 0.128$). The mean parity was 2.3 ± 0.3 births with a range between 0 and 8 deliveries ($p = 0.356$). The only statistically significant difference between the groups was in the frequency of menopause ($p = 0.008$). The stage (FIGO) was I/II in 5 patients (31.8%) and III/IV in 11 patients in the EOC group (68.8%). The tumor was moderately differentiated (G2) in 6 (37.5%) and poorly differentiated in 10 (62.5%) cases.

### *The reliability of the qRT-PCR*

The variation between the number of samples occurred due to the success rate of sufficient quality and quantity DNA/RNA (varying by assays), which determined the sample number for downstream platforms. The RNA extraction success rate was 17/18 (94.4%) for normal ovary, 11/11 (100%) in benign tumor, 8/12 (66.7%) in primary EOC and 8/9 (88.9%) in metastatic EOC samples. For DNA, the success rate of extraction was 100% for all. The absorbance ratios at 260/280 nm for the isolated RNA from the tissue samples were 1.1–2.0 (±0.23).

The efficiency, slope, and $R^2$ values for the reference and target genes were calculated by MxPro analysis software on the Agilent MX 3005P device. The $R^2$ value is a calculated assessment of the fit of the standard curve to the data points plotted.

Some housekeeping genes, which were already used in various studies, were validated by our group employing GeNorm [25] to determine the expression stability. Within all of the genes tested, the *Tbp* gene was found to have the most stable gene expression (data not shown); therefore, this gene was used for subsequent normalization of the ovarian tissue.

### *The gene expression data*

Significant differences were found in the *TRAIL-R3* expression levels in the ovarian tumor groups (Fig. 1). Ovarian serous cystadenoma tumors and metastatic EOC were associated with a

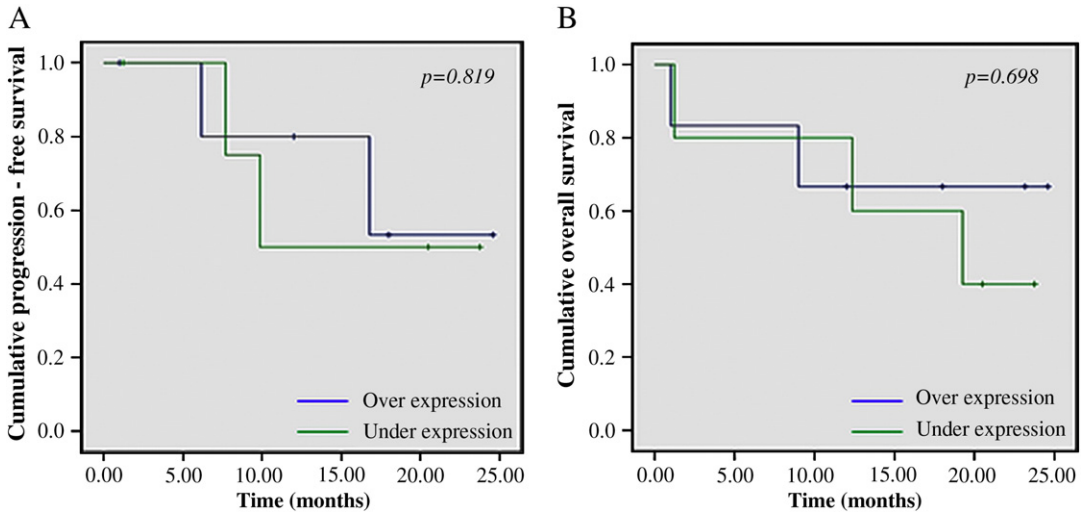


**Fig. 2.** A Kaplan–Meier analysis of the cumulative progression-free survival (A) and overall survival (B) among 11 women with primary EOC grouped according to their TRAIL-R3 expression levels. EOC: epithelial ovarian carcinoma.

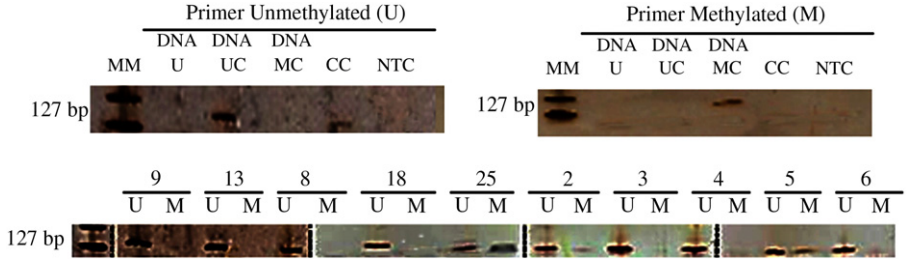


**Fig. 3.** An analysis of the CpG island promoter methylation status in TRAIL-R3 by the methylation-specific polymerase chain reaction (MSP) assay. The 127-base-pair TRAIL-R3 product was analyzed on 4–15% PhastGels. U represents amplified products from primers specific to an unmethylated DNA sequence in the TRAIL-R3 promoter, and M represents amplified products from primers specific to a methylated sequence in the TRAIL-R3 promoter. MM: DNA molecular marker; DNA U: unmethylated control DNA; DNA UC: unmethylated control DNA after bisulfite conversion; MC: bisulfite converted methylated control DNA (Qiagen, Hilden, Germany) serves as control for the methylated and unmethylated sequences; CC: serves as methylSEQr™ bisulfite conversion control; 8, 18, 2, 3, 5 and 6: cystadenoma tumors; 9, 13 and 4: primary EOC samples; 25: normal ovarian tissue. The sample was considered to be unmethylated when the product was detected with primer U, and the sample was considered to be hemimethylated when the product was detected with primers U and M.

higher *TRAIL-R3* expression compared to primary EOC ($p = 0.005$ and $p = 0.043$; respectively).

The median *TRAIL-R3* expression ratio in the ovarian serous cystadenoma was 21.87 (2.97—39.88), while in primary EOC the expression ratio was 0.93 (0.47–8.1). In this case, a significant difference in the *TRAIL-R3* expression level was observed between the cystadenoma tumor group ($n = 11$) and the primary EOC group ($n = 8$) ($p = 0.005$). In metastatic EOC, overexpression of *TRAIL-R3* (≥38-fold higher than the basal level) was also detected with a median expression ratio of 4525.36 (997.9–38,400). This level of *TRAIL-R3* expression was also significantly higher than the level found in primary EOC ($p = 0.043$) (Fig. 1).

No significant associations were observed between the *TRAIL-3* expression level in primary EOC and the cumulative progression-free survival or the overall survival (Fig. 2).

### *The DNA methylation status of TRAIL-R3*

With the use of primers specific for methylated or unmethylated *TRAIL-R3*, a 127-base-pair *TRAIL-R3* product was detectable in all positive controls from a MSP that used bisulfite-treated genomic DNA as the template. Representative examples of the MSP products run on 4–15% PhastGels are shown in Fig. 3.

All of the normal tissues tested were completely unmethylated, whereas the methylation of at least one allele (hemimethylation) of *TRAIL-R3* was found in 45.4% (5/11) of the cystadenoma tumors, 8.3% (1/12) of the primary EOC samples and 11.1% (1/9) of the metastatic EOC samples ($p = 0.018$) (Fig. 4).

No statistically significant associations were found between the methylation status of the *TRAIL-R3* promoter and the cumulative progression-free survival or the overall survival of the EOC patients (Fig. 5).

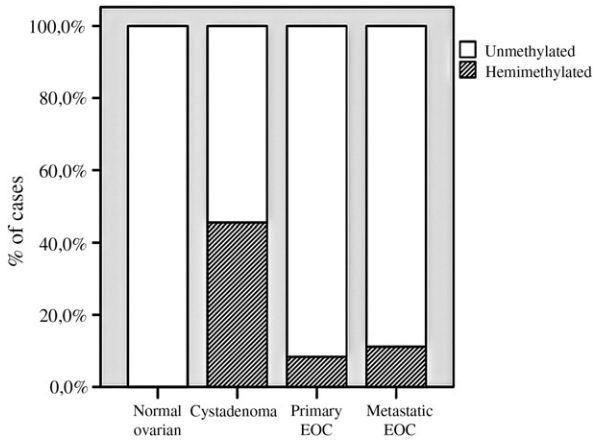


**Fig. 4.** The frequency of aberrant CpG island methylation in the TRAIL-R3 promoter. All normal tissues tested were completely unmethylated. Hemimethylation was detected in 45.45% (5/11) of the cystadenoma tumors, 8.3% (1/12) of the primary EOC samples and 11.11% (1/9) of the metastatic EOC samples. The differences between the groups were evaluated by the Kruskal–Wallis test ($p = 0.018$).

## Discussion

EOC is the deadliest gynecologic malignancy, and considerable variation exists between patients in the extent of the response to current therapies [3,26,27]. An improved understanding of the molecular pathogenesis of ovarian cancer will provide new treatment possibilities. Because apoptosis is a gene-controlled process that plays an important role in development and the progression of carcinoma, it makes an attractive target for cancer treatment. However, tumors that are resistant to apoptosis are likely to be resistant to cancer therapy and therefore would be responsible for relapses [28].

Death receptors have emerged as potential anticancer targets. However, despite the ability of TNF and FasL to induce apoptosis in cancer cells, severe toxic side effects have prevented both ligands from being used as anticancer therapies. The systemic administration of TNF, FasL or the agonistic anti-Fas antibody caused an inflammatory response resembling septic shock in humans and lethal liver injuries in preclinical models [29]. In contrast, TRAIL exogenously administered has shown a potent tumoricidal activity is observed in cancer cells both *in vitro* and *in vivo*. [14,18,29]. TRAIL treatment also appeared to not induce toxicity in normal cells [5,18,19]. TRAIL therapies are currently in phase I and phase II clinical trials after having previously shown promising results in animal models [19].

Using quantitative PCR, we investigated the expression of *TRAIL-R3* in ovarian cystadenoma, primary and metastatic EOC considering normal ovary tissue as the baseline for the expression of the gene of interest. The results were calculated as relative quantity to the NO, where NO sample was assigned an arbitrary quantity of "1" and all tumors samples are expressed in terms of their fold difference to this sample [30]. We found that the ovarian cystadenoma and metastatic EOC tissue samples tested expressed significantly more *TRAIL-R3* mRNA than primary EOC. The higher level of *TRAIL-R3* expression found in cystadenoma could arise from the increased proliferation inherent of this tumor type.

The 38-fold higher level of *TRAIL-R3* expression in metastatic EOC compared to primary EOC could potentially be attributed to the increased proliferation rate and apoptosis resistance found in metastasis. Multiple studies have demonstrated that the overexpression of TRAIL-R3 or TRAIL-R4 confers resistance to TRAIL-induced cell death in several tumor cell lines and primary tumors [31–34]. To our knowledge, there is no other study addressing specifically the role of TRAIL-R3 and TRAIL-4 in metastatic tumors.

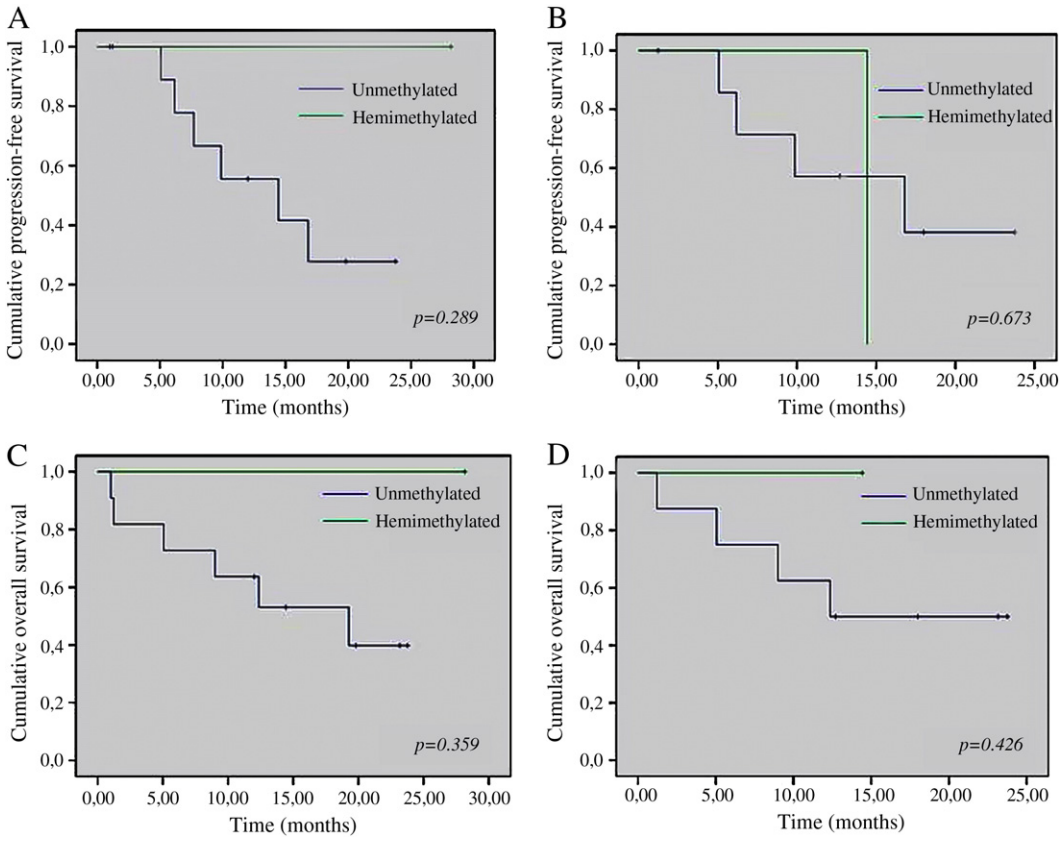


**Fig. 5.** A Kaplan–Meier analysis of the cumulative progression-free survival and overall survival among women with primary EOC (A and C) and metastatic EOC (B and D) grouped according to their TRAIL-R3 methylation status. The associations between TRAIL-R3 hemimethylation and the survival times did not reach statistical significance. EOC: epithelial ovarian carcinoma.

Previously, one of the simplest explanations proposed for TRAIL resistance was the occurrence of mutations in the genes encoding the death receptors [35]. However, the TRAIL receptors without an intracellular death domain or a truncated cytoplasmic death domain are reported to act as nonfunctional "decoy receptors" that compete for TRAIL binding and protect cells from TRAIL-mediated apoptosis [18,20,35,36]. In addition to TRAIL-R3 and TRAIL-R4 leading to apoptosis resistance, recent investigations have shown that these receptors also can induce non-apoptotic signaling pathways, including Akt, NF-kB and MAPK signaling. TRAIL-R3 and TRAIL-R4 have also been shown to enhance cellular proliferation, differentiation and growth [15,20,37]. TRAIL-R3 and TRAIL-R4 could be responsible for the apoptosis evasion and metastasis in EOC. Therefore, the lower *TRAIL-R3* mRNA expression found in the primary EOC tissue samples could potentially be used as a biomarker for determining the therapeutic index for TRAIL-mediated therapy in EOC. The increasing knowledge of the apoptotic pathways in EOC provides many theoretical opportunities to manipulate the apoptotic components that lead to an increased rate of tumor cell death.

To analyze the molecular mechanisms involved in the regulation of *TRAIL-R3* expression, we examined the methylation pattern of the *TRAIL-R3* promoter, as hypermethylation can selectively down-regulate gene expression. The methylation of CpG islands located in the promoter regions of genes is especially important to examine as these regions can be used as biomarkers with clinical implications [38]. Our study noted significant differences between methylation profile and ovarian histological subtypes. Promoter methylation was absent in NO tissue, whereas *TRAIL*-R3 methylation was a frequent event found in at least one allele of the *TRAIL-R3* gene in ovarian serous cystadenoma, metastatic and primary EOC samples respectively. We also found fewer methylated CpG islands in both normal and ovarian tumor tissues compared to other results reported for ovarian cell lines. Notably, the DNA methylation levels tended to be higher in the ovarian cell lines compared to the clinical ovarian tumor samples [39].

In contrast with recent studies that correlated the methylation of tumor-suppressor genes with the down-regulation of gene expression in tumor samples and cell lines [39,40], we found that the presence of hemimethylation of the *TRAIL-R3* promoter in tumors was not associated with *TRAIL-R3* epigenetic silencing, suggesting the presence of other mechanisms to control this gene expression in EOC. Neither the *TRAIL-R3* expression level in primary EOC nor the presence of *TRAIL-R3* hemimethylation was significantly associated with the cumulative progression-free survival and overall survival.

The current findings add substantially to our understanding of the carcinogenesis process in EOC. The lower *TRAIL-R3* expression in EOC suggests the idea for the potential use of TRAIL-mediated therapy in EOC. Promoter DNA methylation was not the single mechanism that led to *TRAIL-R3* gene silencing. Therefore, broader research is needed to determine other targets in TRAIL signaling network in EOC. The most important limitation lies in the fact that the number of patients and controls was relatively small. Further studies with a larger number of patients and longer follow-up are necessary to assess the accuracy of the diagnostic and prognostic impact of these results.

**Conflict of interest statement**
The authors have no conflicts of interest to declare.

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*Advances in Brief*

# Molecular Determinants of Response to TRAIL in Killing of Normal and Cancer Cells[1]

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## Abstract

**The tumor necrosis factor-related apoptosis-inducing ligand (TRAIL or Apo2L) is a potent inducer of death of cancer but not normal cells, which suggests its potential use as a tumor-specific antineoplastic agent. TRAIL binds to the proapoptotic death receptors DR4 and the p53-regulated proapoptotic KILLER/DR5 as well as to the decoy receptors TRID and TRUNDD. In the present studies, we identified a subgroup of TRAIL-resistant cancer cell lines characterized by low or absent basal DR4 or high expression of the caspase activation inhibitor FLIP. Four of five TRAIL-sensitive cell lines expressed high levels of DR4 mRNA and protein, whereas six of six TRAIL-resistant cell lines expressed low or undetectable levels of DR4 ($\chi^2$; $P < 0.01$). FLIP expression appeared elevated in five of six (83%) TRAIL-resistant cell lines and only one of five (20%) TRAIL-sensitive cells ($\chi^2$; $P < 0.05$). Two TRAIL-resistant lines that expressed DR4 contained an A-to-G alteration in the death domain encoding arginine instead of lysine at codon 441. The K441R polymorphism is present in 20% of the normal population and can inhibit DR4-mediated cell killing in a dominant-negative fashion. The expression level of KILLER/DR5, TRID, TRUNDD or TRID, and TRUNDD did not correlate with TRAIL sensitivity ($P > 0.05$). These results suggest that the major determinants for TRAIL sensitivity may be the expression level of DR4 and FLIP. TRAIL-resistant cells became susceptible to TRAIL-mediated apoptosis in the presence of doxorubicin. In TRAIL-sensitive cells, caspases 8, 9, and 3 were activated after TRAIL treatment, but in TRAIL-resistant cells, they were activated only by the combination of TRAIL and doxorubicin. Our results suggest: (*a*) evaluation of tumor DR4 and FLIP expression and host DR4 codon 441 status could be potentially useful predictors of TRAIL sensitivity, and (*b*) doxorubicin, in combination with TRAIL, may effectively promote caspase activation in TRAIL-resistant tumors.**

## Introduction

TRAIL[3], a member of the TNF cytokine family and a type II membrane protein, was initially identified by homology to the C-terminal extracellular domain of other TNF family members, such as Fas ligand (FasL), TNF-α, and lymphotoxin α (1). TRAIL is a potent inducer of apoptosis in a variety of transformed or cancer cells of human and mouse origin but not normal cells (1, 2).

The therapeutic use of the Fas/FasL or the TNF-α/TNFR1 system in cancer treatment has been hampered by severe side effects (3). The systemic administration of TNF causes a septic shock-like response possibly mediated by nuclear factor-κB activation, and the injection of agonist Ab to Fas can be lethal (3, 4). Compared to TNF-α or Fas, TRAIL may be a safer alternative because normal cells appear to be resistant, and it activates nuclear factor-κB only weakly (5). Recently, evidence for the safety and potential efficacy of TRAIL therapy against breast and colon cancer was obtained in a severe combined immunodeficiency mouse model (6, 7). Additionally, in cell culture, the human leucine zipper (LZ)-TRAIL had no cytotoxic effects on normal cells, including human mammary epithelial cells, human renal proximal tubule epithelial cells, human lung fibroblasts, and human skeletal muscle cells but was toxic toward mammary adenocarcinoma cells (6). The *in vivo* experiments showed that the systemic administration of LZ-TRAIL into mice inoculated with breast cancer cells prolonged survival. These studies suggest that TRAIL may have a potential use for cancer treatment.

TRAIL can modulate an apoptotic response by binding to one of four cell-surface receptors: Death receptor (DR) 4 (TRAIL-R1; Ref. 8), KILLER/DR5 (TRAIL-R2, TRICK2; Refs. 9–12), TRID (DcR1, TRAIL-R3, or LIT; Refs. 5, 10, 13, and 14), and TRUNDD (DcR2 or TRAIL-R4; Refs. 15–17). DR4 and KILLER/DR5 have two cysteine-rich extracellular ligand-binding domains and a cytoplasmic death domain that signals downstream caspase activation (2, 18). KILLER/DR5 was identified as a candidate p53 target gene, linking DNA

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[3] The abbreviations used are: TRAIL, tumor necrosis factor-related apoptosis-inducing ligand; Ab, antibody; TNF, tumor necrosis factor; MTT, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide; GAPDH, glyceraldehyde-3-phosphate dehydrogenase; RT-PCR, reverse transcription-PCR; TRUNDD, TRAIL decoy receptor containing a truncated death domain; TRID, TRAIL decoy receptor lacking an intracellular domain; KILLER/DR5, p53-regulated proapoptotic KILLER/death receptor 5; FLIP, FLICE inhibitory protein; PARP, poly ADP-ribose polymerase; FADD, FAS-associated death domain protein; CMV-β-gal, cytomegalovirus β-galactosidase; mAb, monoclonal Ab.

damage signaling from p53 to downstream caspase activation and cell death (9). The extracellular domain of TRID shares a homology with DR4 and KILLER/DR5, but it does not have a cytoplasmic death domain, and it is anchored to the membrane through a glycosyl phosphatidyl inositol linkage. TRUNDD has a substantially truncated cytoplasmic death domain. These two decoy receptors have been reported to protect cells from TRAIL-mediated apoptosis by competing with DR4 and KILLER/DR5 for binding to TRAIL (10).

The TRAIL-mediated biochemical signaling pathway leading to apoptosis is not yet clear. Previously, it was reported that the ectopic expression of FADD-DN (dominant-negative FADD, which blocks apoptotic signaling by the Fas/APO1 death receptor) does not efficiently block apoptosis triggered by TRAIL, and that overexpression of DR4 could induce apoptosis in FADD-deficient embryonic fibroblasts (19). These studies suggest that a FADD-independent pathway may link TRAIL to the caspase cascade (2, 19, 20). Moreover, it was shown that DR4 does not efficiently recruit FADD, TNF receptor-associated death domain (TRADD) protein, receptor interacting protein (RIP), or RIP-associated ICH-1/CED-3 homologous protein (RAIDD; Ref. 10). Although at present there is a missing link between TRAIL death receptors and caspase activation, it is clear that once TRAIL binds to its receptors, apoptosis ensues through the activation of caspases (5, 8, 10). Initiator caspases (caspases 8, 9, and 10) are composed of an N-terminal prodomain that contains the region for homotypic protein-protein interaction with adaptor molecules together with one large and one small subunit. When cells receive death-inducing signals, the prodomain is cleaved, and an active heterodimeric tetramer containing two small and two large subunits is formed. It was reported that caspases 3 and 8 became activated when HeLa cells were treated with TRAIL (21) and also that in TRAIL-sensitive breast cancer cell lines, caspase 3 cleavage was observed (22). In addition, a recent report that T lymphocytes that have catalytically inactive caspase 10 are TRAIL-resistant implicates caspase 10 in TRAIL-mediated apoptosis (23).

Although the efficacy and potential use of TRAIL in cancer treatment has been suggested, little is known about the factors that determine the sensitivity of cancer cells to killing by TRAIL. Recently, there were some reports on the determinants of TRAIL sensitivity in breast cancer cells (22), melanoma (24), and brain tumors (25, 26). The results have been somewhat controversial in that some reports showed no correlation between TRAIL sensitivity and the expression level of proapoptotic death receptors, whereas others demonstrated a correlation between them.

We investigated the expression level of various TRAIL receptor family members as determinants for TRAIL sensitivity and whether a DNA-damaging chemotherapeutic drug such as doxorubicin might have additive effects with TRAIL in killing cancer cells. We report here that the expression of the proapoptotic TRAIL receptors, in particular DR4, and the caspase activation inhibitor FLIP may be major determinants of TRAIL sensitivity. In addition to the expression level of DR4, a polymorphism found in the death domain region of DR4 prevents DR4-mediated cell killing in a dominant-negative fashion. Finally, we also report that a DNA damaging agent such as doxorubicin can sensitize cells to TRAIL-mediated cell killing. Our results provide essential preclinical information that may be useful in the design of clinical trials using recombinant TRAIL in the therapy of human cancer.

## Materials and Methods

**Cell Lines.** Human lung fibroblast WI38 and human foreskin fibroblast HS27 cells were obtained from the American Type Culture Collection (Rockville, MD). The human ovarian cancer cell line SKOV3, the human breast cancer cell line SKBr3, and the human nasopharyngeal squamous cancer cell line FADU were also obtained from the American Type Culture Collection. The human lung cancer cell lines H460 Neo/E6, the human colon cancer cell lines HCT116 Neo/E6, the human ovarian cancer cell lines PA1 Neo/E6, and the human colon cancer cell line SW480 were maintained as described previously (27). The J82 human bladder cancer cell line was a gift from T. McGarvey and B. Malkowicz (University of Pennsylvania, Philadelphia, PA), and the A875 human melanoma cell line was a gift from D. George (University of Pennsylvania, Philadelphia, PA).

**Assessment of Cell Viability.** Recombinant soluble human TRAIL was purchased from Kamiya Biomedical Co. (Seattle, WA), and the anti-FLAG M2 mAb was purchased from Sigma (Saint Louis, MI). Three thousand cells were seeded into each well of a 96-well plate. After 24 h, the cells were treated with TRAIL (200 ng/ml) and cross-linked with the anti-FLAG M2 mAb (2 μg/ml). Cell viability was measured by using the MTT assay at 16 h after treatment (28). When normal cells were treated with both doxorubicin and TRAIL, the cells were treated with increasing concentrations of chemotherapeutic drugs alone (doxorubicin, 0, 0.1, 1, 10, and 100 μg/ml) or in combination with TRAIL (20 ng/ml) cross-linked with the anti-FLAG M2 Ab (2 μg/ml). To assess the long-term effect of TRAIL, a total of $5 \times 10^4$ of each cell line were seeded in triplicate into 24 wells, and at 24 h, cells were treated with TRAIL (50 ng/ml) and the anti-FLAG M2 Ab (2 μg/ml). The media containing TRAIL and Ab was changed every 48 h, and the culture was maintained for 7 days, at which time the remaining cells were stained with Coomassie Blue.

**Semiquantitative RT-PCR.** Total RNA was isolated from cell lines as described (29). cDNA was generated from 2 μg of total RNA in a final volume of 20 μl using SuperScript II (Life Technologies, Inc., Gaithersburg, MD) and random primers. The sequences of specific primers used in this experiment were as follows: DR4 F, 5′-CGATGTGGTCAGAGCTGGTACAGC-3′; DR4 R, 5′-GGACACGGCAGAGCCTGTGCCATC-3′; KILLER/DR5 F, 5′-GGGAGCCGCTCATGAGGAAGTTG G-3′, KILLER/DR5 R, 5′-GGCAAGTCTCTCTCCCAGCGTCTC-3′; TRID F, 5′-GTTTGTTTGAAAGACTTCACTGTG-3′, TRID R, 5′-GCAGGCGTTTCTGTCTGTGGGAAC-3′; TRUNDD F, 5′-CTTCAGGAAACCAGAGCTTCCCTC-3′, TRUNDD R, 5′-TTCTCCCGTTTGCTTATCACACGA-3′; GAPDH F, 5′-ACCACAGTCCATGCCATCAC-3′, GAPDH R, 5′-TCCACCACCCTGTTGCTGTA-3′.

To analyze the expression level of the death receptors, 2 μl (out of 20 μl) of synthesized cDNA was amplified in a total volume of 50 μl containing 200 μM each of all four dNTPs, 2 μCi α-$^{32}$P-dCTP (3000 Ci/mmol), 2 μM each of death receptor-

specific primer set along with 2 μM each of the GAPDH primers, and 1 unit of *Taq* DNA polymerase (Perkin-Elmer). The cycle numbers that showed linear growth of product were initially determined for each PCR product by analyzing a 10-μl sample from multiple identical amplification reactions (Fig. 2*A* and data not shown). In the case of DR4 and KILLER/DR5, 23 cycles were chosen; for TRID and TRUNDD, 24 cycles were chosen; and in the case of GAPDH, 18 cycles were chosen. During PCR, 10 μl of the reaction were remove at the indicated cycle numbers. PCR conditions were as follows: 1 cycle, 5 min/95°C; 23 or 24 cycles, 30 s/95°C, 30 s/55°C (for DR4, KILLER/DR5, and TRUNDD), 52°C (for TRID), or 30 s/72°C. Nondenaturing PAGE (7%) was performed, and the gel was fixed, dried, and autoradiographed. Band intensities were quantitated by using a Phosphorimager Storm 840 (Molecular Dynamics, Sunnyvale, CA).

**Genomic DNA Isolation and Cycle Sequencing.** Whole blood (20 ml) from 10 normal healthy volunteers was drawn, and genomic DNA was isolated using the Blood and Cell culture DNA maxi kit (QIAGEN Inc., Valencia, CA). The DNA (50 ng) was used as a template for the amplification of the DR4 death domain region spanning nucleotide 1322. Sequences of primers used in PCR are as follows: DR4 11, 5′-CTCTGATGCTGTTCTTTGAC-3′, DR4 12, 5′-TCACTCCAAGGACACGGCAGA-3′. After amplification, each PCR product was visualized and purified from an agarose gel using the QIAquick gel extraction kit (QIAGEN Inc.) and was then used as a DNA sequencing template. Cycle sequencing was performed using a SequiTherm cycle sequencing kit (Epicentre Technologies, Madison, WI) according to the manufacturer's instructions.

**Site-directed Mutagenesis and Sequencing.** Site-directed mutagenesis was performed using a Quick change site-directed mutagenesis kit (Stratagene, La Jolla, CA) according to the manufacturer's instructions. To change a base in the death domain region of DR4 (A to G at nucleotide 1322 of DR4), plasmids that contained either the full-length DR4 (f/DR4 (A) in pCEP4, Invitrogen, Carlsbad, CA) or the cytoplasmic domain of DR4 (CD/DR4 (A) in pcDNA3.1-Myc, His; Invitrogen, Carlsbad, CA) were used as templates. The sequences of the primer pairs used for changing the base were as follows: DR4DDMUT F,5′-GGAAGAGAGACATGCAA*G*AGAGAAGATTCAGGACC-3′; DR4DD MUT R, 5′-GGTCCTGAATCTTCTCT*C*TTGCATGTCTCTCTTCC-3′. The sequences of the mutagenized plasmids were confirmed. Sequencing of expression plasmids was performed using a T7 DNA sequencing kit (United States Biochemicals, Cleveland, OH) according to the manufacturer's instructions.

The mutagenized f/DR4 or CD/DR4 was used for transfection into SW480 colon cancer cells as previously described (30). After 24 h of transfection, cell lysates were prepared from each transfectant followed by Western immunostaining for confirmation of expression after mutagenesis.

**Evaluation of Cell Death Induced by Transfected DR4.** For cell death evaluation, cotransfection of the CMV-β-gal marker gene and the DR4 mutant constructs generated was performed as previously described (31). Briefly, $1 \times 10^5$ of SW480 cells were plated per well in 24-well plates and transfected with 2 μg of the corresponding parental vectors, f/DR4 (A), CD/DR4 (A), f/DR4 (G), or CD/DR4 (G), with CMV-β-gal at 10% of the total amount of DNA. At 24 or 48 h later, cells were fixed and stained with 5-bromo-4-chloro-3-indolyl-β-galactopyranoside to quantify the number of blue cells. To determine whether polymorphic DR4 has a dominant-negative effect on cell killing, SW480 cells were transfected with variable ratios of CD/DR4 (A) to CD/DR4 (G), f/DR4 (A) to CD/DR4 (G), or f/DR4 (A) to f/DR4 (G) (4:1, 1:1, and 1:4) along with CMV-β-gal.

**Abs and Western Blot Analysis.** Western blot analysis was carried out as previously described (32). Blotted membranes were immunostained with anti-PARP (1:2000; Boehringer Mannheim, Mannheim, Germany), anti-caspase 3 (E-8, 1:500; Santa Cruz Biotechnologies, Inc., Santa Cruz, CA), anti-caspase 7 (1:500; PharMingen, San Diego, CA), anti-caspase 8 (C-20, 1:500; Santa Cruz Biotechnologies, Inc.), anti-caspase 9 (1:500; IIMGENEX, San Diego, CA), anti-caspase 10 (N-19, 1:500; Santa Cruz Biotechnologies, Inc.), anti-caspase 2 (H-19, 1:500; Santa Cruz Biotechnologies, Inc.), anti-DR4 (1:500, PharMingen), anti-DR5 (1:500; IMGENEX,) anti-FLIP (1:500; IMGENEX), anti-Myc (9E10, 1:500; Santa Cruz Biotechnologies, Inc.), or antiactin (I-19, 1:200; Santa Cruz Biotechnologies, Inc.).

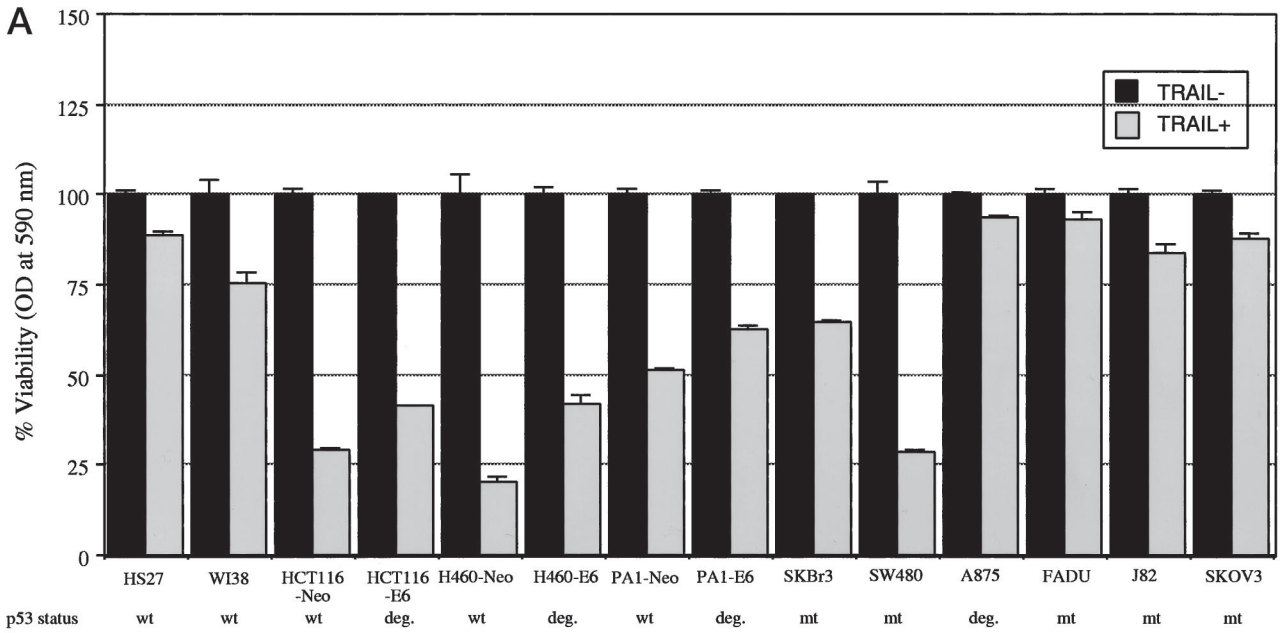
**Statistical Analysis.** The statistical correlation between the expression level of TRAIL death receptors and TRAIL-mediated apoptosis was performed using regression analysis and the correlation between the expression of FLIP and TRAIL sensitivity, or the expression of DR4 and TRAIL sensitivity was performed using the $\chi^2$ test.

## Results

**Normal Cells as Well as a Newly-defined Subset of Cancer Cells Are Resistant to TRAIL-mediated Apoptosis.** We evaluated the cell killing effect of TRAIL on various normal and cancer cell lines. As previously reported by others (1, 3), normal cells (fibroblasts) were resistant to TRAIL treatment (Fig. 1, *A* and *B*). In contrast, cancer cells showed a variable response to TRAIL (Fig. 1). HCT116, H460, PA1, SKBr3, and SW480 were sensitive to TRAIL. TRAIL sensitivity was defined as a <75% cell viability at 16 h after TRAIL treatment is measured by the TRAIL MTT assay. A875, FADU, J82, and SKOV3 cells were found to be resistant to TRAIL. Human Papillomavirus E6-expressing HCT116, H460, and PA1 cells were relatively more resistant to TRAIL than the neocounterparts (Fig. 1*A*). Long-term (7 days) TRAIL treatment of cell lines (Fig. 1*B*) showed nearly the same result as the short-term (16 h) MTT assay results. Based on the observations from the long-term TRAIL treatment assay, certain fractions of cells showed resistance to TRAIL, although the majority of the cells were killed by TRAIL treatment.

Taken together, those results suggest that there is a subgroup of TRAIL-resistant cancer cells and that to a degree, wild-type p53 may modulate TRAIL responsiveness. We further explored the molecular basis of TRAIL resistance in cancer cells.

**Correlation between TRAIL Receptor Expression and TRAIL Sensitivity.** To determine whether there is any correlation between TRAIL sensitivity and the expression level of TRAIL receptors, a semiquantitative RT-PCR assay was per-



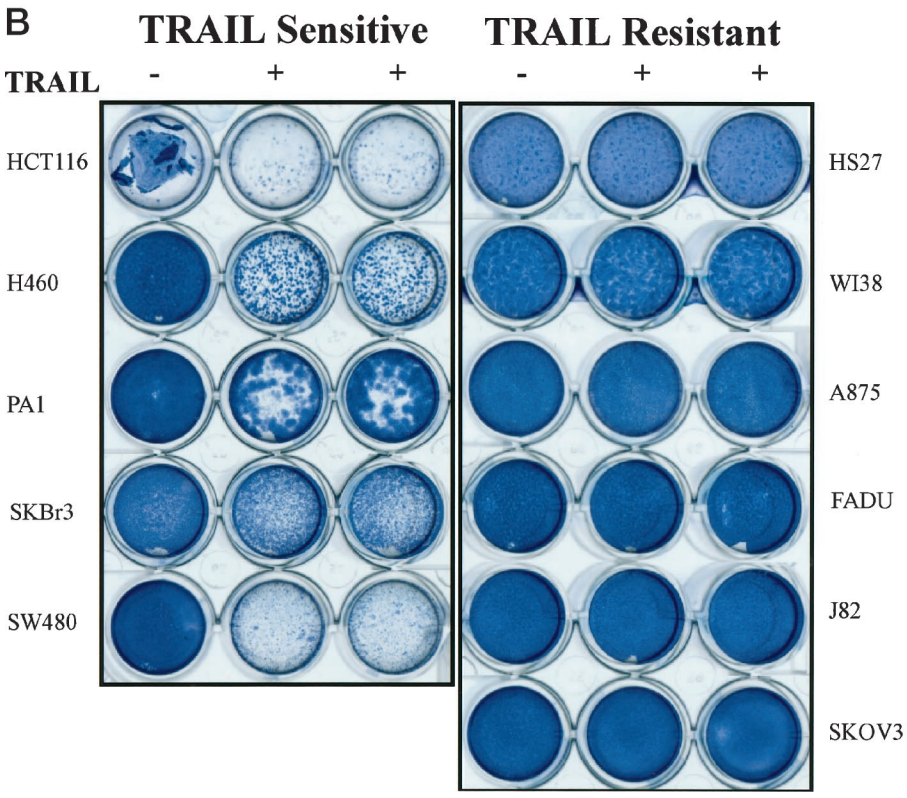




*Fig. 1* *A*, transient and long-term assays reveal variable cytotoxic effects of TRAIL toward normal and cancer cells. Cell viability was evaluated by the MTT assay (See "Materials and Methods"). Cells were incubated for 16 h in the absence (*black bar*) or presence (*gray bar*) of TRAIL (200 ng/ml) and the anti-FLAG M2 mAb (2 μg/ml). The status of the p53 tumor suppressor gene is indicated below the bars for each cell line. *wt*, wild type; *mt*, mutant; *deg*, degraded by HPV E6 or MDM2 (in the case of the A875 cell line that overexpresses MDM2; Ref. 32). All samples were tested in quadruplicate (value ± SD). *B*, long-term (7 days) assays of the TRAIL effect on cell killing. A total of $5 \times 10^4$ cells were seeded in triplicate into each well of a 24-well plate. Cells were either treated with TRAIL (50 ng/ml) and the anti-FLAG M2 Ab (*TRAIL*+) or treated with only Ab (*TRAIL*−). After 7 days of treatment, cells were stained with Coomassie Blue.

formed (Fig. 2). The number of PCR cycles required for linear amplification and detection was initially determined for each death receptor (Fig. 2*A*). KILLER/DR5 was expressed in all cell lines tested (Fig. 2, *B* and *C*), and its mRNA expression level did not correlate with TRAIL sensitivity (Fig. 3*B*). In contrast, the expression level of DR4 varied among different cell lines (Fig. 2*B*). For example, in normal fibroblast cells, DR4 expression was very low or not detectable (Fig. 2*B*, *Lanes 1* and *2*). Cancer cell lines except J82 and SKOV3 that expressed DR4 were sensitive to TRAIL regardless of p53 status (Fig. 1, Fig. 2*B*, and Fig. 3*A*; see below). PA1, A875, and FADU cells did not express detectable DR4 protein (Fig. 2*B*, *Lanes 5*, *6*, and *9*). DR4 protein was highly expressed in HCT116, H460, and SW480 cells (DR4 in Fig. 4, *Lanes 3*, *4*, and *7*), and they were the most sensitive cell lines to TRAIL (Fig. 1, *A* and *B*). The antiapoptotic TRAIL receptors, TRID and TRUNDD, were also

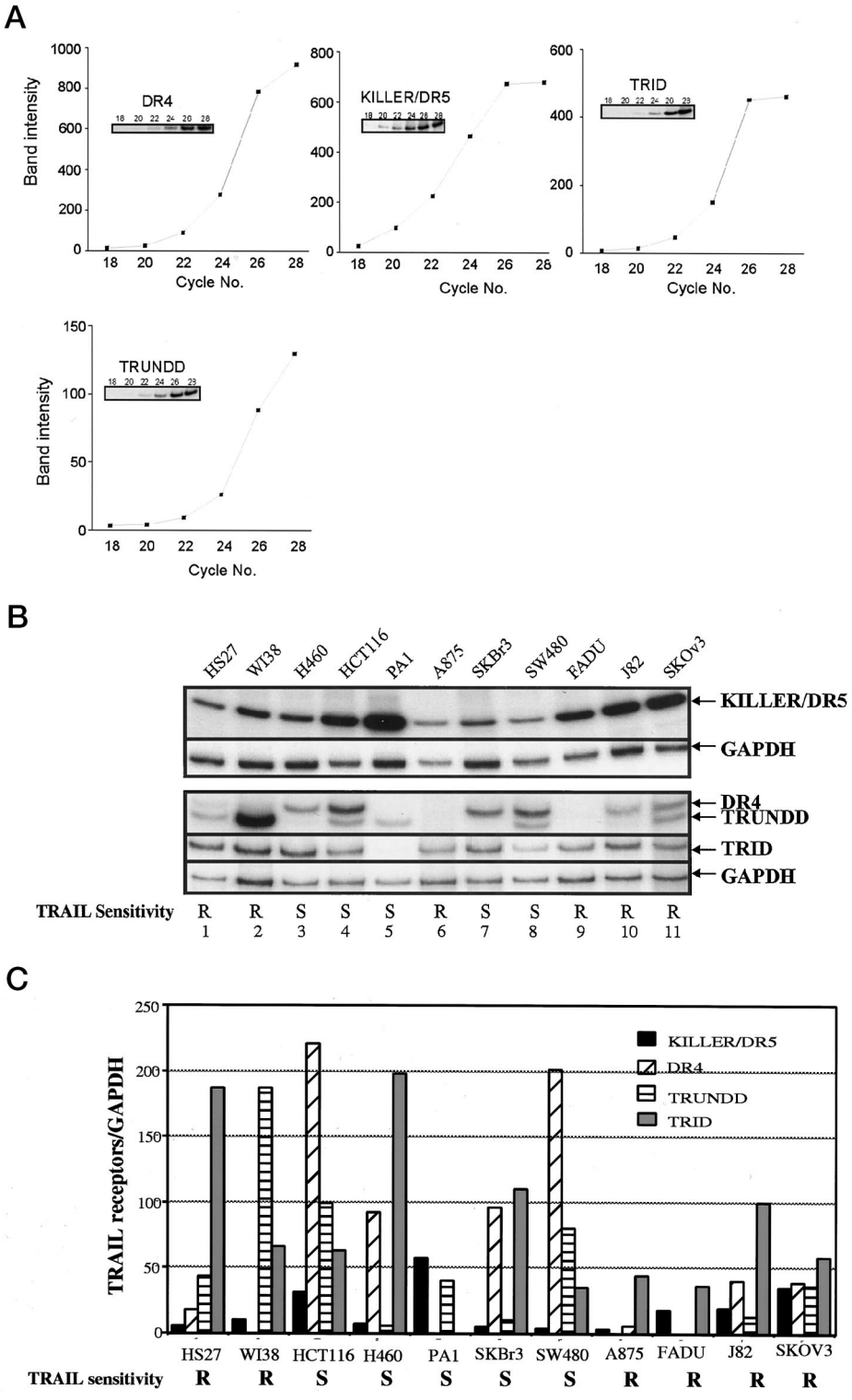



*Fig. 2* Expression level of TRAIL death receptor genes in normal and cancer cells. *A*, kinetics of amplification of mRNA using a semiquantitative-labeled RT-PCR assay (see "Materials and Methods"). Autoradiograms are shown in the *inset* for each experiment, with PCR cycle numbers shown above different lanes. *B*, expression of TRAIL receptor genes using the semiquantitative RT-PCR assays as described in the text. *C*, relative expression of TRAIL receptors normalized with GAPDH expression.

expressed in cancer cells. TRID was expressed in all of the cell lines except PA1 cells, whereas TRUNDD was not expressed in H460, A875, SKBr3, and FADU cell lines (Fig. 2*B, Lanes 3, 6, 7*, and *9*). The high expression of TRID or TRUNDD in the normal cell lines HS27 or WI38 is consistent with previous results implicating high decoy receptor expression as a mechanism of TRAIL resistance. However, neither TRID nor TRUNDD levels adequately explain the observed patterns of

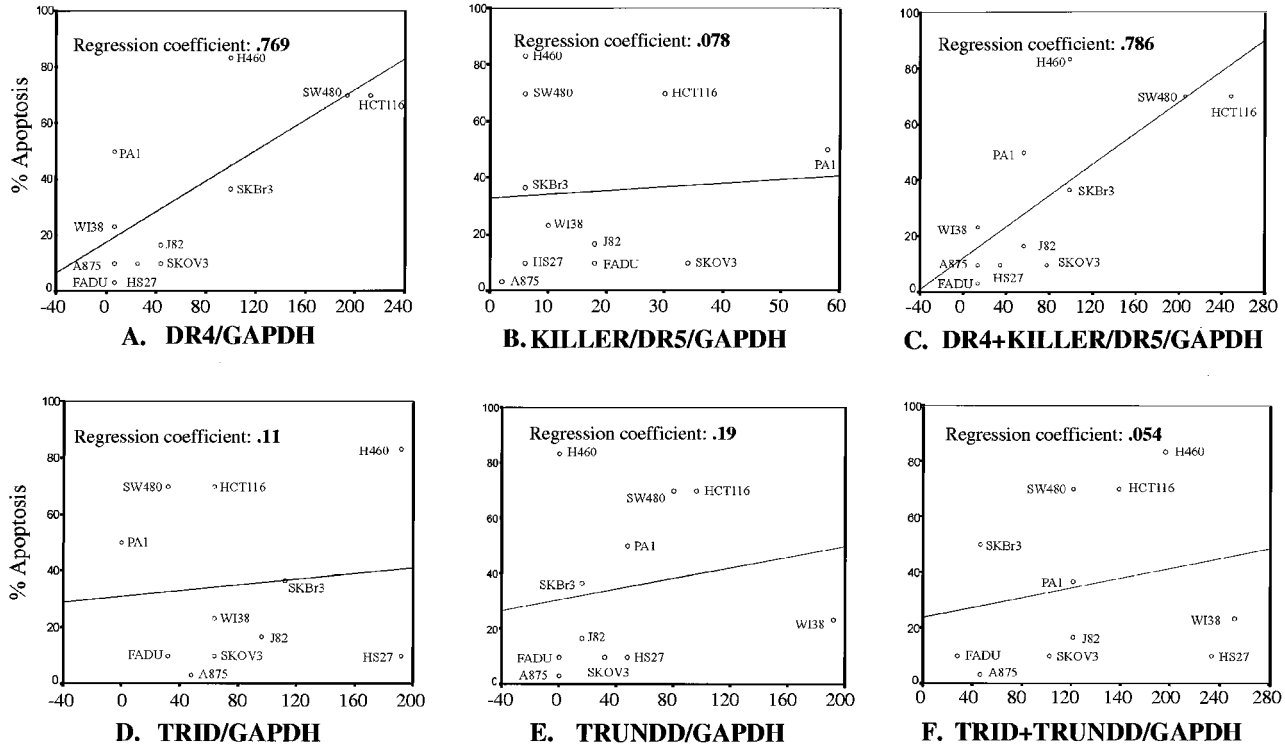



*Fig. 3* Regression analysis of the relation between TRAIL-mediated apoptosis and the expression level of death receptors normalized to GAPDH expression. *A*, *B*, *D*, and *E*, the result obtained from regression analysis between TRAIL-mediated apoptosis *versus* the expression level (determined by RT-PCR) of each TRAIL death receptor. *C* and *F*, the result obtained from regression analysis between TRAIL-mediated apoptosis *versus* the sum of the expression level of the proapoptotic TRAIL death receptors and the antiapoptotic TRAIL death receptors. The regression coefficient for the relation between apoptosis and expression of DR4 or DR4+KILLER/DR5 was 0.769 and 0.786, respectively ($P = 0.006$ and 0.004, respectively).

TRAIL sensitivity in the panel of cancer cells (Fig. 3, *D-F*). The presence of DR4 alone ($r = 0.769$; $P = 0.006$) or DR4 and KILLER/DR5 ($r = 0.786$, $P = 0.004$) appeared to correlate better with TRAIL sensitivity of cancer cells than the expression of decoy receptors (Fig. 3, *A* and *C*).

**FLIP Expression Correlates Well with TRAIL Resistance.** Cellular FLIP is an inhibitor of caspase activation and may be overexpressed in human cancer cells (33). We determined whether the expression level of FLIP might correlate with TRAIL sensitivity. We detected FLIP expression in five of six TRAIL-resistant cell lines including normal cells A875, J82, and SKOV3 (FLIP in Fig. 4, *Lanes 1, 2, 8, 10,* and *11*) but only in one (PA1) of five TRAIL-sensitive cell lines (FLIP in Fig. 4, *Lane 5*). These results suggest that high expression of FLIP may be the another important determinant of TRAIL resistance ($\chi^2$; $P < 0.05$).

**K441R Polymorphism Found in the Death Domain of DR4.** Contrary to our expectation that DR4-expressing cells should be sensitive to TRAIL, J82 and SKOV3 were resistant to TRAIL treatment. Previously, there was a report indicating that Fas carrying a mutation in the death domain region could act as a dominant-negative inhibitor of Fas-induced cell killing (25). To investigate whether there is a DNA sequence change in the death domain of DR4 in J82 and SKOV3 cells, RT-PCR and DNA sequencing was performed. Sequencing results showed that there is an A-to-G alteration in nucleotide 1322 of DR4 both in SKOV3 and J82 cells (Fig. 5*A* and data not shown). This A-to-G transition resulted in the conversion of the amino acid lysine (codon 441) to arginine. To determine whether this alteration is present in normal populations, genomic DNA was isolated from total blood drawn from 10 normal healthy volunteers, and PCR cycle sequencing was performed. The results revealed that 2 (donor 1 and 10) of 10 (20%) normal individuals have the base change (Fig. 5*B*), and thus, we refer to the alteration as a polymorphism. The polymorphism was found in donors 1 and 10, and SKOV3 was heterozygous in all cases (Fig. 5*B*).

**Effect of the K441R Polymorphism in the Death Domain of DR4 on DR4-mediated Cell Killing.** To determine whether the K441R polymorphism has any effect on DR4-mediated cell killing, we generated DR4 mammalian expression constructs containing the polymorphism by using site-directed mutagenesis (Fig. 6, *A* and *B*). Upon transfection, we found that polymorphic DR4 was less effective in cell killing than its wild-type counterpart (Fig. 6, *C* and *D*). In addition, polymorphic DR4 showed an inhibitory effect toward cell killing by wild-type DR4. A potent dominant-negative effect of the K441R polymorphism was observed when the cytoplasmic DR4 (CD/DR4) was expressed. The CD/DR4 (G) rather than f/DR4 (G) showed a nearly complete inhibition of DR4-mediated cell killing (Fig. 6*D*).

These results suggest, at least in terms of TRAIL sensitiv-

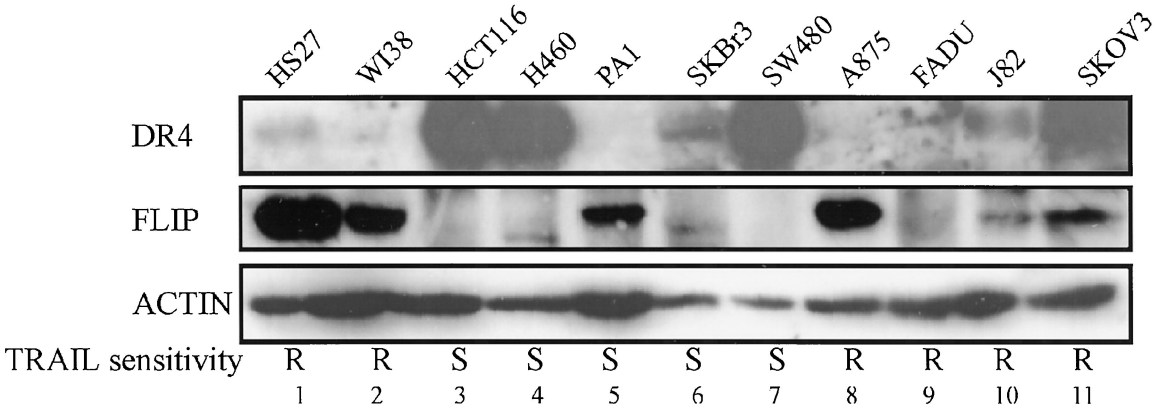



*Fig. 4* Protein expression of DR4 and FLIP. Cell lysates were prepared from each cell line, and an equal amount of protein was loaded on a 15% SDS-PAGE gel. Western immunoblotting was performed with anti-DR4 and anti-FLIP Ab. Actin was used as an internal control for protein loading.

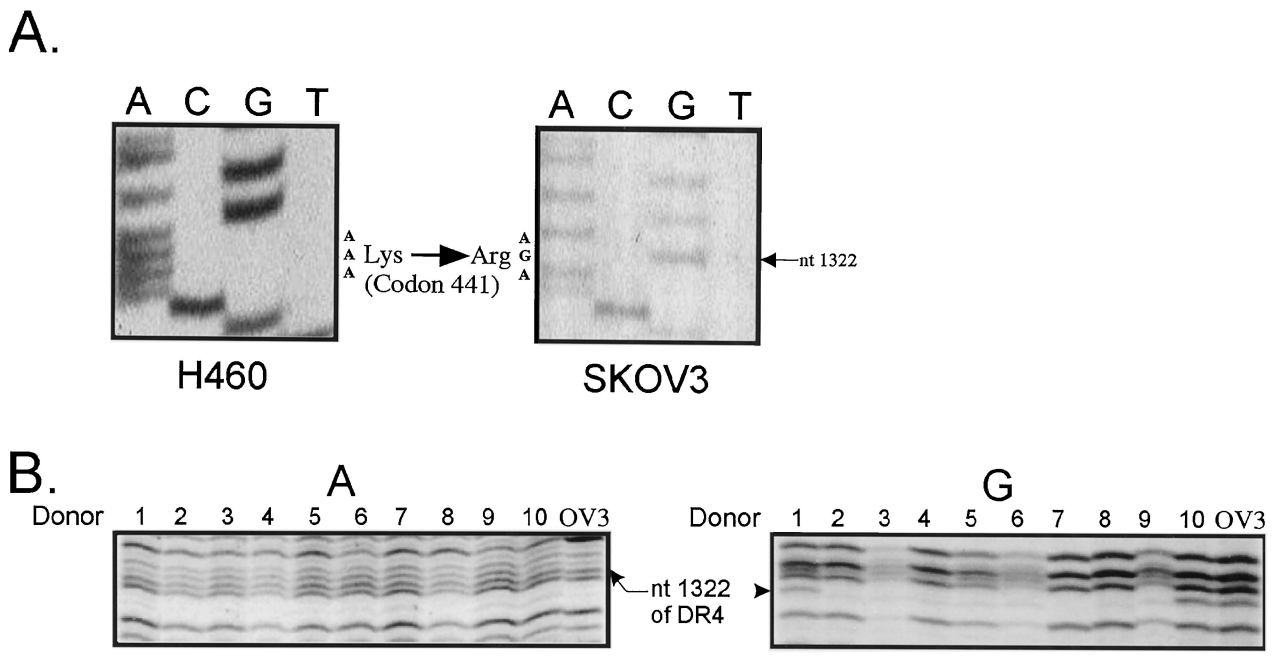



*Fig. 5* K441R polymorphism found in the death domain of DR4. *A,* A-to-G transition at nucleotide 1322 of DR4 in SKOV3 cells. RT-PCR was performed as described in the text. PCR products were cloned into a TA cloning vector (Invitrogen) followed by sequencing using cloned plasmid as a template. Approximately 50% of the clones contained the K441R polymorphism. TRAIL-sensitive DR4-expressing cell lines such as H460 (and HCT116, data not shown) have A at nucleotide 1322, but resistant cell lines such as SKOV3 (and J82, data not shown) have G encoding arginine instead of lysine at codon 441. *B,* A-to-G transition is found in a normal population. PCR amplification using genomic DNA isolated from whole blood of normal healthy donors as a template was performed and followed by cycle sequencing. Samples from each termination mix were loaded together for easy comparison. Donors 1 and 10 showed A-to-G transition, and also, they were heterozygous. SKOV3 also shows an A-to-G transition and is heterozygous.

ity, that the K441R polymorphism in the death domain of DR4 makes cells relatively resistant to TRAIL treatment, although they express DR4 on their cell surface. Thus, this polymorphism found in J82 and SKOV3 could contribute to TRAIL resistance.

**Cell Killing by Combination of Doxorubicin and TRAIL in TRAIL-resistant Cell Lines.** Normal cells such as HS27 and WI38 are resistant to TRAIL in part due to a low or undetectable expression of DR4, a high expression level of decoy receptors, and a high expression level of FLIP (Fig. 2 and Fig. 4). However, when these cells were treated with the combination of doxorubicin and TRAIL, viability was dramatically reduced (Fig. 7*A*) and PARP cleavage became evident (Fig. 7*B*). Western immunostaining (Fig. 7*C*) showed that there was a significant induction of KILLER/DR5 protein expression. This

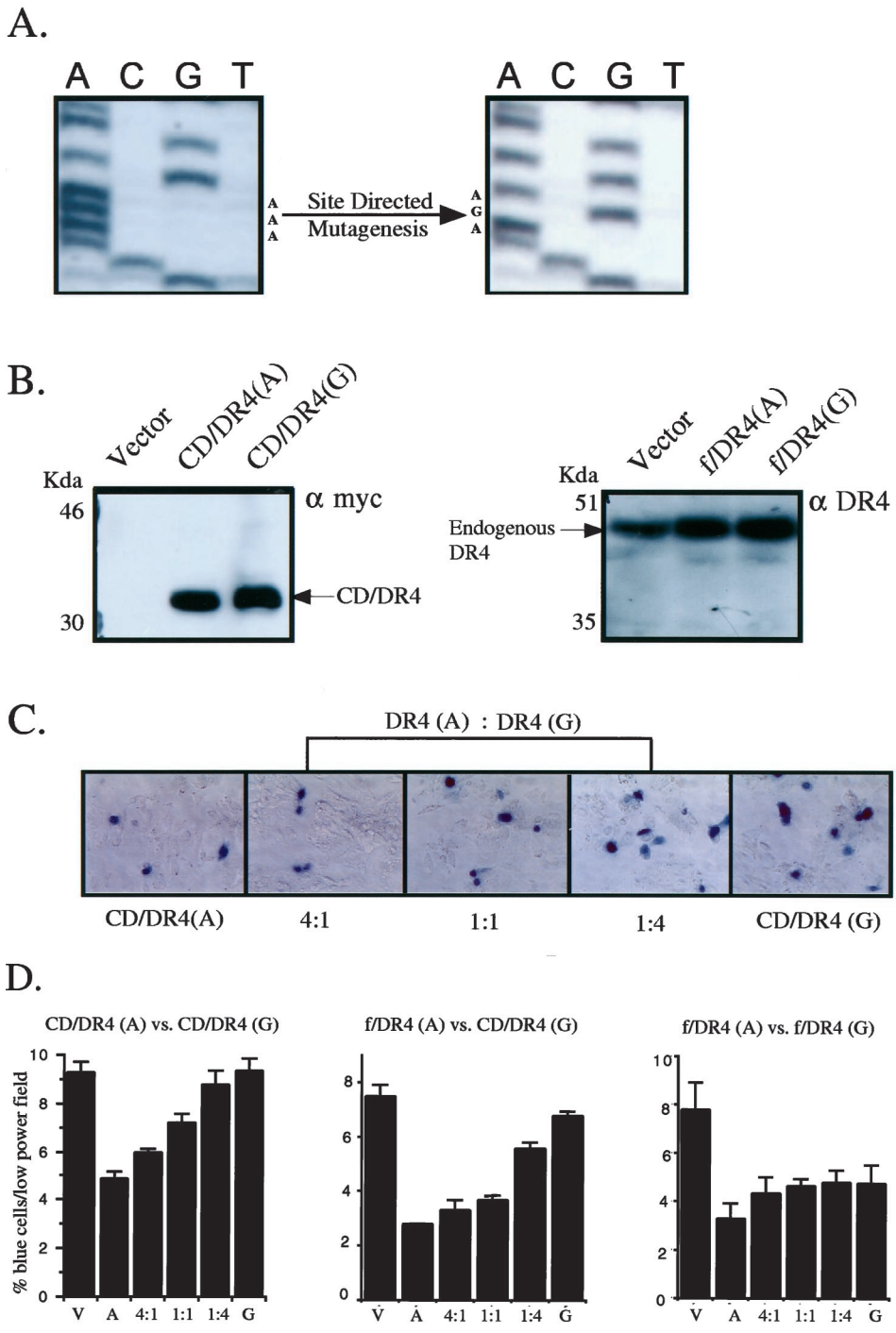



*Fig. 6* Functional effect of the polymorphism on the DR4-mediated cell killing. *A*, site-directed mutagenesis of a DR4 expression plasmid. F/DR4 (A) or CD/DR4 (A) that can express a full-length or cytoplasmic domain of DR4 cloned in pCEP4 or pcDNA 3.1, respectively, was used for mutagenesis. Mutagenesis was confirmed by sequencing. The resulting constructs were named f/DR4 (G) or CD/DR4 (G). *B*, Western blot analysis to confirm the protein expression of CD/DR4 and f/DR4 constructs before and after mutagenesis. SW480 cells were transfected with each DR4 expressing construct. At 20 h after transfection, cell lysates were prepared, and Western immunoblotting was performed using anti-DR4 for f/DR 4 or anti-Myc for CD/DR4. *Arrow*, myc-tagged CD/DR4. *C*, SW480 cells were cotransfected with variable ratios of CD/DR4 (A) to CD/DR4 (G), as indicated, and CMV-β-gal (at 10% of the total DNA) for 48 h. Cells were then stained for the β-galactosidase activity with 5-bromo-4-chloro-3-indolyl-β-D-galactopyranoside. The same high power fields (×320) are shown under phase-contrast microscopy. *D*, dominant-negative effect of polymorphic DR4 on wild-type DR4. The number of blue cells per low power field (×100) was quantified after transfection of SW480 cells as described in *C*. All samples were tested in quadruplicates (value ± SD). *V*, vector; *A*, wild-type DR4; *G*, polymorphic DR4.

induction of KILLER/DR5 by doxorubicin may sensitize normal cells to TRAIL-mediated cell killing. These results suggest that an increase in the ratio of expression between proapoptotic and antiapoptotic molecules may reset the responsiveness of the cells from resistant to sensitive. There was no change in the level of DR4 or FLIP expression after doxorubicin treatment (Fig. 7*C*).

p53 function was compromised in all of the TRAIL-resistant cancer cell lines tested in this study either by mutation (J82, FADU, and SKOV3) or by the overexpression of MDM2 (A875; Ref. 32). Thus, an exposure to a DNA damaging agent such as doxorubicin might not be expected to result in the p53-dependent KILLER/DR5 induction observed in the normal cells. Nevertheless, when those cells were treated with both

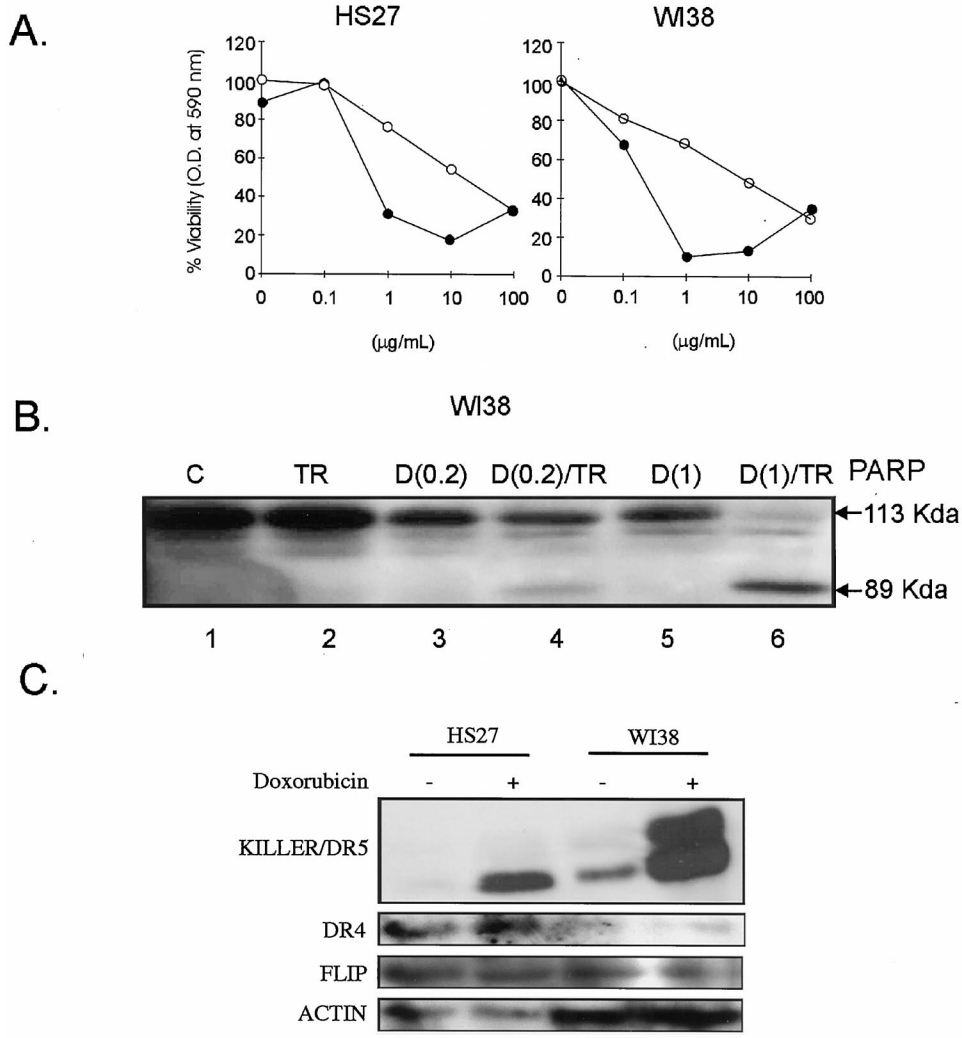



*Fig. 7* KILLER/DR5 but not DR4 induction after doxorubicin exposure correlates with an enhanced sensitivity of normal cells to TRAIL-mediated apoptosis. *A,* effect of combined treatment of doxorubicin and TRAIL on viability of HS27 or WI38. Cells were treated with varying concentrations of doxorubicin in the absence (*open circles*) or presence (*solid circles*) of TRAIL (20 ng/ml) and anti-FLAG M2 mAb (2 μg/ml) for 16 h. Cell viability was evaluated by MTT assay. *B,* cleavage of PARP occurs upon treatment of WI38 with TRAIL and doxorubicin. *C* represents control cells (*Lane 1*); *TR* represents cells treated with TRAIL only (*Lane 2*); *D(0.2)* represents cells treated with doxorubicin (0.2 μg/ml; *Lane 3*); *D(0.2)/TR* represents cells treated with doxorubicin (0.2 μg/ml) and TRAIL (*Lane 4*); *D(1)* represents cells treated with doxorubicin (1 μg/ml; *Lane 5*); and *D(1)/TR* represents cells treated with doxorubicin (1 μg/ml) and TRAIL (*Lane 6*). *C,* Western blot analysis revealed that there was an induction of KILLER/DR5 but no change in DR4 or FLIP expression after doxorubicin treatment. Actin was used as an internal control for protein loading.

doxorubicin and TRAIL, PARP cleavage became evident (PARP in Fig. 8*C, Lanes 4, 8, 12,* and *16*).

Because there were no changes in the expression level of DR4, DR5, or FLIP after doxorubicin treatment in TRAIL-resistant cancer cell lines (data not shown), we investigated the effect of TRAIL or doxorubicin on the activation of caspases. In terms of doxorubicin sensitivity, TRAIL-resistant cancer cell lines can be divided into doxorubicin-sensitive (FADU) and doxorubicin-resistant (A875, J82, and SKOV3) cells (Fig. 8*C* and morphological data not shown).

In doxorubicin-sensitive FADU cells, caspase 8 was activated by doxorubicin treatment alone (caspase 8 in Fig. 8*C, Lane 7*). Caspase 9 was also activated by doxorubicin treatment alone in FADU cells (caspase 9 in Fig. 8*C, Lane 7*). Unexpectedly, however, although there was activation of caspases 8 and 9 ("initiator" caspases) in doxorubicin-treated FADU cells, we did not observe complete procaspase 3 ("executioner" caspase) depletion (caspase 3 in Fig. 8*C, Lane 7*). In the doxorubicin-resistant cell lines (A875, J832, and SKOV3), caspase activation was not observed after exposure to either doxorubicin alone or TRAIL alone (Fig. 8*C*). Interestingly, caspases 8, 9, and 3 became activated after exposure to the combination of doxorubicin and TRAIL (caspases 8, 9, and 3 in Fig. 8*C, Lanes 4, 12,* and *16*). In contrast to TRAIL-resistant cancer cells, cleavage of caspases 8, 9, and 3 was observed after TRAIL treatment of the TRAIL-sensitive HCT116 colon cancer cell line (Fig. 8*A*). When HCT116 was treated with TRAIL, PARP cleavage was evident by 4 h after TRAIL addition, and caspases 8, 9, 3, and 7 became activated at approximately the same time point (4 h after the TRAIL addition; Fig. 8*B*).

## Discussion

The cytokine TRAIL is a promising agent for cancer therapy and is presently under investigation (6, 7). The importance of TRAIL as a potential anticancer agent is that it appears to be a potent cancer-specific cytotoxic drug and is not as toxic as other cytokines. TNF-α or Fas have not been successful in clinical trials when administered systemically because of toxicity (3, 4).

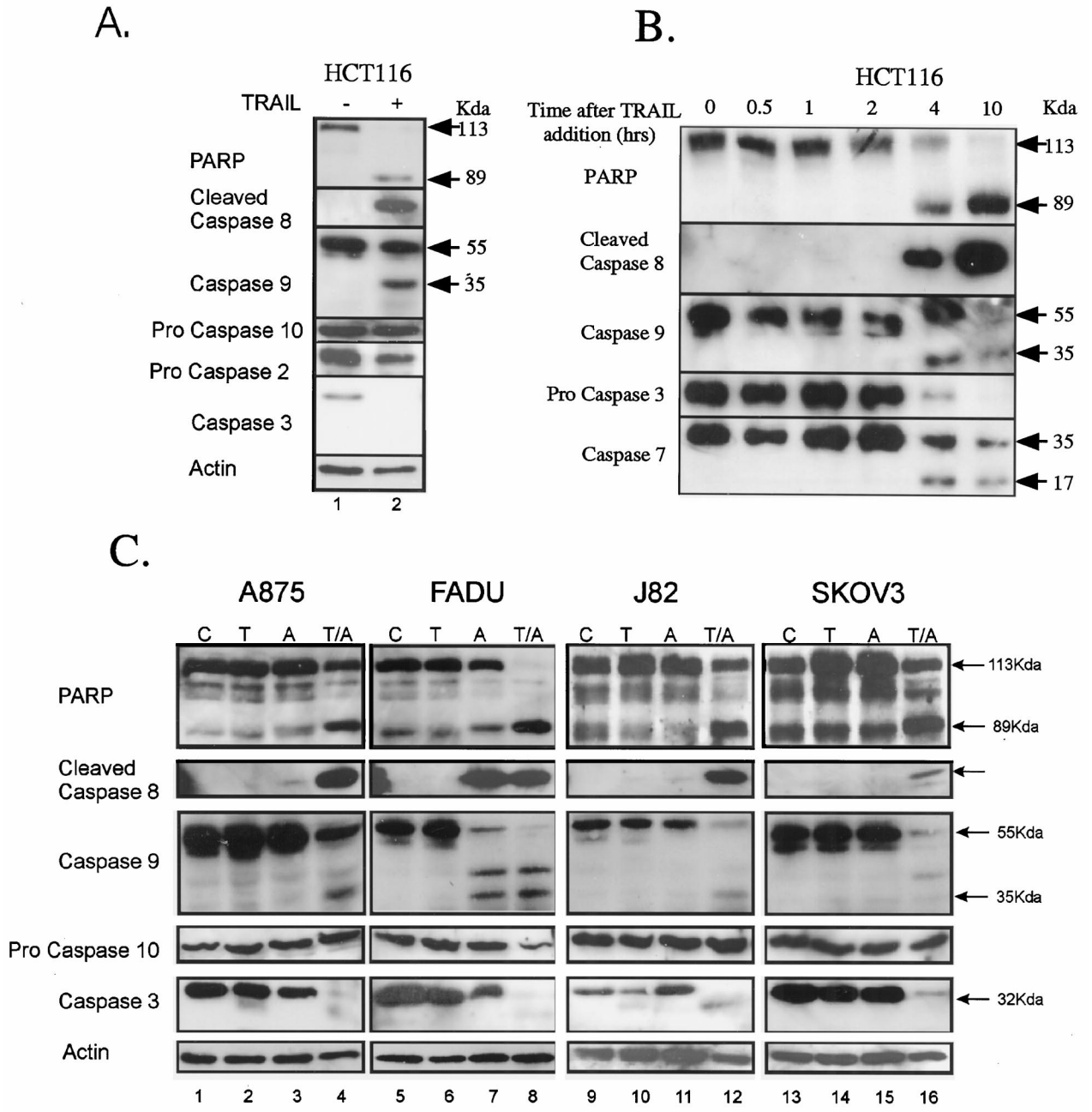



*Fig. 8* Caspase activation after treatment by TRAIL alone or combined treatment using doxorubicin and TRAIL in TRAIL-sensitive and TRAIL-resistant cells. *A*, TRAIL-sensitive HCT116 cells were treated with TRAIL (200ng/ml) and cross-linked with the anti-FLAG M2 Ab (2 μg/ml). *B*, time course activation of caspases in HCT116 after treatment of TRAIL (200 ng/ml) cross-linked with anti-FLAG M2 Ab (2 μg/ml). Lysates were prepared at the indicated times shown above the figure. *C*, TRAIL-resistant cells were treated with TRAIL (200 ng/ml) cross-linked with the anti-FLAG M2 Ab (2 μg/ml) alone (*T*), doxorubicin (5 μM) alone (*A*), or with both (*T/A*) for 16 h. Cell lysates were prepared, and an equal amount of cellular protein was used for Western immunoblotting. *C* represents mock treatment.

Our results provide novel basic information relevant to TRAIL therapy of cancer in the following respects. First, we report that TRAIL resistance is mainly determined by the expression of its proapoptotic death receptors, especially DR4 ($r = 0.769$, $P = 0.006$). In fact, cell lines that were resistant to TRAIL were found to have a relatively low or undetectable expression level of DR4. Normal cell lines, such as HS27 and WI38, which are resistant to TRAIL, have extremely low expression of DR4 mRNA or protein (Fig. 2*B*, Fig. 3*A*, and Fig. 4), and a subgroup of TRAIL-resistant cells also have low or undetectable DR4 expression (Fig. 2*B* and Fig. 4). For DR4 expression alone, a $\chi^2$ analysis revealed that this parameter is a

highly significant predictor of TRAIL sensitivity when expression is high *versus* low or undetectable ($P < 0.01$). For the $\chi^2$ analysis, high expression was defined as DR4/GAPDH > 50 as shown in Fig. 2*C*. It is important to note that mRNA levels do not always correlate with protein levels and that the strength of the correlation between DR4 expression and TRAIL sensitivity (Fig. 2 and Fig. 3) might be stronger or weaker if the measured DR4 protein levels (Fig. 4) were actually quantitated. The expression of KILLER/DR5, however, does not correlate well with TRAIL sensitivity (Fig. 2 and Fig. 3*B*). Our observation is supported by a recent report that TRAIL sensitivity in melanoma cells correlates well with the expression level of DR4 (24). Contrary to our observation, J82 and SKOV3 expressed DR4 (Fig. 2*B* and Fig. 4) but were resistant to TRAIL treatment. A previous report that mutation in the death domain region of Fas can act as in a dominant-negative fashion in cell killing (25) prompted us to examine the death domain region of DR4 in J82 and SKOV3 cells. Indeed, J82 and SKOV3 have an A-to-G alteration at codon 441 in the death domain region of DR4 (Fig. 5*A*). However, that change is also found in 20% (2 of 10) of a normal population and thus, we refer to the DR4 K441R alteration as a polymorphism. Polymorphic DR4 acted in a dominant-negative manner in DR4-mediated cell killing (Fig. 6, *C* and *D*). We make no claim about any disease susceptibility associated with the K441R polymorphism in the DR4 gene. However, the presence of the K441R DR4 polymorphism in cancers may reduce their sensitivity to TRAIL, at least *in vitro.*

It is important to note the differences observed when full-length *versus* cytoplasmic domain expression constructs were used to express DR4. In particular, Fig. 6, *C* and *D* demonstrates that the cytoplasmic domain of DR4 does not itself induce cell death when it contains 441R. In addition, this variant of the cytoplasmic is capable of completely inhibiting death induced by the 441K allele. However, *full-length* DR4 containing the K441R mutation does not share these properties. Instead, full-length DR4 containing the 441R allele induces apoptosis in ~50% of transfected cells and poorly inhibits killing by the full-length 441K allele (Fig. 6*D, right*). These results suggest that the polymorphic 441R allele may contribute but cannot alone explain the observed resistance to TRAIL in certain cancer cell lines (J82 and SKOV3). These cell lines express somewhat increased levels of FLIP (Fig. 4), which may also contribute to their resistance to TRAIL (see below).

Second, the inhibitor of caspase activation FLIP may confer resistance to TRAIL at a point downstream of the death receptors. We found that 83% (five of six cell lines) of TRAIL-resistant cell lines showed a detectable expression of FLIP, whereas only one of five (20%) TRAIL-sensitive lines expressed FLIP (Fig. 4; $\chi^2$; $P < 0.05$). However, the fact that FLIP-expressing PA1 cells are sensitive to TRAIL suggests that even in the presence of FLIP, cells can be killed if there is enough of an input signal for inducing apoptosis.

We measured the expression level of five genes (DR4, KILLER/DR5, TRID, TRUNDD, and FLIP) and tested for correlations with TRAIL sensitivity. The expression of two of the parameters (DR4 and FLIP) appeared to independently correlate with TRAIL sensitivity. From the regression analysis shown in Fig. 3, the *P* value for the DR4 correlation with TRAIL sensitivity is 0.006 (see legend of Fig. 3). Thus, we would have had to test 167 variables to reach the 0.006 level of significance at random for DR4 due to the effect of multiple testing. Moreover, the design of our study was hypothesis driven, with a biological basis giving a reasonable pretest probability of certain correlations. For example, we tested biologically plausible determinants of TRAIL sensitivity. One of the concerns with multiple correlations arises when one tests a very large number of variables (without a hypothesis), such as in a questionnaire with several hundred questions or perhaps a query of an expression of several thousand genes on a DNA microarray chip, and then develops the hypothesis based on any observed correlations at the $P < 0.05$ level. Of course, if one tests enough variables, there is a random chance that a few will appear to be significant but will actually be meaningless. Thus, because we believed that correcting for multiple testing artifacts would not significantly alter our *P*s or conclusions, we have not corrected our calculations for the effects of multiple comparisons. Thus, there is a small chance that our analysis may be limited by the effects of multiple comparisons, and it remains to be seen if others will find a similar significance of DR4 and FLIP expression levels using larger sample sizes and testing fewer variables.

Third, the targeted destruction of p53 to generate otherwise isogenic cancer cell lines revealed that TRAIL sensitivity could be modulated somewhat by p53 (Fig. 1). This is a preliminary observation that requires further investigation. It is clear from our data that wild-type p53 is not required for the apoptotic response to TRAIL.

Fourth, the combination of doxorubicin and TRAIL can kill TRAIL-resistant cancer cells, although each treatment alone cannot effectively kill the cells. The mechanism(s) of this additive killing is not clear yet. We have ruled out changes in the expression level of death receptors or FLIP as a basis for enhanced cell killing by doxorubicin plus TRAIL (data not shown). The fact that FADU cells show caspase 8 and 9 activation upon doxorubicin treatment suggests that the caspase activation axis from caspase 8 through Bcl2 inhibitory protein (Bid) to caspase 9 might be intact in FADU cells but not in other TRAIL-resistant cell lines (Fig. 8*C*). As recently reported (22) and observed in our experiments, doxorubicin and TRAIL could activate caspases in augmenting the killing effect. However, although TRAIL resistance can be overcome by combined treatment with doxorubicin, careful consideration should be given to the dose of doxorubicin given the observed sensitization of normal cells to TRAIL-mediated apoptosis (Fig. 7).

Fifth, among TRAIL-sensitive cancer cells, a certain fraction appears to be resistant to TRAIL-mediated killing (Fig. 1*B*). A recent report also showed that subclones of TRAIL-sensitive cancer cells display a variable response to TRAIL, although the expression level of TRAIL death receptors or FLIP was not changed (24). We do not know the underlying mechanism of this TRAIL resistance yet.

Our findings suggest that although TRAIL may be useful as a therapeutic agent in cancer, particular attention to molecular determinants of sensitivity needs to be considered to optimize such therapy. TRAIL does not appear to have harmful effects toward normal cells and can kill cancer cells irrespective of p53 status if wild-type DR4 is expressed on their cell surface. Our results also indicate that doxorubicin can sensitize cells to

TRAIL-mediated cell killing *in vitro*, thereby raising hopes that such a strategy may be useful in cancer therapy.

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# Identification of suitable reference genes for gene expression studies of human serous ovarian cancer by real-time polymerase chain reaction

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ABSTRACT

Quantitative real-time RT-PCR (RT-qPCR) has proven to be a valuable molecular technique in gene expression quantification. Target gene expression levels are usually normalized to a stably expressed reference gene simultaneously determined in the same sample. It is critical to select optimal reference genes to interpret data generated by RT-qPCR. However, no suitable reference genes have been identified in human ovarian cancer to date. In this study, 10 housekeeping genes, ACTB, ALAS1, GAPDH, GUSB, HPRT1, PBGD, PPIA, PUM1, RPL29, and TBP as well as 18S rRNA that were already used in various studies were analyzed to determine their applicability. Totally 20 serous ovarian cancer specimens and 20 normal ovarian epithelial tissue specimens were examined. All candidate reference genes showed significant differences in expression between malignant and nonmalignant groups except GUSB, PPIA, and TBP. The expression stability and suitability of the 11 genes were validated employing geNorm and NormFinder. GUSB, PPIA, and TBP were demonstrated as the most stable reference genes and thus could be used as reference genes for normalization in gene profiling studies of serous ovarian cancer, while the combination of two genes (GUSB and PPIA) or the all three genes should be recommended as a much more reliable normalization strategy.



Quantitative real-time reverse transcription-polymerase chain reaction (RT-qPCR)[1] has become an established and powerful technique for gene expression studies. Relative quantification is a crucial and frequently used method to assess RT-qPCR data, while target gene expression levels are associated with a stably expressed internal reference gene determined in the same biological sample at the same time. Identification of suitable reference genes is an important problem involved in this approach. The expression of an ideal reference gene should be stable, unregulated, and invariable under the conditions of experiment [1–3].

In the literature, the widely used reference genes include housekeeping genes, such as glyceraldehydes-3-phosphate dehydrogenase (GAPDH) and β-actin (ACTB) as well as ribosomal RNA (18S rRNA and 28S rRNA). However, some studies revealed that the expression levels of the commonly used reference genes did not always remain invariable; they varied across tissues [4] and cell types [5], as well as metabolic conditions and treatments [6]. Recently, some authors have discussed the identification of candidate reference genes for the relative quantification of expression data in cancers [7–10]. It has been suggested that all genes are regulated under some conditions and there is probably no universal reference gene with a constant expression in all tissues [11].

Ovarian cancer is the leading course of death from gynecological malignancy. An estimated 21,650 new cases of this malignancy were diagnosed and 15,520 deaths attributed to this disease in the United States during 2008 [12].The most frequent subtype of ovarian cancer is the serous subtype, which accounts for approximately 60 to 80% of ovarian cancer cases [13]. The majority of the patients (about 75%) are related to extraovarian spread at the time of diagnosis. The 5-year survival rate for women diagnosed with early-stage disease is approximately 95%, while survival rates drop to less than 30% when diagnosis is delayed until late stages. The condition has not been improved over the past few decades. In recent years, gene expression studies in malignant ovarian tissue and normal tissue counterpart have been performed to find new predictive and prognostic molecular markers associated with ovarian cancer. RT-qPCR is a frequently used tool to detect these markers. Thus, a scan on the normalization strategies used in quantitative gene expression studies of ovarian cancer is necessary. Combining the MeSH terms "ovarian cancer" and "real-time PCR," we performed a PubMed search of articles published from January 1, 2004 to

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[1] *Abbreviation used*: RT-qPCR, quantitative real-time reverse transcription-polymerase chain reaction.

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May 1, 2009 and got 119 available articles that use 21 various reference genes. Surprisingly, only 11 (9.2%) out of 119 studies used multiple reference genes for data normalization. Within the other 108 (90.8%) studies that applied a single reference gene, GAPDH was the most frequently used normalizer (52 times, 43.7%), followed by ACTB (23 times, 19.3%) and 18S rRNA (11 times, 9.2%). Apart from the three genes, all the other cited genes accounted for only 0.8 to 3.4%, such as HPRT1, GUSB, RPL29, PBGD, and TBP. Moreover, housekeeping genes and rRNAs were used as reference genes without any preliminary evaluation of suitability. The search results also clearly reveal that a systematic study on the selection of appropriate reference genes for gene expression studies in ovarian cancer has not been carried out until now and it is urgent to perform a specific evaluation of the currently used reference genes.

Therefore, the goal of our study was to identify the most suitable gene or set of genes as reference genes in gene expression studies of ovarian cancer. In the current study, we validated the stability of a panel of 11 putative reference genes in ovarian cancer tissues and normal ovarian epithelial tissues, each from 20 patients. The 11 candidate genes are commonly used as endogenous controls in the context of, but not restricted to, ovarian cancer: ACTB, ALAS1, GAPDH, TBP, HPRT1, RPL29, PBGD, PPIA, PUM1, GUSB, and 18S rRNA. Some of them have been identified as optimal reference genes in some other cancer types, such as TBP [14] and HPRT1 [3].We were able to evaluate gene expression stability between ovarian cancer and normal ovarian epithelium employing geNorm software [15,16] and NormFinder [11,17].

## Materials and methods

### *Patients and samples*

Primary tumor samples ($n = 20$) were obtained from untreated ovarian cancer patients (mean age 56 years, range 39–71 years; 5 premenopausal and 15 postmenopausal) underwent tumor resection surgery. Normal ovarian epithelial tissue samples ($n = 20$) were derived from postmenopausal women who required bilateral adnexectomy when undergoing surgery because of other gynecological diseases (uterine prolapse, hysteromyoma, endometrial polyps, and ovarian simple cyst). All tumors were primary serous ovarian carcinoma. Histological analysis of H&E-stained sections showed that all cancer samples contained at least 90% tumor cells without necrosis. All the normal ovarian samples were verified to be free of any pathology. Tumor stage and grade were determined according to the International Federation of Gynecology and Obstetrics standards (FIGO). One of the 20 tumors was classified as stage I, 5 tumors stage II, 11 tumors stage III, and two tumors stage IV. The histological grading was one G1, 4 G2, and 15 G3. All of the specimens were collected at the Women's Hospital, School of Medicine, Zhejiang University, China. After excision, specimens were immediately snap-frozen in liquid nitrogen within about half an hour and stored at −80 °C until RNA extraction. Informed consent was obtained from each woman, and the study received the approval of the Ethical Committee for Clinical Research of Women's Hospital, School of Medicine, Zhejiang University.

### *RNA extraction and cDNA synthesis*

Preserved tissue samples (50–100 mg) were homogenized in 1 ml TRIzol reagent (Invitrogen, Carlsbad, CA, USA) using a bench-top homogenizer (Polytron PT1600E, Kinematica AG, LittauLuzem, Switzerland) and total RNA was isolated from homogenized tissues according to the manufacturer's protocol. An additional step of RNase-free DNase I ((TaKaRa Biotechnology, Japan) treatment was performed. Concentrations of the isolated RNA and the 260/280 absorbance ratio were measured with a Nanodrop ND-1000 spectrophotometer (Nanodrop Technologies, DE, USA). The integrity of RNA samples was confirmed by electrophoresis on a 1% agarose gel. The criterion to include RNA samples was $260/280 \approx 2$ (1.9 to 2.2) and 28S/18S ratio $\geqslant 1.7$. The concentration of RNA was adjusted to 0.5 μg/μl with nuclease-free water. One microgram total RNA was reverse-transcribed to cDNA using a PrimeScript RT reagent kit (perfect real-time) (TaKaRa Biotechnology, Japan) in a total volume of 20 μl according to the manufacturer's instructions. The kit uses PrimeScript RTase, which is based on reverse transcriptase originated from M-MLV, and offers a fast, complete, and high-yield cDNA synthesis for real-time PCR. Briefly, RNA samples, buffer, RNase free water, enzyme mix, random 6 mers, and oligo (dT) were mixed and incubated for 15 min at 37 °C, followed by 5 s at 85 °C to inactivate enzymes. Primer complementary DNA was stored at −80 °C until use.

### *Real-time quantitative PCR*

Eleven putative reference genes were selected for investigation to identify the most stable reference gene that could be used for normalization in RT-qPCR studies of ovarian cancer: ACTB, ALAS1, GAPDH, TBP, HPRT1, RPL29, PBGD, PPIA, PUM1, GUSB, and 18S rRNA (Table 1). They belong to different abundance and functional classes. Oligonucleotide primers were designed with primer5 software according to the sequences obtained from GeneBank database (Table 2). All primers except for 18S rRNA spanned at least one intron to minimize inaccuracies due to genomic DNA contamination in RNA samples. The specificity of the primer sequences were confirmed by BLAST searches. SYBR green real-time PCR was performed with an Applied Biosystems 7900HT Fast Real-time PCR system using the SYBR Premix Ex Taq (perfect real time) (TaKaRa Biotechnology).The PCR volume was 20 μl, containing 1 μl cDNA. The following cycling conditions were used [95 °C for 10 s, (95 °C for 10 s, 60 °C or 63 °C for 30 s) × 40 cycles]. All reactions were run in duplicate and all 40 samples were analyzed in the same run in order to exclude between-run variations. No tem-

**Table 1**
Putative reference genes evaluated.

| Gene symbol | GeneBank Accession No. | Gene name | Genomic localization | Molecular function |
|---|---|---|---|---|
| 18S | NR_003286 | 18S ribosomal RNA | 22p12 | Ribosome subunit |
| ACTB | NM_001101 | Beta-actin | 7p15–p12 | Cytoskeletal structural protein |
| ALAS1 | NM_000688 | Aminolevulinate, delta-, synthase 1 | 3p21.1 | 5-Aminolevulinate synthase |
| GAPDH | NM_002046 | Glyceraldehyde-3-phosphate dehydrogenase | 12p13 | Oxidoreductase in glycolysis and gluconeogenesis |
| GUSB | NM_000181 | Beta-glucuronidase | 7q21.11 | Galactosidase |
| HPRT1 | NM_000194 | Hypoxanthine phosphoribosyltransferase 1 | Xq26 | Metabolic salvage of purines |
| PBGD | NM_000190 | Porphobilinogendeaminase | 11q23 | Hydroxymethylbilane synthase |
| PPIA | NM_021130 | Peptidylprolyl isomerase A | 7p13 | Cyclosporin binding protein |
| PUM1 | NM_001020658 | Pumilio homolog 1 (Drosophila) | 1p35.2 | RNA binding |
| RPL29 | NM_000992 | Ribosomal protein L29 | 3p21.3–p21.2 | Structural constituent of ribosome |
| TBP | NM_003194 | TATA box binding protein | 6q27 | General transcription factor |

**Table 2**
Details of primers and amplicons for the 11 evaluated genes.

| Gene | Forward primer sequence[5′ → 3′] | Genomic position | Reverse primer sequence[5′ → 3′] | Genomic position | Amplicon length |
|---|---|---|---|---|---|
| 18S | CGGCTACCACATCCAAGGAA | 1st Exon | GCTGGAATTACCGCGGCT | 1stExon | 186 bp |
| ACTB | AGAAAATCTGGCACCACACC | 3rd Exon | TAGCACAGCCTGGATAGCAA | 4th Exon | 173 bp |
| ALAS1 | GGCAGCACAGATGAATCAGA | 4th Exon | CCTCCATCGGTTTTCACACT | 5th Exon | 150 bp |
| GAPDH | GACAGTCAGCCGCATCTTCT | 1st Exon | TTAAAAGCAGCCCTGGTGAC | 3rd Exon | 127 bp |
| GUSB | AGCCAGTTCCTCATCAATGG | 6th Exon | GGTAGTGGCTGGTACGGAAA | 7th Exon | 160 bp |
| HPRT1 | GACCAGTCAACAGGGGACAT | 4th Exon | CCTGACCAAGGAAAGCAAAG | 6th Exon | 132 bp |
| PBGD | AGTGTGGTGGGAACCAGC | 9th Exon | CAGGATGATGGCACTGAACTC | 10, 11th Exon | 144 bp |
| PPIA | AGACAAGGTCCCAAAGAC | 2nd Exon | ACCACCCTGACACATAAA | 4th Exon | 118 bp |
| PUM1 | CAGGCTGCCTACCAACTCAT | 16th Exon | GTTCCCGAACCATCTCATTC | 17, 18th Exon | 211 bp |
| RPL29 | GGCGTTGTTGACCCTATTTC | 1st Exon | GTGTGTGGTGTGGTTCTTGG | 2nd Exon | 120 bp |
| TBP | TGCACAGGAGCCAAGAGTGAA | 4th Exon | CACATCACAGCTCCCCACCA | 5th Exon | 132 bp |

plate controls (no cDNA in PCR) were included in each assay run for each gene. A melting curve was constructed for each primer pair to confirm product specificity.

Threshold cycles ($C_t$ values), the cycle number at which the fluorescence signal of the sample exceeds background fluorescence, were determined for quantitative comparison of the amplification of the candidate genes. $C_t$ values were transformed to relative quantities for analysis considering the PCR efficiencies of the candidate reference genes according to the equation, $E^{(\text{minCt}-\text{sampleCt})}$, in which min$C_t$ = lowest $C_t$ value over a range of samples for a given primer pair and $E$ = amplification efficiency (2 = 100%) [16].

*PCR efficiency*

A 10-fold dilution series was created from a random pool of cDNA from our sample groups ranging from ×1 dilution to ×100,000 dilutions. PCR were performed as described above in triplicate. The PCR efficiency and correlation coefficients ($R^2$) of each primer pair were generated using the slops of the standard curves. The efficiencies were calculated by the formula: efficiency (%) = $(10^{(-1/\text{slope})} - 1) * 100$.

*Date analysis*

Statistical analyses were performed with SPSS 15.0 program. The distribution fitting procedure according to the D'Agostino–Pearson omnibus normality test and Student's *t*-tests were applied. Since type II error is uncontrollable in a two-sided *t*-test, we also performed an equivalence test suggested by Haller et al. [18]: whether the difference of the expected logarithmized expression level $\delta$ is bounded by a determined number $\varepsilon$ is concerned in this test. The hypothesis is defined as $H_0$: $\delta \notin [-\varepsilon; \varepsilon]$ versus $H_1$: $\delta \in [-\varepsilon; \varepsilon]$. If the confidence interval (CI) for the difference $\delta$ of the expected logarithmized expression values is included by the determined deviation area, a candidate reference gene can be considered as equivalent in expression on level $\alpha$. The analyst constructs a $100(1-2\alpha)\%$ confidence level (CI) for the difference between the two mean values of two groups and compares it with the determined deviation area, $[-\varepsilon; \varepsilon]$. If the CI for the difference of the expected logarithmized expression values in two groups is completely contained within the interval $[-\varepsilon; \varepsilon]$, candidate reference genes can be considered as equivalent in expression on level $\alpha$. The lower border and the upper border of the CI can be calculated according to the formula [18]

$$\text{CI}(\delta) = [\delta\text{L}; \delta\text{H}], \tag{1}$$

$$\delta_{\text{L,U}} = (\overline{X}_1 - \overline{X}_2) \mp S\sqrt{\frac{1}{N_1} + \frac{1}{N_2}} \times t_{1-\alpha,N_1+N_2-2} \tag{2}$$

$$S = \sqrt{\frac{(N_1-1)\times S_1^2 + (N_2-1)\times S_2^2}{N_1+N_2-2}} \tag{3}$$

In which $S_1$ and $S_2$ are the standard deviation of the logarithmized expression values in groups 1 and 2; $N_1$ and $N_2$ are the number of samples in the two groups; $t_{1-\alpha,N_1+N_2-2}$means $1-\alpha$ quantile of the $t$ distribution with $N_1+N_2-2$ degrees of freedom. As noted above, if $[\delta_L; \delta_H] \in [-\varepsilon; \varepsilon]$, $H_0$ could be rejected. In addition, $[\delta_L; \delta_H]$ must contain 0.

Correlations between gene expression level (a continuous scale variable) and tumor stage and FIGO stage as well as menopausal status were characterized by the Spearman's rank test. Association between gene expression and patient age was assessed applying Pearson's test. A constant level $\alpha = 0.05$ were used for rejection of null hypothesis in all statistical tests. $P < 0.05$ was considered statistically significant.

For stability comparisons of candidate reference genes, the software geNorm, version 3.5, and NormFinder programs were applied according to the recommendations. The program geNorm is available on the internet http://medgen.ugent.be/genorm/. It calculates the expression stability measure ($M$) for candidate reference genes and by stepwise exclusion of the gene with highest $M$ value in each step allows ranking of the tested genes according to their expression stability. It also provides a way to determine how many reference genes were needed for accurate normalization. NormFinder is a Microsoft Excel add-in and calculates a stability value for each individual candidate reference gene and ranks the genes according to their expression stability value in certain samples derived from a designed experiment [11]. The stability value is based on the combined estimate of intra- and intergroup variation of gene expression. A low stability value indicates a low combined variation and reveals high expression stability. Employing NormFinder, a best combination of two reference genes is also calculated.

## Results

*Quality control*

To avoid erroneous conclusions, only RNA samples with high quality were included in this study. The selected RNA samples isolated from 20 malignant and 20 nonmalignant specimens all exhibited a high quality. The mean $A_{260/280}$ ratio of the RNA samples was 2.01 ± 0.045 (range from 1.95 to 2.12) and reflected pure and protein-free RNA. The integrity of RNA samples was characterized by the 28S/18S ratio (>1.7) on a 1% agarose gels.

The amplification efficiencies and correlation coefficients ($R^2$) of the 11 candidate genes were generated using the slopes of the standard curves obtained by serial dilutions. Correlation coefficients ($R^2$) ranged from 0.995 to 0.999 and PCR efficiencies from 98 to 108% (Supplementary Fig. 1). The amplification specificity for each qRT-PCR analysis was confirmed by melting curve analysis (Supplementary Fig. 2). Furthermore, PCR products were separated by 1.5% agarose gel to confirm an expected single band at the right amplicon size.

*Expression levels of candidate reference genes*

The 11 candidate reference genes displayed a wide expression range, with $C_t$ values between 9.54 and 33.03. All genes showed a normal distribution pattern proved by the D'Agostino–Pearson fitting procedure in both the malignant and the nonmalignant tissue samples. As shown in Fig. 1, the nonmalignant and the malignant samples were separately shown as box plots with ranges as whiskers to demonstrate the total expression ranges. Among these genes, 18S rRNA is the most abundant transcript with mean (±SD) $C_t$ values of 10.67 ± 0.9 in malignant and 11.33 ± 0.85 in nonmalignant samples. PBGD is the lowest expressed gene with mean (±SD) $C_t$ values of 26.83 ± 1.2 in malignant and 29.98 ± 2.2 in nonmalignant samples. Significant differences in gene expression between malignant and nonmalignant samples were observed for all candidate reference genes, except GUSB ($P = 0.121$), PPIA ($P = 0.27$), and TBP ($P = 0.49$). Interestingly, compared with nonmalignant samples, the expressions of 18S rRNA, ACTB, ALAS1, GAPDH, HPRT1, PUM1, and RPL29 were all significantly increased in malignant samples with a very low $P$ value ($P < 0.001$).

We used a fold change of 3 in equivalence test as suggested by Haller et al. [18]. Thus, the $[-\varepsilon; \varepsilon] = [\log_2 1/3; \log_2 3] = [-1.58496, 1.58496]$. The CI ($\delta$) values for GUSB, PPIA, and TBP were [−0.11283; 1.11183], [−0.17239; 1.35239], and [−0.36503; 0.87403], respectively, which were completely contained within [−1.58496, 1.58496] and contain 0. Thus, the expressions of GUSB, PPIA, and TBP are equivalent in the tumor and control groups. The CI ($\delta$) value for 18S, [0.09086; 1.23634], was part of the determined deviation area but did not contain 0 and thus the null hypothesis could not be rejected. The CI ($\delta$) values for ACTB [2.19612; 3.88787], ALAS1 [2.30874; 3.66726], GAPDH [3.27525; 4.87175], HPRT1 [0.58475; 2.46525], PBGD [2.15847; 4.13653], PUM1 [1.68741; 3.26359] and RPL29 [2.99850; 4.18250] were not bounded by the determined deviation area, and therefore the eight candidate reference genes were not equivalently expressed in the two groups. Hence, the possibility of a type II error (false negatives) in the $t$-test was excluded and the results were further confirmed through this approach.

Additionally, the expression of these candidate genes did not depend on age (correlation coefficient = −0.111 to 0.345; $P = 0.136$ to 1.000), menopausal status (correlation coefficient = −0.132 to 0.208; $P = 0.379$ to 1.000), FIGO stage (correlation coefficient = −0.336 to 0.203; $P = 0.147$ to 0.922), and tumor degree (correlation coefficient = −0.093 to 0.255; $P = 0.279$ to 0.977).

*Expression stability of candidate reference genes*

Including the 3 suitable genes, all 11 candidate reference genes were included in the program geNorm and ranked according to their $M$ values (Fig. 2a). The $M$ value is the average pairwise variation of an individual gene with all other control genes. The $M$ values for GUSB, PPIA, TBP, 18S rRNA, HPRT1, PUM1, RPL29, ALAS1, and ACTB were lower than the geNorm default threshold of 1.5, while the two remaining genes, GAPDH and RPL29, showed $M$ values greater than the threshold. GUSB and PPIA (both $M = 0.842$) were identified as the two most stable genes according to geNorm analysis. After excluding the 8 genes noted that differ in expression between groups, the geNorm analysis was repeated. The most stable genes were still PPIA and GUSB, followed by TBP, which was in accord with the previous finding. To determine the optimal number of genes required for RT-qPCR date normalization, geNorm calculates the pairwise variation ($Vn/Vn + 1$) between sequential normalization factors (NF) (NF$n$ and NF$n + 1$). A large variation means that the added gene has a significant effect and should preferably be included for calculation of a reliable normalization factor [16]. As shown in Fig. 2b, the pairwise variation ($v$) on normalization with the three most stable reference genes, PPIA, GUSB, and TBP, and introduction of the fourth one was 0.188. The trend of the value became roughly stable after the addition of the eighth gene.

To compare the result generated from geNorm, another free tool available on the internet to validate the expression stability was also used. The stability data calculated by that program was a combined estimate of intra- and intergroup expression variations of the genes studied. It could reveal the expression differences of the genes observed between normal and tumor groups. The result of the analysis by NormFinder appeared to be similar to the one determined by geNorm (Table 3). The three genes GUSB, PPIA, and 18S rRNA achieved the best stability values, and the best combination of two genes was that of GUSB and PPIA.

## Discussion

It is well recognized that the reference gene should be properly validated for a particular experiment to ensure that gene expres-

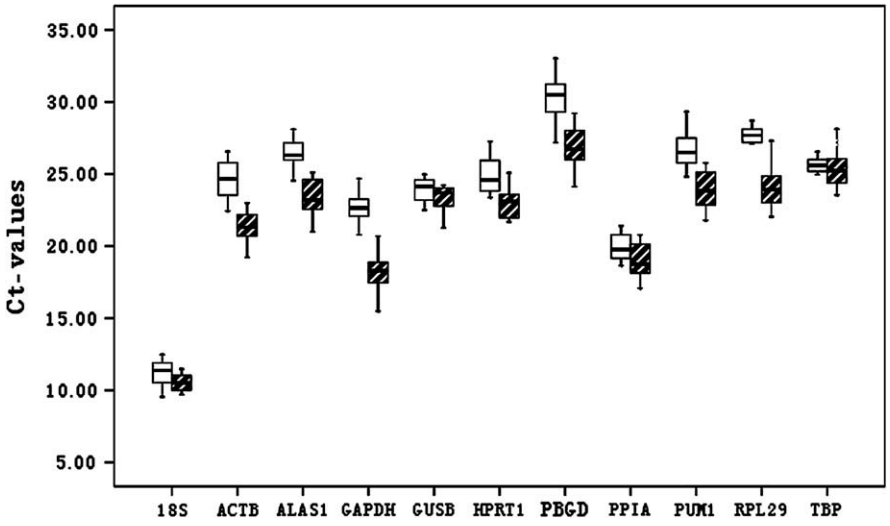


**Fig. 1.** Expression levels of candidate reference genes in normal ovarian epithelia and serous ovarian cancer samples. Values are given as real-time PCR cycle threshold numbers ($C_t$ values). Boxes (blank, normal; cross-striated, cancer) represent the lower and upper quartiles with medians; whiskers represent the ranges for the data of the 20 samples in each group.

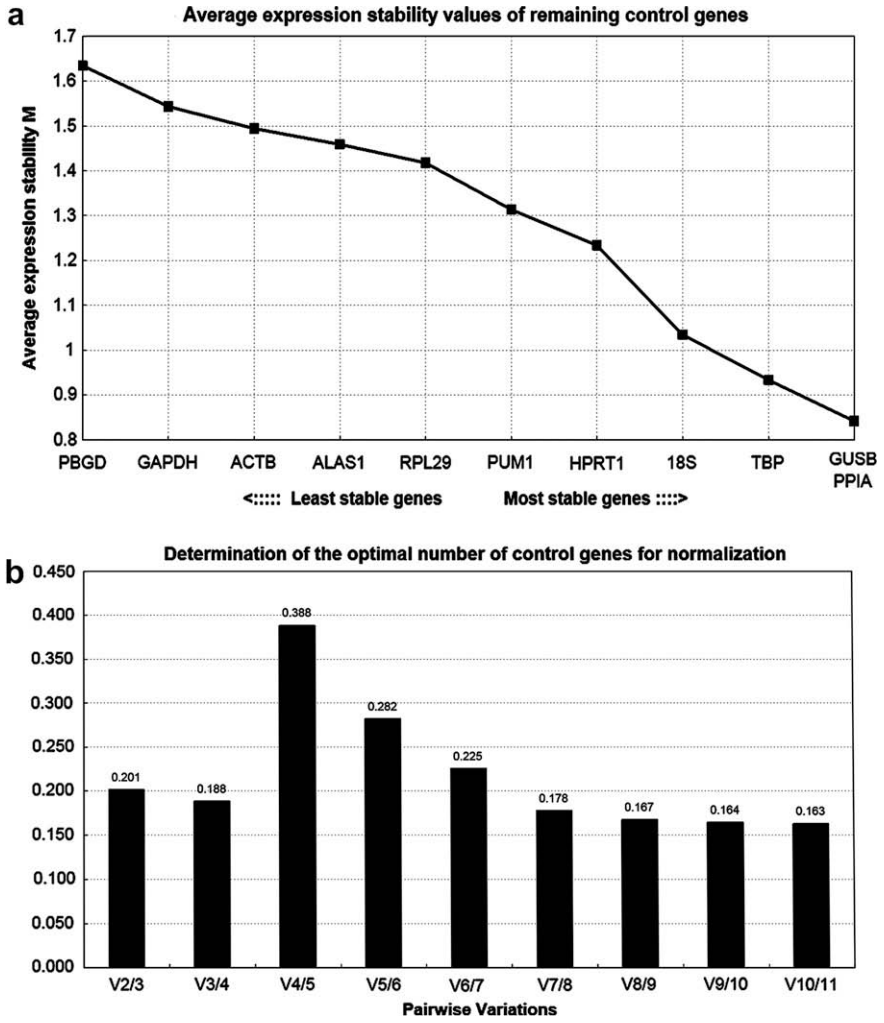


**Fig. 2.** GeNorm analysis of the candidate reference genes. Results are presented according to the output file of the geNorm program. (a) Stepwise exclusion of the least stable genes by calculating the average expression stability measure *M*. The value of *M* was calculated for each gene, and the least stable gene with the highest *M* value was automatically excluded for the next calculation round. The *x*-axis from left to right indicates the ranking of the reference genes according to expression stability and the *y*-axis indicates the stability measure, *M*. (b) Determination of the optimal number of reference genes for normalization.

**Table 3**
Candidate reference genes for normalization listed according to their expression stability calculated by the NormFinder program.

| Raking order | Gene name | Stability value |
|---|---|---|
| 1 | PPIA | 0.338 |
| 2 | GUSB | 0.345 |
| 3 | 18S | 0.401 |
| 4 | TBP | 0.492 |
| 5 | PUM1 | 0.633 |
| 6 | ALAS1 | 0.795 |
| 7 | ACTB | 0.839 |
| 8 | PBGD | 0.906 |
| 9 | RPL29 | 0.950 |
| 10 | GAPDH | 1.160 |
| 11 | HPRT1 | 5.226 |

sion is unaffected by the experimental treatment. As far as we are aware, there are no published articles about optimal reference gene selection for ovarian cancer. We report herein the first systematic comparison of expression stability of candidate reference genes in ovarian carcinoma samples and benign counterparts.

A group of widely used reference genes have been applied in recent ovarian cancer gene profiling studies, such as GAPDH, ACTB, TBP, 18S rRNA, RPL29, GUSB, and HPRT1, for RT-PCR [19–24]. In the present study, we evaluated a panel of 11 candidate reference genes to determine the most reliable one for accurate normalization of gene expression.

To obtain reliable data, we carefully designed our study before RT-qPCR analysis based on the following features: (1) The majority of patients with ovarian cancer are diagnosed at late stages, when the whole ovary has been damaged and it is difficult to get tumor tissues and valid paratumor tissues in the same ovary. Thus, we obtained normal ovarian epithelial tissues from patients receiving surgery because of benign gynecological diseases, though it is known that the use of paired samples from the same patient may minimize the interindividual variation [3,8]. (2) We used strict RNA quality control, precise RNA concentration determination, and gene-specific primer selection, (3) simultaneous examination of a considerable number of 11 candidate genes from different function classes, and (4) employment of two received software, geNorm and NormFinder, combined with a *t*-test and a equivalence test to rank the candidate reference genes according to their stability.

The expression of candidate reference genes can be influenced not only by tissue types but also by physiological or pathological factors like age, tumor stage, and tumor grade. Thus, it should be decided whether the expression is correlated with the biological

conditions listed above. The results of our data proved that the expression of these genes in this cohort was independent on age, FIGO stage, and tumor grade. Additionally, because ovarian epithelial tissues obtained from postmenopausal women were used as normal control, we also evaluated the correlation between candidate gene expression and menopausal status. The results showed there was no association between the two variables and thus the use of a control group described above was warranted and feasible. However, due to the reduced size of the cohort of patients in this study, a definite correlation between gene expression and clinic pathologic features should be further determined in a larger sample.

In the current study, we calculated the best performing reference genes using two distinct statistical models, a pairwise comparison model, geNorm, and an ANOVA-based model, NormFinder. Finally, geNorm identified GUSB, PPIA, and TBP as the three most stably expressed reference genes while NormFinder indicated GUSB, PPIA, and 18S rRNA as the three genes with the best stability, followed by TBP. However, the previously performed *t*-test and equivalence test analyses of gene expression in malignant and nonmalignant groups revealed that only three genes GUSB, PPIA, and TBP did not differ in their expression in the two groups. It could be concluded only the three genes fulfill the criterion of expression stability and could be considered as suitable normalizers for relative gene quantification in serous ovarian cancer samples. Thus, 18s RNA should be excluded and GUSB, PPIA, and TBP were finally indicated as the three most stable reference genes for studying target gene profiling in serous ovarian cancer.

However, it is recommended that normalization using a single reference gene should be replaced by normalization based on the several best performing candidate reference genes [15]. A normalization strategy applying multiple reference genes has the benefit of minimizing the influence of minor fluctuations and making accurate data normalization is also suggested by some other authors [25,26]. In the present study, we found GUSB, PPIA, and TBP yield a variation value of 0.188. As reported by Vandesompele et al. [16], though GeNorm proposes a pairwise variation of 0.15 as the cutoff under which the inclusion of an additional reference gene is unnecessary, the cutoff of 0.15 should not be considered in a strict sense, but rather as guidance to determine the optimal number of reference genes. Sometimes the observed trend can be equally informative, and using the three best reference genes is, in most cases, a valid normalization strategy. Therefore, GUSB, PPIA, and TBP is a reliable set of genes for normalizing data generated from RT-qPCR analysis in serous ovarian cancer. Additionally, GUSB and PPIA were also indicated as the best combination of two genes by NormFinder.

Nevertheless, as a limitation of our study, we should note that the present study is limited to the serous ovarian cancer subtype. However, it is the most frequent subtype of ovarian carcinoma. The applicability of the three recommended reference genes GUSB, PPIA, and TBP in other subtypes of ovarian cancer was not tested and further studies are needed to confirm their potential use.

In conclusion, our current study demonstrated that the three most stable genes GUSB, PPIA, and TBP could be used as reference genes for normalization in gene profiling studies of serous ovarian cancer and the combination of two genes (GUSB and PPIA) or the all three genes should be recommended as a much more reliable normalization strategy.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ab.2009.07.022.

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