Constitutive Activation of Signal Transducers and Activators of Transcription 3 Correlates with Cyclin D1 Overexpression and May Provide a Novel Prognostic Marker in Head and Neck Squamous Cell Carcinoma¹

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Abstract

The precise mechanism responsible for the frequent overexpression of cyclin D1 in human head and neck squamous cell carcinoma (HNSCC) is not known. In view of the fact that signal transducers and activators of transcription 3 (Stat3) is often activated in HNSCC cells, we examined the effects of Stat3 on cyclin D1 expression and cell proliferation in the YCU-H891 HNSCC cell line that displays constitutive activation of Stat3. Expression of a dominant negative Stat3 construct in YCU-H891 cells inhibited proliferation, cyclin D1 promoter activity, and cellular levels of cyclin D1 mRNA and protein. The levels of the antiapoptotic Bcl-2 and Bel-Xₐ proteins were also inhibited. In 51 primary tumor samples from patients with squamous cell carcinoma of the p. o. tongue, there was a significant correlation between increased levels of the activated form of Stat3, phosphorylated-Stat3, and increased levels of cyclin D1 (P < 0.0001). Increased tumor levels of phosphorylated-Stat3 were also associated with lower survival rates (P < 0.01). This study provides the first evidence that in HNSCC, constitutive activation of Stat3 plays a causative role in overexpression of cyclin D1, and in clinical studies, Stat3 activation may provide a novel prognostic factor. Furthermore, agents that target Stat3 may be useful in the treatment of HNSCC.

Introduction

Overexpression of the G₁ cell cycle control protein cyclin D1, and or the related mRNA, occurs in >50% of cases of human HNSCC(1, 2), and overexpression of this protein is a marker of poor prognosis in this disease (1). Furthermore, in vitro and in vivo introduction of an antisense cyclin D1 sequence into HNSCC cells inhibits their growth and tumorigenicity, induces apoptosis, and also enhances their sensitivity to chemotherapeutic agents (3, 4). In ~20% of the cases of HNSCC, the cyclin D1 gene is amplified (1, 5). However, in the majority of these cases, the gene is not amplified, suggesting that the increased expression of cyclin D1 is because of defects at the level of gene transcription. A similar discrepancy between cyclin D1 overexpression and gene amplification has also been reported in breast and colon cancers (6, 7). Recent studies indicate that aberrant β-catenin/
The relationship between either the levels of p-Stat3 or cyclin D1 and clinicopathological factors was assessed with the \( \chi^2 \) test. For survival analysis, the Kaplan-Meier method was used, and the statistical significance was analyzed by the Log-rank test. To determine whether the prognostic value of Stat3 is independent of cyclin D1 expression, T stage, the presence of nodal metastasis, or the clinical stage, the influence of these factors on patient survival was analyzed by the multivariate Cox proportional hazards method. Differences were considered to be statistically significant when: \( P < 0.05 \).

**Results and Discussion**

**Effects of Transient Expression of a Dominant Negative Mutant of Stat3, Stat3D, on Cyclin D1 Expression.** As mentioned in the “Introduction,” cyclin D1 is overexpressed frequently in primary HNSCC (1), and it is also expressed at a high level in YCU-H891 cells (13). Therefore, it was of interest to determine whether Stat3 plays a role in controlling the transcription of cyclin D1 in these cells. For this purpose, we assessed the effect of a dominant negative mutant of Stat3, Stat3D, in transient transfection assays using a cyclin D1 promoter luciferase reporter. Because there is evidence that activation of the ras-ERK pathway can transcriptionally up-regulate cyclin D1 expression (18), we added the mitogen-activated protein/ERK kinase inhibitor PD98059 to some of these assays so that we could more specifically examine the role of activated Stat3. The optimal concentration of this inhibitor was first determined by Western blot analysis of the phosphorylated ERK (Fig. 1A). YCU-H891 cells were grown in serum minus medium for 16 h, pretreated with 0, 5, or 10 \( \mu \)M PD98059 for 30 min, and then stimulated with 50 ng/ml TGF-\( \alpha \) for an additional 24 h. We found that 10 \( \mu \)M PD98059 strongly inhibited the phosphorylation of ERK1/2 that was stimulated by TGF-\( \alpha \) (Fig. 1A). Therefore, we used this concentration of PD98059 in the cyclin D1 promoter luciferase assays and found that it did not inhibit these assays significantly, either in the absence or presence of TGF-\( \alpha \) (Fig. 1A). However, the dominant negative Stat3D construct strongly inhibited both basal and TGF-\( \alpha \)-stimulated cyclin D1 promoter activity (Fig. 1A).

**Effects of Stable Expression of Stat3D on Gene Expression in Derivatives of YCU-H891 Cells.** In view of the above results, we examined the effects of dominant negative Stat3 on cyclin D1 expression in two clonal derivatives of YCU-H891 cells (designated Stat3D666 and StatDN99) that stably express the HA-tagged dominant negative Stat3D protein. The development of these derivatives and some of their properties are described elsewhere (14). We included in these studies a vector control cell line that had been transfected with only the empty vector pCAGGS-neo (14). In our previous study (14), we confirmed that the HA-tagged Stat3 D protein functions as a dominant negative in the two Stat3D clones, by using a luciferase reporter construct that contains a Stat3-responsive element. The parental YCU-891 cells, the vector control cells, and the two Stat3D clones were transfected transiently with the cyclin D1 promoter luciferase reporter, with or without stimulation of the cells with TGF-\( \alpha \) (Fig. 1B). In the Stat3D666 cells, both basal and TGF-\( \alpha \)-stimulated cyclin D1 promoter activity were markedly inhibited, when compared with the parental or vector control cells (Fig. 1B). In the Stat3DN99 cells, the basal activity of the cyclin D1 promoter was almost the same as that of the parental cells, but TGF-\( \alpha \)-stimulated promoter activity was strongly inhibited (Fig. 1B).

Because dominant negative Stat3 strongly inhibited cyclin D1 promoter activity, we examined cellular levels of the endogenous cyclin D1 mRNA using semiquantitative RT-PCR. In both the Stat3D666 and Stat3DN99 cells, the levels of cyclin D1 mRNA were markedly decreased when compared with the parental and vector control cells (Fig. 1C).
Dominant Negative Stat3 Inhibits Cellular Levels of the Cyclin D1, Bcl-2, and Bcl-XL Proteins. We did Western blot analysis of cell extracts to compare the levels of expression of the cyclin D1, Bcl-2, and Bcl-XL proteins in the parental, vector control, and two Stat3D clones (Fig. 1D). These results, taken together with the above results in transient transfection cyclin D1 promoter activity assays (Figs. 1, A and B) and semiquantitative RT-PCR assays (Fig. 1C), provide strong evidence that activated wild-type Stat3 transcriptionally up-regulates cyclin D1 expression in YCU-H891 cells. We found that the levels of the Bcl-2 and Bcl-XL proteins were also reduced in both the Stat3DN66 and Stat3DN99 cells (Fig. 1D), providing evidence that activated wild-type Stat3 also stimulates the expression of these proteins.

Effects of Dominant Negative Stat3 on Cell Proliferation. To assess biological effects of stable expression of the dominant negative Stat3 mutant, we compared the growth curves of the Stat3DN66 and Stat3DN99 clones to those of parental and vector control cells, when cells were grown in medium containing 10% serum and in serum minus medium (Fig. 1E). In the medium containing 10% serum, both the clones of the stably expressed dominant negative Stat3 protein displayed slower growth rates and a lower saturation density than the parental or vector control cells (Fig. 1E). These studies are consistent with studies by Grandis et al. (19) in other HNSCC cell lines. In the medium minus serum, the stat3DN66 and Stat3DN99 cells showed initial growth rates that were slower than those of the parental and vector control cells, and then both clones displayed a decline in cell numbers (Fig. 1E), presumably decreasing viability in the absence of serum.

The Levels of p-Stat3 Correlate with the Level of Cyclin D1, Nodal Metastasis, Clinical Stage, and Poor Prognosis in SCC Tumors of the p.o. Tongue. Because the above-described in vitro assays provided evidence that constitutive activation of Stat3 up-regulates cyclin D1 expression and cell proliferation in HNSCC cells, it was of interest to determine whether in primary HNSCC tumors there is an association between activation of Stat3 and the overexpression of cyclin D1 and whether activation of Stat3 correlates with various clinicopathological parameters in patients with HNSCC. Samples of 51 individual primary SCC of the p.o. tongue, which had been obtained from patients before therapy, were analyzed by immunohistochemistry for nuclear staining with an antibody specific for phospho-Stat3, i.e., the activated form of Stat3. In parallel studies, the same samples were analyzed by immunohistochemistry for nuclear staining for cyclin D1, using a cyclin D1-specific antibody. Representative examples of immunohistochemical staining are shown in Fig. 2A. Tumors were scored positive for p-Stat3 if they displayed strong staining, i.e., if ≥50% of the tumor cells displayed nuclear staining with the respective antibody and were scored positive for cyclin D1 if ≥5% of the tumor cells displayed nuclear staining with
the respective antibody (see “Materials and Methods”). Table 1 indicates that of the 51 tumors, 19 were positive for p-Stat3 (~37%). Of the remaining tumors, 19 were negative, 10 gave weak, and 3 gave moderate staining for p-Stat3 (data not shown). Table 1 indicates 24 of 51 tumors were positive for cyclin D1 (~47%). When these data were analyzed by the $\chi^2$ test, there was a highly significant ($P < 0.001$; Table 1) correlation between positive expression of p-Stat3 and positive expression of cyclin D1. Using Pearson’s correlation coefficient, we also found a significant association ($r = 0.431$, $P = 0.0014$) between these two parameters. These findings are consistent with our in vitro data (Fig. 1), indicating that activation of Stat3 enhances the expression of cyclin D1 in a HNSCC cell line.

When we examined possible correlations with various clinicopathological parameters, we found that increased levels of p-Stat3 significantly correlated with the existence of nodal metastasis ($P = 0.016$) and the clinical stage ($P = 0.03$) but not with tumor stage, whereas increased levels of cyclin D1 did not significantly correlate with any of these three parameters (Table 2). Kaplan-Meier survival curves indicated that patients positive for increased p-Stat3 demonstrated significantly ($P < 0.01$) lower disease-specific survival rates (Fig. 2B). Increased cyclin D1 levels were also associated ($P = 0.019$) with poorer prognosis (Fig. 2C), which is consistent with a previous large-scale study of cyclin D1 immunostaining on SCC of the p.o. tongue (20, 21). In a multivariate Cox analysis, we found that p-Stat3 ($P < 0.01$) was a predictor of poor prognosis, independent of cyclin D1 expression, T stage, the presence of nodal metastasis, or clinical stage. In this analysis, we found that cyclin D1 ($P = 0.025$), T stage ($P = 0.0005$), the presence of nodal metastases ($P < 0.0001$), and clinical stage ($P < 0.0001$) were also independent prognostic factors.

Thus, the present studies provide the first evidence that the frequent overexpression of cyclin D1 in HNSCC (see “Introduction”) may be attributable, at least in some cases, to increased activation of Stat3, which, in turn, is because of frequent autocrine activation of the TGF-α/EGFR pathway in HNSCC (8). Indeed, in a recent study (13), we found that in YCU-H891 cells, inhibition of EGFR activity by egigallocatechin-3-gallate, a major biologically active component of green tea, inhibits Stat3 activation and cyclin D1 promoter activity and decreases the cellular level of the cyclin D1 protein. There is also previous evidence that increased expression of cyclin D1 correlates with an aggressive phenotype in HNSCC (1). Therefore, aberrant

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Table 1  Correlation between nuclear expression of p-Stat3 and cyclin D1

<table>
<thead>
<tr>
<th>p-Stat3 staining</th>
<th>cyclin D1 staining</th>
<th>Negative</th>
<th>Positive</th>
<th>Total</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$n = 28$</td>
<td>$n = 23$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Negative $n = 32$</td>
<td></td>
<td>24 (47%)</td>
<td>16 (31%)</td>
<td>32 (65%)</td>
<td>&lt;0.0001$^a$</td>
</tr>
<tr>
<td>Positive $n = 19$</td>
<td></td>
<td>18 (36%)</td>
<td>16 (31%)</td>
<td>19 (37%)</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>42 (53%)</td>
<td>47 (47%)</td>
<td>51 (100%)</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ $\chi^2$ test.

Table 2  Correlations between nuclear p-Stat3 or cyclin D1 and clinicopathological parameters

<table>
<thead>
<tr>
<th></th>
<th>No.</th>
<th>p-Stat3 positive</th>
<th>$P$</th>
<th>cyclin D1 positive</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T stage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I and II</td>
<td>41</td>
<td>15 (37%)</td>
<td>0.84</td>
<td>20 (49%)</td>
<td>0.62</td>
</tr>
<tr>
<td>III and IV</td>
<td>10</td>
<td>4 (40%)</td>
<td>4 (40%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nodal metastasis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Negative</td>
<td>39</td>
<td>11 (28%)</td>
<td>0.016</td>
<td>17 (44%)</td>
<td>0.37</td>
</tr>
<tr>
<td>Positive</td>
<td>12</td>
<td>8 (67%)</td>
<td>7 (58%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clinical stage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I and II</td>
<td>36</td>
<td>10 (27%)</td>
<td>0.03</td>
<td>15 (41%)</td>
<td>0.23</td>
</tr>
<tr>
<td>III and IV</td>
<td>15</td>
<td>9 (60%)</td>
<td>9 (60%)</td>
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</tbody>
</table>
activation of the EGFR-Stat3 pathway in HNSCC (8) may contribute to the malignancy of these cancers, at least in part, through overexpression of cyclin D1. The precise mechanism by which activation of Stat3 enhances transcription from the cyclin D1 promoter remains to be determined.

Our previous finding that expression of a dominant negative Stat3 protein in YCU-H891 cells markedly increases their sensitivity to inhibition by 5-fluorouracil (14) may also be clinically relevant. This effect could be secondary to the above-described suppression of cyclin D1 overexpression and/or the associated decreased expression of the antiapoptotic proteins Bcl-2 and Bcl-XL (Fig. 1D). Our findings are consistent with previous studies in rodent fibroblast cell lines, indicating that Stat3 can transcriptionally up-regulate the expression of Bcl-XL (10). In addition, abrogation of Stat3 function causes down-regulation of the Bcl-2 and/or Bcl-XL proteins and thereby enhances cellular sensitivity to treatment with UV or mitomycin C in ras-transfected intestinal epithelial cells (22) and causes an increase in apoptosis in a human HNSCC xenograft model (9). Our clinical data provide the first evidence that there is a strong association between increased levels of the activated form of Stat3 (p-Stat3) and cyclin D1 overexpression in HNSCC (Table 1) and that activation of Stat3 might provide an independent prognostic factor in this and possibly other malignancies. It is of interest that p-Stat3, but not cyclin D1, was increased levels of the activated form of Stat3 (p-Stat3) and cyclin D1 overexpression in primary hypopharyngeal carcinomas. Cancer (Phila.), 97: 329–339, 2002.


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