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Clarifying the spectrum of driver oncogene mutations in biomarker-verified squamous carcinoma of lung: lack of *EGFR/KRAS* and presence of *PIK3CA/AKT1* mutations

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Abstract

Purpose—There is persistent controversy as to whether *EGFR/KRAS* mutations occur in pulmonary squamous cell carcinoma (SQCC). We hypothesized that the reported variability may reflect difficulties in the pathologic distinction of true SQCC from adenosquamous carcinoma (AD-SQC) and poorly-differentiated adenocarcinoma (ADC) due to incomplete sampling or morphologic overlap. The recent development of a robust immunohistochemical approach for distinguishing squamous vs glandular differentiation provides an opportunity to reassess *EGFR/KRAS* and other targetable kinase mutation frequencies in a pathologically homogeneous series of SQCC.

Experimental Design—Ninety-five resected SQCC, verified by immunohistochemistry as $\Delta Np63+/TTF-1-$, were tested for activating mutations in *EGFR*, *KRAS*, *BRAF*, *PIK3CA*, *NRAS*, *AKT1*, *ERBB2/HER2*, and *MAP2K1/MEK1*. Additionally, all tissue samples from rare patients with the diagnosis of *EGFR/KRAS*-mutant “SQCC” encountered during 5 years of routine clinical genotyping were reassessed pathologically.

Results—The screen of 95 biomarker-verified SQCC revealed no *EGFR/KRAS* (0%; 95% CI 0–3.8%), 4 *PIK3CA* (4%; 95% CI 1–10%) and 1 *AKT1* (1%; 95% CI 0–5.7%) mutations. Detailed morphologic and immunohistochemical reevaluation of “*EGFR/KRAS*-mutant SQCC” identified during clinical genotyping (n=16) resulted in reclassification of 10 (63%) cases as AD-SQC and 5 (31%) cases as poorly-differentiated ADC morphologically mimicking SQCC (i.e. ADC with “squamoid” morphology). One (6%) case had no follow-up.

Conclusions—Our findings suggest that *EGFR/KRAS* mutations do not occur in pure pulmonary SQCC, and occasional detection of these mutations in samples diagnosed as “SQCC” is due to challenges with the diagnosis of AD-SQC and ADC, which can be largely resolved by comprehensive pathologic assessment incorporating immunohistochemical biomarkers.

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INTRODUCTION

Adenocarcinoma (ADC) and squamous cell carcinoma (SQCC) represent the two major types of non-small cell lung carcinoma (NSCLC). Historically, the subtype of NSCLC has not been a major factor in determining patient management, and fundamental differences in the molecular pathogenesis of these tumors were not well established. It is only in recent years that it has become apparent that lung ADC and SQCC have distinct driver mutation profiles, which underlies their divergent responses to targeted therapies (1). In particular, since the early identification of *EGFR* and *KRAS* mutations in NSCLC – the predictors of sensitivity and resistance, respectively, to EGFR tyrosine kinase inhibitors (TKIs) – it was noted that these mutations have a remarkable predilection for ADC (2–5). Despite the general agreement that *EGFR* and *KRAS* mutations occur almost exclusively in ADC, there has been a persistent controversy as to whether these mutations also occur, albeit at a lower frequency, in SQCC. A number of studies have described the detection of activating *EGFR* mutations (range 1–15%) (6–10) and *KRAS* mutations (range 1–9%) (11, 12) in SQCC, although in most studies the detailed pathologic analysis of those samples was not provided. Clarifying this controversy is of interest both as a biological question pertaining to the degree of lineage restriction of *EGFR/KRAS* mutations, and as a practical clinical question pertaining to the optimal triage of patient samples for predictive molecular testing based on the pathologic diagnosis.

There are several well-known limitations in the traditional diagnosis of NSCLC subtypes. In particular, it is well established that poorly-differentiated ADC and SQCC can appear indistinguishable by routine light microscopy, particularly in small biopsies and cytology samples, leading to a historically high rate of unclassified NSCLC and the potential for erroneous subtype assignment (13). Largely driven by the recent molecular and clinical insights on the significance of NSCLC subtypes, there has been an explosion in research aimed at circumventing the limitations of traditional morphology through the use of immunohistochemical (IHC) biomarkers to more precisely and objectively determine cell lineage in poorly-differentiated NSCLC (14–17). We (14) and others investigators (15) have shown that IHC for TTF-1 and p63 – the developmental transcription factors and master-regulators in glandular and squamous cell lineages, respectively – can effectively identify a tumor cell type in clinical samples of NSCLC with equivocal morphology. In particular, recent studies show the value of IHC for ΔN isoform of p63 – a highly squamous-specific variant of p63 (18, 19). Several studies have already shown that incorporation of IHC leads to a dramatic decline in the rate of unclassified NSCLC, as well as an increase in the accuracy and reproducibility of ADC vs SQCC diagnoses both in the investigational setting (17, 20) and in clinical practice (21, 22). For these reasons, IHC is now widely advocated to be incorporated into routine diagnosis of NSCLC that are difficult to classify by morphology (23). However, to what degree the lack of precision in the morphologic diagnosis of NSCLC subtypes in pre-IHC era may have contributed to atypical molecular findings has not been investigated in detail.

Another well-known confounder in the accurate determination of NSCLC subtype is adenosquamous carcinoma (AD-SQC) -a rare tumor, representing 0.4–4% of NSCLC (24), which shows bi-directional differentiation with morphologically and immunophenotypically distinct squamous and glandular components. Preoperative diagnosis of AD-SQC is notoriously difficult because it requires simultaneous sampling of both components, which

cannot be reliably achieved in small tissue fragments (14, 21, 23). As a result, this tumor may be diagnosed as “SQCC” or “ADC” depending on which component is sampled. Importantly, AD-SQC is known to harbor a spectrum of *EGFR/KRAS* mutation that is similar to ADC (25–30). Several investigators have previously suggested that the detection of *EGFR* mutations in small samples diagnosed as “SQCC” could be a result of incomplete sampling of AD-SQC (2, 25). However, this possibility has not been formally investigated.

Based on these issues, we hypothesized that the reported variability of *EGFR/KRAS* mutations in samples diagnosed as SQCC could be a result of the above difficulties in the pathologic distinction of true SQCC from ADC and AD-SQC, particularly in samples diagnosed prior to the recent advances in IHC. The goal of the study was therefore to combine mutational analysis with detailed pathologic assessment incorporating IHC. The study design included two separate approaches. First, we performed a screen for *EGFR/KRAS* mutations in a large series of surgically resected SQCC (n=95) in which the diagnosis was verified by IHC to exclude the possibility of inadvertent testing of ADC that morphologically mimics SQCC. Second, we performed detailed histologic and IHC reassessment of cases diagnosed as “SQCC” found to harbor *EGFR/KRAS* mutations during 5 years of routine molecular testing at our institution (n=16). In addition, we used this highly validated, pathologically homogenous group of pure resected SQCC to investigate mutation frequencies in six other therapeutically-targetable signaling molecules- *BRAF*, *PIK3CA*, *NRAS*, *AKT1*, *ERBB2/HER2*, and *MAP2K1/MEK1*.

MATERIALS AND METHODS

Study design

This study was approved by the institutional review board of Memorial Sloan-Kettering Cancer Center (MSKCC), New York, NY. For the first part of the study (mutation screen of resected IHC-verified SQCC), a search of the electronic medical records from the Department of Pathology at MSKCC was performed to identify 100 lung resections with a diagnosis of SQCC. A representative formalin-fixed paraffin-embedded (FFPE) tumor block was selected and used for IHC with Δ Np63 and TTF-1, as described below. Sufficient archival material was available for 98 cases. Of those, only cases with immunoprofiles compatible with the diagnosis of SQCC (n=95) were included in the mutation screen, as described below.

For the second part of the study (reassessment of clinical samples), a separate search was performed to identify specimens with the diagnosis of SQCC which were found to harbor *EGFR* or *KRAS* mutations during routine clinical genotyping at our institution between January 2006 and February 2011 (n=16) by methods described previously (31). Although routine testing for *EGFR/KRAS* mutations at our institution during this time period generally excluded tumors with the diagnosis of SQCC, testing of some samples with this diagnosis was performed at the request of the individual treating oncologists. All available pathologic samples from these patients were evaluated by light microscopy, as well as IHC for Δ Np63/TTF-1 and *EGFR/KRAS* mutations if not previously performed and if sufficient tissue was available.

Immunohistochemistry

Immunohistochemistry was performed on a Bench Mark series automated stainer (Ventana, Tucson, AZ) as previously described (14, 18). Briefly, primary antibodies included Δ Np63 (p40 clone, 5–17, CalBiochem/EMD Biosciences, 1:2000 dilution) and TTF-1 (SPT24 clone, Novocastra, 1:50 dilution). Antigen retrieval was performed using CC1 (Cell Conditioning 1; citrate buffer pH 6.0, Ventana, Tucson, AZ) for 30 minutes. Interpretation

of Δ Np63/TTF-1 immunoprofiles was performed as recently described (18, 19). Briefly, Δ Np63-diffuse/TTF-1-negative profile supported SQCC. Rare cases with diffuse Δ Np63 and weak/focal coexpression of TTF-1 (known to occasionally occur in SQCC with SPT24 clone of TTF-1 antibody) were further confirmed as SQCC by diffuse expression of CK5/6 and negative Napsin A (data not shown), and such TTF-1 reactivity was regarded as non-specific. Profiles that supported ADC were TTF-1-positive/ Δ Np63-negative (Δ Np63 reactivity in isolated tumor cells was scored as negative). TTF-1/ Δ Np63 double-negative profile was interpreted as indeterminate but favoring ADC because negative Δ Np63 is highly unusual for SQCC, whereas TTF-1-negative ADC are not uncommon (14, 18, 19). Double-negative carcinomas were further evaluated by Napsin A and mucicarmine, which were non-contributory in all cases, and this data is not shown. Reactivity for Δ Np63 and TTF-1 in distinct cell populations was used to support bi-phenotypic differentiation (i.e. AD-SQC).

Mutational Analysis

DNA Extraction—Hematoxylin and eosin-stained sections corresponding to the selected FFPE tumor blocks were reviewed to identify areas of tumor. Macrodissection on 10 corresponding 5- μ m thick unstained sections was performed to ensure greater than 50% tumor nuclei for each case. Genomic DNA was extracted using the DN easy Tissue kit (QIAGEN, Valencia, CA) following the manufacturer's recommendations. Extracted DNA was quantified on the NanoDrop8000 (Thermo Scientific, Wilmington, DE).

Mutation analysis by Sequenom mass spectrometry genotyping—Tumors were genotyped by Sequenom Mass ARRAY system (Sequenom Inc., San Diego, CA). Briefly, samples were tested in duplicate using a series of multiplexed assays designed to interrogate the hot-spot mutations in 8 oncogenes: *EGFR*, *KRAS*, *BRAF*, *PIK3CA*, *NRAS*, *AKT1*, *ERBB2/HER2*, and *MAP2K1/MEK1*. A total of 92 non-synonymous mutations were tested in 6 multiplex reactions (see Supplemental Figure 1 for complete list of tested mutations). Genomic DNA amplification and single base pair extension steps were performed using specific primers designed with the Sequenom Assay Designer v3.1 software. The allele-specific single base extension products were then quantitatively analyzed using matrix-assisted laser desorption/ionization-time of flight mass spectrometry (MALDI-TOF MS) on the Sequenom Mass Array Spectrometer. All automated system mutation calls were confirmed by manual review of the spectra (M.E.A., M.L.).

EGFR exon 19 fragment analysis—Fragment analysis of fluorescently labeled PCR products was performed in duplicate. Briefly, a 207-bp genomic DNA fragment encompassing the entire exon 19 was amplified using the following fluorescently labeled primers (FW1: 5'-GCACCATCTCACAATTGCCAGTTA-3'; REV1: 5'-Fam-AAAAGGTGGGCCTGAGGTTCA-3'). PCR products were detected by capillary electrophoresis on an ABI 3730 Genetic Analyzer (Applied Biosystems, Foster City, CA).

RESULTS

Immunohistochemical verification and mutation screen of 95 resected pure squamous cell carcinomas

Immunohistochemistry for Δ Np63 and TTF-1 was performed on 98 resected lung tumors with the diagnosis of SQCC. Ninety-five cases had immunoprofiles supporting SQCC (Δ Np63+/TTF-1-), whereas immunoprofiles of 3 tumors were inconsistent with the diagnosis of SQCC due to diffuse expression of TTF-1 and/or lack of Δ Np63 (Supplemental Table 2). Microscopically, the 3 tumors with atypical immunoprofiles were poorly-differentiated non-small cell carcinomas that had a solid growth pattern, abundant

eosinophilic cytoplasm, and sharp cell borders – a morphology resembling SQCC (i.e. “squamous”), but lacking the defining features of true SQCC (i.e. no keratinization or intercellular bridges). In conjunction with biomarker immunoprofile supporting glandular rather than squamous lineage, these tumors were reclassified as solid ADC and excluded from further analysis.

Mutation screen was performed on 95 pure IHC-verified SQCC. Clinicopathologic characteristics of these patients are summarized in Table 1, and molecular results are shown in Table 2. None of the tested SQCC harbored *EGFR* or *KRAS* mutations (0% observed incidence; 95% CI 0 – 3.8%). Four tumors harbored *PIK3CA* mutations (4.2%; 95% CI 1.2 – 10.4%) and 1 tumor harbored an *AKT1* mutation (1.1%; 95% CI 0 – 5.7%). No mutations were identified in *BRAF*, *NRAS*, *ERBB2/HER2* or *MAP2K1/MEK1*. *PIK3CA* mutations occurred both in the helical domain encoded by exon9 (E542K, E545K) and in the catalytic domain encoded by exon 20 (H1047R, n=2). The clinicopathologic features of individual patients with *PIK3CA/AKT1* mutations are summarized in Table 3. *PIK3CA/AKT1* mutations did not show a significant association with age, gender, pack-year smoking history, tumor size, stage, and grade of differentiation (Supplemental Table 3).

Reassessment of 16 *EGFR/KRAS*-mutant “squamous cell carcinomas”

During routine genotyping of clinical samples for *EGFR/KRAS* mutations, 16 samples were encountered which had a pathologic diagnosis of SQCC and were found to harbor *EGFR* (n=10) or *KRAS* (n=6) mutations. *EGFR* mutations included exon 19 deletions (n=7) and L858R mutations (n=3), and *KRAS* mutations included G12C (n=2), G12V (n=2), G12D (n=1) and G12S (n=1). The detailed histologic and IHC reassessment of the index samples (mutant “SQCC”) and all other samples available for these patients is shown in Table 4 and is described next.

In one group of patients (#1–10; n=10), the diagnosis of SQCC in the index sample was verified by morphologic and IHC reassessment. Remarkably, in all but one of these patients (#1–9; n=9), definitive evidence of glandular differentiation in the form of either ADC or AD-SQC was uncovered in second or third tissue samples from other sites or time-points. In most cases, the glandular component was apparent on conventional morphology, but in two cases (#1 and 8) a minor glandular component was revealed with the aid of IHC.

Importantly, despite the distinct histologies, different samples from an individual patient harbored identical *EGFR* or *KRAS* mutations (whenever molecular data was available), indicating they were clonally-related and therefore represented components of a single AD-SQC. Paired samples represented primary tumor vs metastasis/recurrence (n=7), tumors at different metastatic sites (n=1), and preoperative biopsy vs same-site resection (n=1). The latter case (#9) was particularly informative in that it was comprised of a preoperative biopsy showing a *KRAS*-mutant “SQCC” with subsequent same-site resection revealing AD-SQC with 80% squamous and 20% glandular components, which directly confirmed that squamous histology in the biopsy represented incomplete sampling of AD-SQC.

Interestingly, one case (#7) was a lobectomy in which the completely resected primary tumor was an *EGFR*-mutant SQCC whereas a hilar lymph node metastasis was ADC with an identical *EGFR* mutation. A thorough review of the primary tumor failed to uncover the evidence of glandular differentiation, suggesting that glandular metastases arose from a minor glandular component not represented in the sections of primary tumor used for microscopic evaluation (of note, there was no pathologic or clinicoradiologic evidence of another primary tumor in this patient). In this group, there was only a single patient (#10; never smoker) with the diagnosis of *EGFR*-mutant SQCC in two small biopsies, in whom evidence of ADC could not be identified in either sample. Because a resection of the primary tumor was not performed, the possibility of an underlying AD-SQC could not be either confirmed or excluded, and the final diagnosis was therefore considered

“indeterminate”. Examples of microscopic findings for this group of patients are illustrated in Figure 1 (A–L).

The other group of *EGFR/KRAS*-mutant “SQCC” (#11–15; n=5) consisted of poorly differentiated carcinomas with “squamous” morphology but with Δ Np63/TTF-1 immunoprofiles inconsistent with a diagnosis of SQCC, and instead supporting or favoring ADC. Similar to “SQCC” excluded from the mutation screen described above, these were poorly differentiated carcinomas with solid histology resembling SQCC but lacking keratinization or intercellular bridges (Figure 1 M–O).

In addition to the above two groups, case #16 (*KRAS*-mutant “SQCC”) was a tumor with squamous and glandular components, but in which glands occupied only 5% of the tumor mass. This tumor was, as a result, classified as SQCC based on the World Health Organization (WHO) 2004 definition of AD-SQC requiring >10% of each component (24).

The above findings are summarized in Table 5. Overall, of 16 cases with the diagnosis of “SQCC” harboring *EGFR/KRAS* mutations, 10 (63%) were reclassified as AD-SQC (including the tumor with 5% glandular component), 5 (31%) as ADC, and one case (6%) was indeterminate. Notably, the majority (7/10; 70%) of patients with *EGFR*-mutant “SQCC” were never-smokers.

DISCUSSION

In this study, we combined mutational analysis of lung cancers diagnosed as SQCC with rigorous IHC-assisted pathologic verification in an attempt to resolve the persistent controversy regarding the occurrence of *EGFR/KRAS* mutations in this tumor type. The main finding of this study is that *EGFR/KRAS* mutations do not occur in pure biomarker-verified SQCC, and that the main culprits responsible for the detection of these mutations in samples diagnosed as “SQCC” are 1) incomplete sampling of AD-SQC and 2) poorly-differentiated ADC morphologically mimicking SQCC. In addition to addressing the above controversy, we used a highly homogeneous series of IHC-verified SQCC to investigate the rate of mutations in other signaling molecules, for which targeted agents are either available or are at various stages of clinical development.

While the possibility that incomplete sampling of an underlying AD-SQC is a potential culprit for the detection of *EGFR/KRAS* mutations in samples diagnosed as “SQCC” has been suggested by several investigators in the past (2, 25), our data provide direct supporting evidence for this hypothesis. AD-SQC is uncommon but harbors a similar rate of *EGFR/KRAS* mutations as ADC (25–30), with our data supporting previous observations that these mutations are present uniformly in both the glandular and squamous components of this tumor type (25–29). These findings indicate that squamous histology per se is not incompatible with *EGFR/KRAS* mutations, but that these mutations are restricted to squamous histology that represents a component of AD-SQC, whereas they are not a feature of pure SQCC. Notably, this situation in SQCC is remarkably similar to the findings in small cell lung carcinoma (SCLC). While *EGFR/KRAS* mutations are not a feature of SCLC in general, these mutations may be present in SCLC that has a clonal relationship with ADC, as seen in rare instances when SCLC is combined with ADC or in recently-described small cell transformation of ADC after prolonged treatment with EGFR TKIs (32–36). These findings suggest that *EGFR/KRAS*-mediated tumorigenesis is specific to progenitor/stem cells giving rise to ADC, but that subsequent (or inherent) clonally-related phenotypic divergence accounts for the occasional detection of these mutations in unexpected histologies. Other than the presence of ADC-specific mutations, both SQCC and SCLC arising from ADC are otherwise morphologically and immunophenotypically identical to their pure counterparts.

The analysis of driver mutations can provide insights into tumor origin and clonal relationships in these settings.

As mentioned above, a key issue with the diagnosis of AD-SQC is that small biopsy or cytology specimens may contain only one of the two histologic components. A further diagnostic challenge is that metastases derived from AD-SQC sometimes consist entirely of a single histology (37, 38), as exemplified by case 6 in this study. These factors make it impossible to determine whether squamous histology in a small biopsy or even a metastectomy represents a true SQCC vs a component of AD-SQC. On the other hand, because AD-SQC is a rare tumor, the diagnosis of SQCC in a small specimen is statistically very likely to represent true SQCC (as discussed below, a patient's clinical characteristics, particularly the never-smoker status, may serve as a clue to an underlying AD-SQC). Although these challenges in the diagnosis of AD-SQC in clinical samples are well known (24), that they are the main culprits leading to conflicting molecular data in SQCC has not been previously well documented. This study illustrates that a comprehensive pathologic analysis of all specimens from different sites and time-points from individual patients can reveal both squamous and glandular differentiation in the majority of patients. Furthermore, we show that while IHC cannot circumvent the issue of incomplete sampling, it can improve the diagnosis of AD-SQC in a subset of cases.

The second culprit that we identified as a cause for the conflicting data surrounding *EGFR/KRAS* mutations in SQCC is the ability of poorly-differentiated ADC to grow in a solid pattern closely mimicking SQCC (i.e. "squamoid" or "pseudo-squamous" appearance). We show that the cell lineage in areas with this ambiguous appearance is readily clarified by IHC for Δ Np63 and TTF-1, but that interpretation in the absence of IHC may lead to an erroneous diagnosis of "SQCC" harboring *EGFR/KRAS* mutations. This is an under-recognized morphologic feature in lung ADC, which may be present either focally or as a predominant pattern, and we show here that it may present a diagnostic pitfall in both small specimens and resected tumors. These findings validate the value of IHC, which is becoming widely incorporated into clinical practice in recent years, for the diagnosis of morphologically-challenging NSCLC and for assuring homogeneity of tumor types included in molecular studies. It is of note that, while immunomarkers used in this study are not new, their application to clinical samples was characterized in detail only recently (15–19). We should also emphasize that IHC is not required for the diagnosis of all SQCC; in the majority of cases the line of differentiation is evident based on morphology, and IHC is only needed for a minority of cases that are poorly-differentiated and have equivocal morphology.

The third and least common cause of conflicting molecular data is the definition of AD-SQC itself, which requires that both glandular and squamous components represent at least 10% of the tumor mass (24). This arbitrarily-selected criterion predates the new molecular data showing that any amount of glandular differentiation, even less than 10%, appears to be a harbinger of ADC-specific driver mutations. Similar to our *KRAS*-mutant "SQCC" in which glands represented 5% of the tumor (case #16), detection of *EGFR* mutation in "SQCC" with <10% glands has been described by Ohtsuka et al (26). Therefore any amount of glandular differentiation should qualify a tumor for *EGFR/KRAS* genotyping.

The potential contribution of the above diagnostic challenges to the previous reports of *EGFR/KRAS* mutations in SQCC is difficult to estimate. The vast majority of reported patients with *EGFR*-mutant SQCC had advanced disease (where the diagnosis is typically based on small specimens), and many patients were never-smokers (6, 8, 10), suggesting that, similar to this study, those cases may have represented incompletely sampled AD-SQC. Interestingly, one recent study used a similar approach of combining IHC-based diagnosis

verification with *EGFR* mutation testing in a series of 85 resected SQCC (9). A total of 5 *EGFR*-mutant tumors were identified, of which 2 were re-classified by IHC as AD-SQC and ADC, whereas 3 tumors were verified as SQCC. These latter cases may be similar to case#7 in our series, in which whole tissue sections of the primary tumor showed only SQCC (by morphology and IHC) though a hilar lymph node metastasis showed ADC that harbored an identical *EGFR* mutation as the primary tumor, supporting their clonal relationship. This suggests that in rare cases under sampling of AD-SQC is possible even in whole tissue sections, which may occur because large tumors are examined representatively in pathology laboratories, and therefore a minor glandular component may not be represented in microscopically-scrutinized tissue.

A potential criticism of this study is that although no *EGFR/KRAS* mutations were identified in the screen of 95 IHC-verified pure SQCC, one cannot exclude the possibility of low-frequency mutations in these genes falling within the confidence intervals of this study (95% CI 0–3.8%). However, our conclusions are in equal part supported by the findings that none of the “SQCC” with *EGFR/KRAS* mutations identified in our clinical practice could be confirmed to represent true (i.e. pure) SQCC. Detailed pathologic review, incorporating the modern IHC methods, of *EGFR/KRAS*-mutant carcinomas diagnosed as SQCC at other institutions will be needed to validate the conclusions reached in this study.

What are the implications of our findings for clinical practice? The current recommendation in the National Comprehensive Cancer Network guidelines is to exclude SQCC from *EGFR/KRAS* mutation testing (39). Our findings support this recommendation for SQCC diagnosed in a surgically resected primary tumor (where under-sampling of AD-SQC is highly unlikely). On the other hand, testing patients with SQCC diagnosed in small biopsy or cytology specimens (where the possibility of an underlying AD-SQC cannot be excluded) should be guided by clinical parameters. In particular, similar to ADC, *EGFR* mutations in AD-SQC are associated with a never-smoker status (25, 30), whereas the lack of smoking history is unusual for patients with a true SQCC [2% in this study, 1–3% in other studies (5, 9, 40)]. Indeed, the majority of patients with *EGFR*-mutant “SQCC” with a revised diagnosis of ADC or AD-SQC in this study were never-smokers. We therefore suggest that patients that receive a diagnosis of SQCC based on a small biopsy and who do not have a history of smoking are likely to have an underlying mixed tumor and should be tested for *EGFR/KRAS* mutations. Detailed clinical analysis of the patients in this series, including their *EGFR* TKI sensitivity, will be reported separately (Paik et al, in preparation).

The specificity of *EGFR/KRAS* mutations for carcinomas with glandular differentiation (ADC and AD-SQC), and strict exclusion of these mutations from pure SQCC provides an interesting insight into the histogenetic relationship of these tumors. In the past, it has been questioned whether lung ADC and SQCC represent truly distinct entities vs a spectrum of related tumors (41). The sharp divide in tumor-initiating mutations provides a strong support for the distinct molecular pathogenesis of pure SQCC compared to tumors with glandular differentiation. The biological underpinnings of specificity for ADC of *EGFR/KRAS* and several other driver mutations in NSCLC, including *BRAF* (42) and *EML4-ALK* (43), remain to be elucidated, but these findings are in line with lineage-restriction of many other somatic genetic alterations across human tumors (44).

Lastly, in this study we used a rigorously verified series of pure SQCC to investigate the rate of mutations in other important signaling molecules. We found a low frequency of *PIK3CA* (4%) and *AKT1* (1%) mutations, which is in agreement with prior studies showing a 2–4% rate of *PIK3CA* mutations (45–47) and a ~1% rate of *AKT1* mutations (48, 49) in NSCLC. Prior studies have shown that *PIK3CA* mutations occur in both ADC and SQCC, but are more common in SQCC. Importantly, several PI3K and AKT1 inhibitors are in early

clinical development (50), and screening of lung SQCC for these mutations may be used in the future to select patients for targeted therapies.

In conclusion, we present compelling evidence that *EGFR/KRAS* mutations have a strong specificity for carcinomas with glandular differentiation, whereas they are not a feature of pure SQCC. We describe several pitfalls in the traditional pathologic diagnosis of NSCLC subtypes that can lead to conflicting genotype data, and illustrate how comprehensive pathologic assessment utilizing biomarker expression can clarify the tumor lineage and resolve a typical molecular findings. Our results support incorporating this approach into routine clinical practice and future clinicopathologic and molecular studies.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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STATEMENT OF TRANSLATIONAL RELEVANCE

There is significant variability in the reported prevalence of *EGFR/KRAS* mutations in squamous cell carcinoma (SQCC) of lung, which has raised a concern regarding the pathologic homogeneity of the tumors included in molecular studies. Here we combined mutational analysis with rigorous pathologic verification utilizing immunohistochemistry (IHC). We find that *EGFR/KRAS* mutations do not occur in pure biomarker-verified SQCC, and occasional detection of these mutations in cases reported as “SQCC” is a result of difficulties in the pathologic diagnosis of adenocarcinoma and adenosquamous carcinoma, which in the majority of cases can be resolved by comprehensive pathologic assessment incorporating IHC. The translational relevance is three-fold. First, we highlight the value of IHC in the diagnosis of SQCC, which clarifies the conflicting data on the spectrum of mutations in this tumor type. Second, we establish a sharp biological divide in the patterns of oncogenic driver mutations between lung adenocarcinoma (pure or combined) vs pure SQCC. Third, we determine the rate of several targetable mutations in a pathologically homogeneous set of SQCC.

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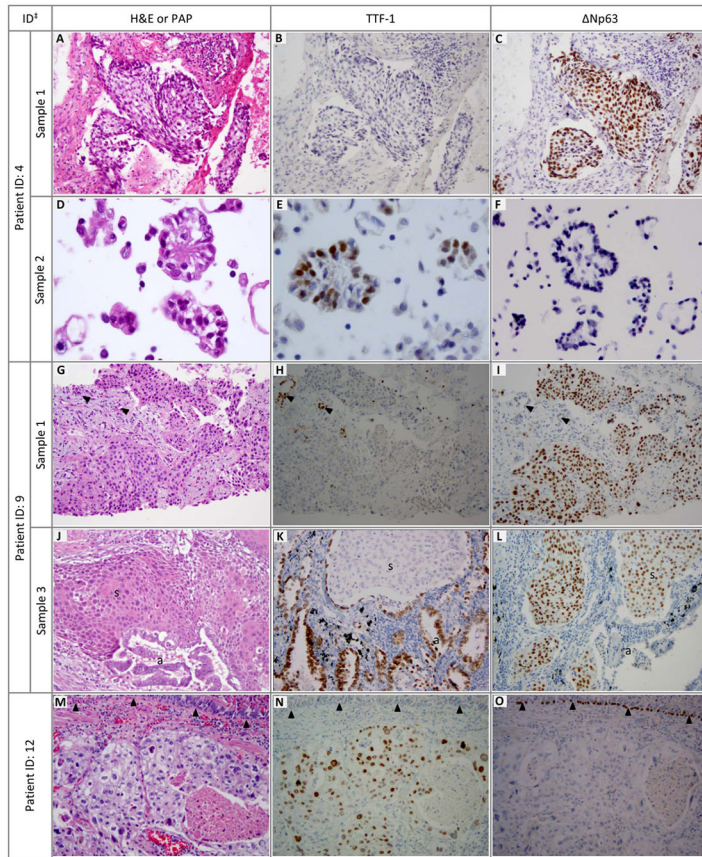


Figure 1. Microscopic features of *EGFR/KRAS*-mutant “squamous cell carcinomas” with a revised diagnosis of adenosquamous carcinoma or solid adenocarcinoma

Patient 4 (A–F) and patient 9 (D–I) illustrate incomplete sampling of AD-SQC leading to the diagnosis of “SQCC” with *EGFR* or *KRAS* mutations. While only squamous component was present in the index sample (core biopsies; A–C and G–I), glandular component was manifest in a cytology sample from another site (pleural fluid; D–F) or subsequent same-site resection (J–L). Glandular and squamous components have distinct morphology and Δ Np63/TTF-1 immunoprofiles as seen indifferent small samples (A–C vs D–F) or different areas of a resected tumor (J–L).

Patient 12 (M–O) illustrates a solid growth pattern in ADC which resembles SQCC morphologically (“squamoid” or “pseudo-squamous” appearance), but it is readily identified as being of a glandular rather than squamous lineage by IHC.

‡ ID corresponds to patient and sample numbers in Table 4.

a adenocarcinoma component, s squamous component, H&E hematoxylin and eosin stain, PAP Papanicolaou stain; arrowheads in G–I – benign pneumocytes (TTF-1+), arrowheads in M–O – benign bronchial basal cells (Δ Np63+)

Table 1

Clinicopathologic characteristics of IHC-verified resected squamous cell carcinomas (N=95).

Characteristic	N (%) or Median (range)
Age	68 (37–88)
Gender	
Male	62 (65)
Female	33 (35)
Smoking	
Never	2 (2)
Current or former	93 (98)
Smoking pack years	58 (0–132)
Tumor size	2.5 (0.7–11.5)
Tumor differentiation grade	
Well or moderate	44 (46)
Poor	51 (54)
Stage (pathologic) [†]	
IA	48 (51)
IB	9 (10)
IIA	16 (17)
IIB	10 (11)
IIIA	10 (11)
IIIB/IV	2 (2)
Surgical procedure	
Wedge	31 (33)
Segmentectomy	2 (2)
Lobectomy	49 (52)
Pneumonectomy	9 (10)
En block resection of lung and chest wall	1 (1)
Bronchial tumor resection	3 (3)
Immunohistochemistry [‡]	
ΔNp63+/TTF-1–	95 (100)

[†]American Joint Commission on Cancer Staging Manual 7th Edition.

[‡]See Supplemental Table 2 for details.

Table 2

Spectrum of driver oncogene mutations in 95 squamous cell carcinomas.

Gene	N (%) with mutation	95% confidence intervals
<i>EGFR</i>	0	0 – 3.8%
<i>KRAS</i>	0	0 – 3.8%
<i>PIK3CA</i>	4 (4.2%)	1.2 – 10.4%
<i>AKT1</i>	1 (1.1%)	0 – 5.7%
<i>BRAF</i>	0	0 – 3.8%
<i>NRAS</i>	0	0 – 3.8%
<i>ERBB2/HER2</i>	0	0 – 3.8%
<i>MAP2K1/MEK1</i>	0	0 – 3.8%
Any mutation	5 (5.3%)	1.7 – 11.9%

Table 3
 Clinicopathologic characteristics of individual patients with *PIK3CA* and *AKT1* mutations in squamous cell carcinoma.

Case ID	Mutation	Age Gender	Smoking (pack years)	Tumor size (cm)	Stage (pathologic)	Grade of differentiation	DFS (months)
1	<i>PIK3CA</i> E542K	81F	48	5.5	IIA	Poor	63+
2	<i>PIK3CA</i> E545K	51F	3	4	IIIA	Poor	12
3	<i>PIK3CA</i> H1047R	62M	35	2.6	IA	Poor	22+
4	<i>PIK3CA</i> H1047R	60M	120	2.5	IIB	Moderate	19
5	<i>AKT1</i> E17K	65F	63	2	IA	Moderate	23+

DFS disease free survival, + remains disease free, F female, M male

Table 4 Reassessment of 16 *EGFR/KRAS*-mutant “squamous cell carcinomas”, identified by routine clinical genotyping.

Pt ID	Age Gender	PY	Pathology					IHC		Mutation	Interpretation
			Sample # [±] ; site (time in months)	Specimen type	Diagnosis (original → Apost-review ^f)	TTF-1	ANp63				
1	61M	0	1) Spine (0)	Bx	SQCC		nd	nd	EGFR L858R	“SQCC” = component of AD-SQC	
			2) Lung (-26)	Bx	SQCC → AD-SQC		nd	nd	EGFR L858R		
2	71F	0	1) Lung, RLL (0)	Bx	SQCC		-	+	EGFR ex 19 15 bp Δ	“SQCC” = component of AD-SQC	
			2) Lung, RLL (-23)	Bx	ADC		+	nd	EGFR ex 19 15 bp Δ		
3	58M	0	1) Bronchus (0)	Bx	SQCC		-	+	EGFR ex 19 15 bp Δ	“SQCC” = component of AD-SQC	
			2) Lung, RUL (-9)	Bx	AD-SQC		nd	nd	EGFR ex 19 15 bp Δ		
			3) Lung, LLL (+21)	Bx	ADC		+	-	EGFR ex 19 15 bp Δ		
4	45F	0	1) Sacrum (0)	FNA	SQCC		-	+	EGFR ex 19 15 bp Δ	“SQCC” = component of AD-SQC	
			2) Lung (-17)	Pleural fluid	ADC		+	-	EGFR ex 19 15 bp Δ		
5	46M	0	1) Lung (0)	FNA	SQCC		-	+	EGFR ex 19 9 bp Δ	“SQCC” = component of AD-SQC	
			2) SCLN (+1)	Bx	ADC		+	-	EGFR ex 19 9 bp Δ		
6	73M	25	1) Adrenal (0)	Resection	SQCC		-	+	EGFR ex 19 18 bp Δ	“SQCC” = component of AD-SQC	
			2) SCLN (-9)	Bx	AD-SQC		f [±]	f [±]	EGFR ex 19 18 bp Δ		
7	68M	45	1) Lung (0)	Lobectomy	SQCC		-	+	EGFR ex 19 15 bp Δ	“SQCC” = component of AD-SQC	
			2) Hilar LN (0)	Dissection	ADC		+	-	EGFR ex 19 15 bp Δ		
8	50M	63	1) Skin (0)	FNA	SQCC		nd	nd	KRAS G12C	“SQCC” = component of AD-SQC	
			2) Lung (-5)	FNA	ADC		nd	nd	nd		
			3) SCLN (-5)	Bx	SQCC → AD-SQC		-	f [±]	f [±]	KRAS G12C	
9	63F	0	1) Lung, LUL (0)	Bx	SQCC		-	+	KRAS G12D	“SQCC” = component of AD-SQC	
			2) Lung, LUL (0)	FNA	ADC		nd	nd	nd		
			3) Lung, LUL (+5)	Lobectomy	AD-SQC		f [±]	f [±]	f [±]	KRAS G12D	

Pt ID	Age Gender	PY	Pathology					Mutation	Interpretation
			Sample # [‡] ; site (time in months)	Specimen type	Diagnosis (original → Δpost-review [‡])	IHC			
						TTF-1	ΔNp63		
10	58M	0	1) Bronchus (0) 2) Spine (+1)	Bx Bx	SQCC SQCC	- -	+ +	EGFR L858R nd	Indeterminate
11	89F	0	Lung	Bx	SQCC → ADC	+	-	EGFR L858R	"SQCC" = PD ADC
12	56F	31	Lung	Lobectomy	SQCC → ADC	+	-	EGFR ex 19 18 bp Δ	"SQCC" = PD ADC
13	49F	33	Bronchus	Bx	SQCC → ADC	+	-	KRAS G12V	"SQCC" = PD ADC
14	69F	34	Hilar LN	FNA	SQCC → ADC	+	-	KRAS G12V	"SQCC" = PD ADC
15	63M	80	Bone	Bx	SQCC → favor ADC	-	-	KRAS G12S	"SQCC" = favor PD ADC
16	58M	51	Lung	Bronchial excision	SQCC with 5% glands	f (5%) [‡]	f (95%) [‡]	KRAS G12C	"SQCC" = biphasic tumor with <10% glands

[‡]Sample order is non-chronological. sample 1 represents an index case (*EGFR*/*KRAS*-mutant "SQCC").

[‡]Review diagnosis was based on a combination of morphology and IHC; in the absence of IHC, tumor type was considered verified if morphology was diagnostic.

[‡]TTF-1 and ΔNp63 labeled distinct cell populations.

+diffusely positive, f focally positive, - negative, Δ deletion or change, ADC adenocarcinoma, AD-SQC adenosquamous carcinoma, Bx biopsy, bp base pair, ex exon, FNA fine needle aspiration, IHC immunohistochemistry, LN lymph node, LLL left lower lobe, LUL left upper lobe, nd not done (tissue insufficient or unavailable), PD poorly differentiated, Pt patient, PY pack years, RLL right lower lobe, SCLN supraclavicular lymph node, SQCC squamous cell carcinoma

Table 5

Reassessment of 16 *EGFR/KRAS*-mutant “squamous cell carcinomas” identified by routine clinical genotyping: Summary.

Characteristic [#]	N (%)
Specimen type	
- Small specimen (biopsy or cytology)	12 (75)
- Surgical resection	4 (25)
Tumor site	
- Lung primary	8 (50)
- Metastasis (lymph node, adrenal, bone, skin)	6 (38)
- Recurrence	2 (11)
Interpretation after morphologic and IHC reassessment	
- Reclassified as AD-SQC [§]	10 (63)
- Reclassified as solid ADC by IHC	5 (31)
- Indeterminate	1 (6)
Smoking status by mutation	
- <i>EGFR</i> -mutant “SQCC”	10 (63)
■ Never	7
■ Current or former	3
- <i>KRAS</i> -mutant “SQCC”	6 (37)
■ Never	1
■ Current or former	5

[#]Data for index samples (*EGFR/KRAS*-mutant “SQCC”), corresponding to samples #1 in Table 4.

[§]Includes patients with a small biopsy/cytology diagnosis of “SQCC” in an index sample, but evidence of glandular differentiation in other (non-index) tissue sample(s) (n=9), and one resected tumor with 5% glandular component.

ADC adenocarcinoma, AD-SQC adenosquamous carcinoma, IHC immunohistochemistry, SQCC squamous cell carcinoma