# ITK in TSCC

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Interleukin-2–inducible T-cell kinase (ITK) is a member of the Tec family of non-receptor tyrosine kinases and is expressed in T-cells and mast cells.

tongue squamous cell carcinoma IL2-inducible T-cell kinase (ITK)

trifunctional purine biosynthetic protein adenosine-3 (GART)

## 1. Introduction

A number of molecular-targeted drugs, including kinase-targeted drugs, are used clinically in the treatment of many types of cancer to improve the survival time of patients. However, cetuximab, a monoclonal antibody that blockades the epidermal growth factor receptor (EGFR), is the only kinase-targeted drug available for treating tongue squamous cell carcinoma (TSCC) <sup>[1]</sup>. Thus, additional therapeutic strategies focused on the inhibition of a wide variety of kinases are needed to treat patients more effectively with TSCC.

Interleukin-2–inducible T-cell kinase (ITK) is a member of the Tec family of non-receptor tyrosine kinases and is expressed in T-cells and mast cells. In T-cells, ITK functions downstream of the T-cell receptor and plays an important role in T-cell activation, development, differentiation, and production of pro-inflammatory cytokines <sup>[2]</sup>. It was recently reported that ITK gene expression is higher in tumor tissues than in normal tissues and associated with poor prognosis in head and neck cancer <sup>[3]</sup>. ITK protein expression reportedly increases with nevus to metastatic melanoma progression and is associated with tumor development and progression in melanoma <sup>[4]</sup>. However, little is known about ITK protein expression and function in almost all types of solid tumors. Trifunctional purine biosynthetic protein adenosine-3 (GART) is an enzyme in the de novo purine biosynthesis pathway. Purine metabolism is reportedly enhanced in proliferating cancer cells <sup>[5]</sup>. However, the mechanism of the de novo purine biosynthesis pathway through GART in TSCC has not been elucidated in detail.

### 2. ITK Protein Expression in Patients with TSCC

The expression of ITK protein in patients with TSCC was examined using IHC with an anti-ITK rabbit monoclonal antibody that was purchased from CST (details described in the 'Methods' section; antibody clone number Y401). First, we confirmed the specificity of the anti-ITK rabbit monoclonal antibody and observed no cross-reactivity for other molecules of the Tec family. Expression of ITK protein was not observed in normal tongue mucosa adjacent to the tumor (**Figure 1**A,B), and lymphocytes were stained by the ITK antibody in all 86 patient TSCC tissues on

the same pathology sections as the internal controls (**Figure 1**E,H). Immunofluorescence double staining was performed with anti-CD4 antibody and anti-ITK rabbit monoclonal antibody. ITK-positive CD4<sup>+</sup> T-cells were stained with both anti-CD4 antibody and anti-ITK rabbit monoclonal antibody. Of 86 patients with TSCC, 73 (84.9%) were ITK negative (**Figure 1**C,D), and 13 (15.1%) were ITK positive (**Figure 1**F,G). The Kaplan–Meier curves showed a statistically significant difference between the ITK-negative and ITK-positive groups in both OS (log-rank trend test P = 0.0129) (**Figure 1**I) and DFS (log-rank trend test P = 0.0002) (**Figure 1**J). The correlations between clinical findings and ITK expression pattern are summarized in **Table 1**. Statistically significant differences were observed between ITK expression and mode of invasion (P = 0.0000), late metastasis of cervical lymph nodes (P =0.0006), and lymphovascular invasion (P = 0.0101). No statistically significant associations were observed between ITK expression and age, sex, clinical stage, clinical histologic differentiation (poorly/moderately differentiated versus well-differentiated), or perineural invasion (**Table 1**).



**Figure 1.** Expression of interleukin-2–inducible T-cell kinase (ITK) in surgically removed tongue squamous cell carcinoma tissue, correlation between ITK expression and prognosis, and proliferation of oral cancer cell lines associated with ITK expression in vitro and in vivo. (**A** and **B**) Representative expression of ITK protein in the normal tongue mucosa (bar, 1 mm) (**A**). (**B**) shows a magnified image of the normal tongue mucosa (bar, 250 µm).

(C-E) Representative images of ITK-negative cases. (B: bar, 2.5 µm; C: bar, 100 µm; D: bar, 50 µm). Red square denotes the part of the cancer lesion image that was magnified (D). Blue square denotes the part of the lymphocyte image that was magnified (E). (F-H) Representative images of ITK-positive cases (E: bar, 5 µm; F and G: bar, 50 µm). Red square denotes the part of the cancer lesion image that was magnified (G). Blue square denotes the part of the lymphocyte image that was magnified (**H**). (**I**) OS curves for the ITK-positive (red line, n =13) and ITK-negative (blue line, n = 76) subgroups (p = 0.0129). (J) DFS curves for the ITK-positive (red line, n = 76) 13) and ITK-negative (blue line, n = 76) subgroups (P = 0.0002). Statistical significance was assessed using the log-rank test. (K) Western blot analysis of ITK and GART expression in oral cancer cells. β-Actin was blotted as a loading mock control. (L) Western blot analysis of ITK expression in two lines of oral cancer cells that stably express ITK (ITK EX) and mock control cells (Control). β-Actin was blotted as a loading control. (M) Proliferation of ITK-expressing SAS cells and mock control cells and representative photographs of ITK-expressing SAS cell spheroids and mock control cell spheroids after 96 hours of culture. Top panels are overall views (bars, 200 µm); bottom panels are magnified images (bars, 200 µm). (N) Proliferation of ITK-expressing KOSC2 cells and mock control cells and representative photographs of ITK-expressing KOSC2 cell spheroids and mock control cell spheroids after 72 hours of culture. Top panels are overall views (bars, 200 µm); bottom panels are magnified images (bars, 50 µm). (O) Tumor volume of ITK-expressing SAS cells and mock control cells in an inoculation model involving subcutaneous injection of SAS cells in nude mice, and immunohistochemistry using an anti-ITK antibody of transplanted ITK-expressing cells and mock control cells in mice (bars, 100 µm). Error bars indicate standard error. \* *p* < 0.01 (Student's *t*-test).

**Table 1.** Association of ITK protein expression with clinicopathologic characteristics in stage I/II tongue squamous cell carcinoma.

	Number of Cases (%)	ITK-Negative	ITK-Positive	<i>p</i> -value <sup>a</sup>
Total	86	73	13	
Age (years)				0.3655
<64	43 (50.0)	38	5	
≥64	43 (50.0)	35	8	
Sex				0.1715
Male	48 (55.8)	43	5	
Female	38 (44.2)	30	8	
Stage <sup>b</sup>				0.9776
1	46 (53.5)	39	7	
Ш	40(46.5)	34	6	

	Number of Cases (%)	ITK-Negative	ITK-Positive	<i>p</i> -value <sup>a</sup>
Histologic differentiation				0.1760
Poor/Moderate	25 (29.1)	18	6	
Well	61 (70.9)	55	7	
Mode of invasion <sup>c</sup>				0.0000 *
1,2	58 (67.4)	56	2	
3,4	28 (32.6)	17	11	
Late metastasis of cervical lympl	h nodes			0.0006 *
Negative	68 (79.1)	63	5	
Positive	18 (20.9)	10	8	
Lymphovascular invasion				0.0101 *
Negative	75 (87.2)	67	8	
Positive	11 (12.8)	6	5	
Perineural invasion				
Negative	82 (95.3)	71	11	0.1067
Positive	4 (4.7)	2	2	

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Ivmphovascular invasion, and perineural invasion, using univariate and multivariate Cox regression analyses.
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3.544 (95% confidence interval [CI] 1.225-10.247) for ITK protein expression, 3.401 (95% CI 1.264-9.149) for

lymphovascular invasion (**Table 2**). Multivariate analyses indicated that ITK protein expression was an independent positive predictor of death in TSCC patients: HR 3.167 (95% CI 1.089–9.215) (**Table 2**).

Covariate	Univa HR	riate Ar 95%	nalysis ( % Cl	n = 86) <i>p</i> -Value	Multiva HR	ariate A 95%	nalysis 6 Cl	( <i>n</i> = 86) <i>p</i> -Value	
Age (years)									
<64	Reference				Reference				
≥64	2.866	0.923	8.894	0.068	2.611	0.836	8.153	0.099	
ITK protein expression									
Negative	Reference			Reference					
Positive	3.544	1.225	10.247	0.020 *	3.167	1.089	9.215	0.034 *	
Sex									
Male	Reference								
Female	1.235	0.463	3.296	0.673					
Stage <sup>a</sup>									
Stage I	Reference								
Stage II	1.519	0.567	4.068	0.405					
Histologic differentiation									
Well	Reference								
Poor and moderate	3.401	1.264	9.149	0.015 *					
Mode of invasion <sup>b</sup>									
1, 2		Refe	erence						
3, 4	5.112	1.768	14.783	0.003 *					
Late metastasis of cervical lymph nodes									
Negative		Refe	erence						

Table 2. Hazard ratios for death with stage I/II tongue squamous cell carcinoma—Cox regression model.

Covariate	Univa HR	ariate A 959	nalysis ( % Cl	(n = 86) p-Value	Multiva HR	riate Analysi 95% Cl	is ( <i>n</i> = 86) <i>p</i> -Value
Positive	4.497	1.684	12.010	0.003 *			
Lymphovascular invasion							
Negative		Ref	erence				
Positive	3.497	1.210	10.110	0.021 *			
Perineural invasion							
Negative		Ref	erence				
Positive	N.A. <sup>C</sup>						

ITK expression was not detected in the oral cancer cell lines we investigated (**Figure 1**K). Consequently, we engineered SAS and KOSC2 oral cancer cells that stably express ITK (**Figure 1**L) and investigated the effect of HR, ekpræcedioratio; cell, proditionation interveal did the sign all times and the effect of expression of the effect of expression of the effect of the expression on cell proliferation using in vivo models in which immunodeficient mice were inoculated subcutaneously with cancer cells. ITK-expressing SAS tumor cells grew faster than mock control cells (Figure 10). Ki67 staining was stronger in ITK-expressing SAS tumor cells than in mock control cells. IHC confirmed the expression of ITK in tumor cells (Figure 10). Neither ITK-expressing KOSC2 nor mock control cells colonized mice.

## 5. Proteomic Analysis of ITK Tyrosine Phosphorylation

Because ITK is a tyrosine kinase, we used mass spectrometry to investigate its tyrosine phosphorylation profile to identify novel biological behaviors in newly established oral cancer cell lines expressing ITK. Levels of tyrosine phosphorylation in SAS and KOSC2 cells were significantly higher in ITK-expressing cells than in mock control cells for 45 and 179 peptides, respectively. A total of 26 of the peptides were common to SAS and KOSC2 cells. Excluding ITK peptides, GART peptides exhibited the highest levels of tyrosine phosphorylation among the 26 common peptides in ITK-expressing cells. GART and ITK phosphotyrosine residues common to SAS and KOSC2 cells are shown in **Figure 2**A,B. Compared with mock control cells, levels of a GART-associated specific phosphotyrosine (Tyr348) were significantly increased by 51- to 121-fold in ITK-expressing SAS and KOSC2 cells, respectively (**Figure 2**AB). Tandem mass spectra representing the phosphorylated residues of GART.



**Figure 2.** Phosphotyrosine proteomic analysis of interleukin-2–inducible T-cell kinase (ITK)-expressing cells and mock control cells, and protein–protein interaction between ITK and trifunctional purine biosynthetic protein adenosine-3 (GART). (**A**,**B**) Quantitative comparison of phosphotyrosine residues on GART and ITK in SAS cells (**A**) and KOSC2 cells (**B**). Error bars indicate standard deviation. \* p < 0.05 (Student's *t*-test). (**C**) BRET assay in HEK 293 cells. Red bars indicate HEK 293 cells transfected with HaloTag-fused ITK and NanoLuc-fused GART. Blue bars indicate HEK 293 cells transfected with HaloTag and NanoLuc-fused GART. (**D**) BRET assay in HEK 293 cells. Red bars indicate HEK 293 cells transfected with NanoLuc-fused ITK and HaloTag-fused GART. Blue bars indicate HEK 293 cells transfected with NanoLuc-fused ITK. Error bars indicate standard deviation. \* p < 0.01 (Student's *t*-test). (**E**) Immunofluorescence cytochemistry of HEK 293 cells with anti-ITK (green) and anti-GART (red) antibodies. ITK was transfected, and GART was the endogenous protein. Left panels show HaloTag-fused ITK-transfected HEK 293 cells. Right panels show HaloTag-transfected HEK 293 cells (bars, 5 µm). (**F** and **G**) 3D images of immunofluorescence cytochemistry with anti-ITK (green) and anti-GART (red) antibodies. TK-transfected HEK 293 cells. Right panels show HaloTag-transfected HEK 293 cells (bars, 5 µm); lower panel bars, 3 µm). (**H**) Western blot analysis of ITK and GART expression in HaloTag-fused ITK-transfected or HaloTag-fused ITK-transfected HEK 293 cells as a mock control.  $\beta$ -Actin was blotted as a loading control.

### 6. Elucidation of the Association between ITK and GART

We investigated the direct association between ITK and GART, as GART is endogenously expressed in oral cancer cell lines and HEK 293 cells (**Figure 1**K and **Figure 2**H). In cells transfected with ITK or GART fused to NanoLuc or HaloTag, BRET occurred in a HaloTag concentration-dependent manner. By contrast, BRET was not detected in cells transfected with HaloTag not fused to ITK or GART (**Figure 2**C,D). Immunofluorescence analysis of the intracellular localization of ITK (green) and GART (red) (**Figure 2**E–G) indicated the partial colocalization of ITK and GART in HEK 293 cells (**Figure 2**E). Analyses of 3D images showed that ITK and GART interacted at the non-adherent surface of the cell or close to the tip of the cellar protrusions (**Figure 2**F,G). Expression of transfected ITK and endogenous GART in HEK 293 cells was confirmed by western blotting (**Figure 2**H).

#### 7. Assessment of De Novo Synthesis of Purines in ITK-Expressing Cells

To clarify whether transfected ITK accelerates de novo synthesis of purines via activation of GART enzymatic activity, we performed <sup>13</sup>C-glucose tracing analyses. After replacement of <sup>13</sup>C6-glucose in the culture medium, we simultaneously quantified <sup>13</sup>C-containing metabolites of the purine synthesis pathway, inosine monophosphate (IMP), and 5-phosphoribosyl-1-pyrophosphate (PRPP), as well as lactate and citrate (**Figure 3**A).



**Figure 3.** Metabolomic analysis of interleukin-2–inducible T-cell kinase (ITK)-expressing cells and mock control cells. (**A**) Purine biosynthesis pathway and glycolytic pathway (G6P, glucose 6-phosphate; Ru-5-P, ribulose-5-phosphate; PRPP, 5-phosphoribosyl 1-pyrophosphate; 5-PRA, 5-phosphoribosyl-1-amine; GAR, glycinamide ribonucleotide; FGAR and FGAM, formylglycinamide ribonucleotide; AIR, 5-aminoimidazole ribonucleotide; IMP, inosine monophosphate). Red and black circles indicate the number of <sup>13</sup>C and <sup>12</sup>C atoms in the metabolites, respectively. (**B–E**) Ratio of <sup>13</sup>C- to <sup>12</sup>C-labeled compounds at 0, 0.5, 3, and 6 hours after addition of <sup>13</sup>C6-glucose in SAS cells (B: PRPP; C: IMP; D: lactate; E: citrate). (**F–I**) Absolute amount of each <sup>13</sup>C-labeled compound at 0 and 6 hours after addition of <sup>13</sup>C6 -glucose in SAS cells (F: PRPP; C: IMP; D: lactate; E: citrate). Error bars indicate standard deviation. \* *p* < 0.05, \*\* *p* < 0.001 (Student's *t*-test).

Time-course profiling of the <sup>13</sup>C replacement rate (i.e., a ratio of <sup>13</sup>C6-glucose to <sup>12</sup>C6-glucose) indicated increased influx of <sup>13</sup>C to the PRPP pool (>2-fold) between 3 and 6 hours post-replacement (**Figure 3**B). Such an increase in <sup>13</sup>C influx into IMP was also demonstrated at 6 hours post-replacement, with an almost 2-fold increase (**Figure 3**C), while only small increases in the <sup>13</sup>C replacement rate of lactate and citrate were observed (**Figure 3**D and E).

Increased purine de novo synthesis in ITK-expressing cells was confirmed by quantifying the amounts of <sup>13</sup>C-labeled compounds (**Figure 3**F–I). Compared to mock control cells, the amounts of <sup>13</sup>C5-PRPP, <sup>13</sup>C5-IMP, and <sup>13</sup>C3-lactate were significantly higher in ITK-expressing cells at 6 hours after replacement of <sup>13</sup>C6-glucose (**Figure 3**F–H), while there was no statistically significant difference in citrate amount (**Figure 3**I).

#### 8. Inhibition of CellG and Suppression of GART Phosphorylation and Purine Metabolism Using an ITK Inhibitor

In both SAS and KOSC2 cells, the ITK-associated increase in cell proliferation was diminished by treatment with the ITK inhibitor Cmpd-5 (**Figure 4**A,B). Spheroids of ITK-expressing cells treated with Cmpd-5 were smaller than those of untreated ITK-expressing cells. By contrast, the proliferation rate and spheroid volume of mock control cells were not affected by treatment with the ITK inhibitor (**Figure 4**A,B).



**Figure 4.** Effect of the interleukin-2–inducible T-cell kinase (ITK) inhibitor on ITK-expressing cells and mock control cells. (A) Rate of ITK-expressing SAS cells and mock control cells treated with DMSO or ITK inhibitor (Cmpd-5) for

144 hours. Images are representative photographs of ITK-expressing SAS cell spheroids and mock control cell spheroids treated with DMSO or ITK inhibitor for 144 hours. Left panels of ITK-expressing cell spheroids and mock control cell spheroids are overall views (bars, 1 mm), and right panels are magnified images (bars, 500 µm). \* p < 0.001 (Student's *t*-test) (**B**) Rate of ITK-expressing KOSC2 cells and mock control cells treated with DMSO or ITK inhibitor (Cmpd-5) for 144 hours. Images are representative photographs of ITK-expressing KOSC2 cell spheroids and mock control cell spheroids treated with DMSO or ITK inhibitor for 144 hours. Left panels of ITK-expressing cell spheroids and mock control cell spheroids treated with DMSO or ITK inhibitor for 144 hours. Left panels of ITK-expressing cell spheroids and mock control cell spheroids are overall views (bars, 200 µm), and right panels are magnified images (bars, 50 µm). \* p < 0.001 (Student's *t*-test). (**C**,**D**) ITK-expressing cells and mock control cells were treated with DMSO or ITK inhibitor (Cmpd-5) for 24 hours, and phosphotyrosine residues on GART and ITK were examined (C: SAS cells; D: KOSC2 cells). \*\* p < 0.05 (Student's *t*-test). (**E**-**H**) Absolute amount of each <sup>13</sup>C-glucose metabolite at 0 and 6 hours after addition of <sup>13</sup>C-glucose in ITK-expressing cells and mock control cells treated with ITK inhibitor (E: PRPP; F: IMP; G: lactate; H: citrate). \* p < 0.01, \*\* p < 0.001 (Student's *t*-test). Error bars indicate standard deviation.

Phosphoproteomic analyses revealed that phosphorylation of GART and ITK was significantly suppressed in both ITK-expressing SAS and KOSC2 cells treated with Cmpd-5 compared with untreated cells, whereas the ITK inhibitor had no effect on GART and ITK phosphorylation in the mock control cells (**Figure 4**C,D). In metabolomic analyses with the ITK inhibitor, the absolute amounts of <sup>13</sup>C5-PRPP and IMP were significantly lower in ITK-expressing cells treated with Cmpd-5 at 6 hours after addition of <sup>13</sup>C6-glucose compared to mock control cells treated with the ITK inhibitor (**Figure 4**E,F). There were no statistically significant differences in the absolute amounts of <sup>13</sup>C3- lactate and citrate (**Figure 4**G,H).