Genomic aberrations guiding treatment of non-small cell lung cancer patients

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Non-small cell lung cancer; Next generation sequencing; Targeted therapy; Resistance

\textbf{Abstract}
Lung cancer is the main cause of cancer-related death worldwide and conventional treatment strategies must be improved. In addition to mutations in several well-known cancer-associated genes, recent advances in sequencing technology have led to the discovery of numerous novel gene mutations and translocations. Some of these genomic aberrations occur at similar frequencies in all lung cancer subtypes, whereas others appear to be specific for adenocarcinoma or squamous cell lung cancer. High frequency mutations or recurrent translocations support involvement of the affected genes in the pathogenesis of lung cancer. The presence of activating aberrations is indicative for putative driver genes that might be essential for tumor cell growth and survival. These driver genes are potential targets for developing new treatments for lung cancer patients. Indeed, multiple tyrosine kinase inhibitors (TKIs) are currently used to treat lung cancer patients based on the presence of activating mutations, and novel drugs are under investigation. Patients benefit for about one year from current targeted treatments, but progression of disease inevitably occurs and resistance of the tumor to the TKI used can be observed in re-biopsied tumor samples. The aim of this review is to provide an overview of mutated genes in non-small cell lung cancer, an overview of targeted treatment strategies that are currently applied, and the known resistance mechanisms.

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1. Lung cancer

Lung cancer is the leading cause of cancer-related deaths worldwide, with over 228,000 new cases and more than 159,000 deaths reported in 2013 in the United States \cite{1,2}.
Overall, the 5-year survival rate is about 16% and late diagnosis is significantly associated with poor prognosis [1]. Lung cancer can be divided into two main subtypes based on histology: small cell lung cancer (SCLC) and non-small cell lung cancer (NSCLC). Approximately 85% of lung cancer patients are diagnosed with NSCLC [3], which can be further subdivided into three main groups, i.e., adenocarcinoma (AC), squamous cell carcinoma (SQCC), and large cell carcinoma [4]. The AC subtype used to be more frequent in women and non-smokers, but nowadays it is more frequent than other histological subtypes in both men and women [3]. The diagnosis of lung cancer is made by histology/cytology of a tumor detected by imaging techniques such as computed tomography (CT) and positron emission tomography (PET) [5]. Treatment of lung cancer patients depends primarily on the performance status, stage of the disease, the presence of oligometastases and on histological type [6]. Surgery is the primary treatment for patients with stage I or II NSCLC [7], although adjuvant chemotherapy is advised by many guidelines to increase survival of the patients. In non-resectable, stage III NSCLC disease, chemoradiation is the preferred treatment [8]. Nowadays, treatment of lung cancer patients with advanced disease is guided by mutation analysis in the case of a documented tumor-driver mutation. The number of different tyrosine kinase inhibitors (TKIs) available for the treatment of non-small cell lung cancer patients is rapidly increasing due to new diagnostic developments.

In this review we give a brief overview of genes mutated in lung cancer, followed by a more in depth overview on potential therapeutic targets identified by next generation sequencing (NGS) technology. We also provide an overview of current targeted treatment approaches and the known resistance mechanisms.

2. Mutational landscape of lung cancer

Lung cancer, like other malignant neoplasms, is a result of an accumulation of different genetic alterations during life [9]. The TP53 gene, originally described in 1979 [10], was the first tumor suppressor gene to be discovered. TP53 is mutated in approximately 45% of NSCLC patients [11]. In 1982, a human gene with transforming activity was identified in a lung carcinoma cell line. This gene is homologous to the Kirsten Rat Sarcoma virus [12] and was referred to as KRAS. Mutations in KRAS are mostly found in codons 12, 13, and 61. They occur more frequently in patients with AC (5-40%) than in other subtypes of lung cancer, and are associated with smoking behavior [9].

Developments in sequencing technologies in recent years and the need to identify novel therapeutic targets have encouraged scientists to sequence large numbers of lung cancer samples. Entire gene families like protein kinases [13, 14] or a combination of genes known to be mutated in lung cancer and other cancer types [15] have been analyzed. Analysis of 518 protein kinases in 33 primary lung tumors and cell lines revealed 188 somatic mutations in 141 genes, including genes known to have a role in lung tumorigenesis. For 21 genes, mutations were found in more than two samples. Seven of these genes had mutations in the kinase domain, including BRAF, MAP2K4 and FGFR2. In addition, activating mutations were identified in FGFR1 and EPHA5 and inactivating mutations in ATM [13]. Analysis of 623 genes in 188 lung AC specimens by Ding et al. (2008) revealed 26 frequently mutated genes, including well-known cancer related genes such as TP53, RB1, EGFR and KRAS [15]. In addition, they also identified mutations in oncogenes such as ERBB4 (HER4), ERBB2 (HER2) and in multiple ephrin receptors (EPHAs). Altogether they observed a significant excess of mutations and copy number changes in genes involved in the mTOR, MAPK, Wnt, and the p53 signaling pathways [15]. Mutation analysis of the coding regions of more than 1500 genes of 134 primary lung tumors revealed that 18 and 19 genes were mutated at a frequency significantly above the background mutation rate in AC and SQCC, respectively. Five of these genes including TP53, KRAS, KEAP1, MUC16, and BAI3 were shared between AC and SQCC. Differences in the set of mutated genes for various subtypes suggest that different mechanisms are involved in tumorigenesis [16]. Targeted sequencing of 145 cancer-related genes in 24 NSCLC biopsy samples, by Lipson and colleagues in 2012, revealed recurrent mutations in 21 genes, including well-known lung cancer genes together with mutations in druggable lung cancer genes such as BRAF and EGFR [17].

Together, these initial targeted and high throughput approaches indicated several targets, such as EGFR, KRAS, BRAF and EML4-ALK, that are nowadays treated with selected targeted drugs in the clinic. Although only a small proportion of all NSCLC patients (approximately 7%) will profit from these treatments (patients with complete and partial response), several tens of thousands of patients can still benefit worldwide because about 25% of patients with the subtype histology AC are suitable for studies with targeted therapies.

2.1. Potential therapeutic targets identified by next generation sequencing

Whole genome and exome sequencing (WGS and WES, respectively) have enabled researchers to dig even deeper into the mutational landscape of different cancer subtypes. These developments led to increased output of sequencing studies [18]. NGS gives us the opportunity to generate large amount of sequencing data within limited time period in a more cost effective way compared to conventional sequencing. Although, NGS is being improved every day, still we need to be careful in data interpretation and mutation calling. For instance, artifacts that can occur during sample preparation, amplification bias and DNA polymerase error should be always taken into account while working with NGS data [19].

A comprehensive overview of mutation frequencies per gene for all types of cancer is given in the COSMIC database (http://cancer.sanger.ac.uk/cancergenome/projects/cosmic/). For lung cancer, the top-20 most commonly mutated genes are shown in Fig. 1. The first studies on lung cancer using massively parallel sequencing have been performed on either cell lines or single primary tumors [20-22]. A complete genomic analysis of a single NSCLC primary tumor revealed more than 50,000 somatic variations, including new mutations in genes known
to be mutated at a high frequency in lung cancer, such as \textit{NF1} [20]. Mutation analysis using WGS on a lung AC and a liver metastasis of the same patient resulted in the detection of a \textit{KIF5B-RET} fusion gene [23] similar to the previous report [17]. As \textit{KIF5B-RET} is quite common, it might have an important functional role in the pathogenesis of lung cancer.

Liu and colleagues [24] performed WES on a cohort of 31 primary non-small cell lung cancer (NSCLC) tumors and showed somatic mutations in several known lung cancer genes, including some of the targetable ones such as \textit{EGFR} and \textit{ERBB2} (HER2). Moreover, mutations were identified in \textit{DCC} and \textit{MML3}, which are targets for treatment in colon cancer and leukemia, respectively. \textit{CSMD3} mutations were detected in 19% of the patients; notably, this gene was the second most frequently mutated gene in their cohort after \textit{TP53}.

WGS in a panel of 17 NSCLC primary tumors revealed nine commonly mutated genes, including several known lung cancer genes and three novel lung cancer genes such as \textit{DACH1}, a tumor suppressor gene in prostate cancer and gliomas, and two fusion genes: \textit{EML4-ALK} and \textit{KDELR2-ROS1} [25]. They also detected mutations in \textit{JAK2} similar to a previous report using a targeted approach [17]. \textit{JAK2} inhibitors are used to treat patients with myelofibrosis [26].

One of the largest studies to date performed WES on 178 lung SQCC samples and identified over 48,000 non-silent mutations [27]. As expected, \textit{TP53} was the most commonly mutated gene with a frequency of 81%. Inactivating mutations in \textit{CDKN2A}, \textit{KEAP1}, \textit{CUL3}, \textit{NOTCH1} and \textit{NOTCH2} were identified, as well as activating mutations in and amplification of \textit{NFE2L2}, a key component of the oxidative stress response pathway [27]. Activation of the \textit{NFE2L2-KEAP1} signaling pathway through mutations in \textit{NFE2L2} is a characteristic of pediatric liver tumors as well [28]. The Cancer Genome Atlas (TCGA) Network also found \textit{SOX2} and \textit{TP63} to be activated via amplification. These two genes are important components of the squamous cell differentiation pathway. They identified three tyrosine kinase families which are potentially targetable, including \textit{ERBB}, \textit{FGFR} and \textit{JAK}, all of which were mutated and/or amplified [27].

In a study [29] of 183 lung AC samples, 25 genes were significantly mutated, of which 19 had been reported previously and six were novel genes in lung AC, including
CHEK2 and BRD3. In this study the authors also found inactivating mutations in STK11, PTEN, RB1, SETD2 and CDKN2A [29] and CTNNB1 was found to be mutated in 3% of the patients. This gene is highly mutated (70%) in liver cancer patients and it is a component of WNT-CTNNB1 pathway [28,29].

A study [30] on a large cohort of Korean patients (n=104) with SQCC showed a good overlap with sequencing data previously published by TCGA Network [27], but also reported some marked differences. CDKN2A mutations were less common in Korean patients, while mutations in RB1 were significantly more frequent. Interestingly, they found activating mutations in PIK3CA, which is one of the therapeutic targets of the PI3K/AKT/mTOR pathway. In one of the Korean lung cancer samples, an FGFR3-TACC3 fusion transcript was detected [30]. FGFR3 has been reported as a potential therapeutic target in glioblastoma and bladder cancer [31,32]. Together, these next generation studies have made significant contributions to the identification of genes that are of interest as novel targets for therapy. To select the most promising target, it is essential to reveal the impact of the mutations and to discriminate between activating driver mutations and non-driver or inactivating mutations. In summary, next generation and targeted sequencing indicate that genes such as ERBB2 (HER2), ERBB4, JAK2, RET, ROS1, DCC, MLL3 might be good candidates for targeted treatment in lung cancer patients. In addition, inhibitors of the MEK kinase could be tested in tumors with NF1 mutations. More importantly, PIK3CA seems to be a suitable candidate, together with FGFR3 and NFE2L2, for treatment of patients with SQCC. At the moment, inhibitors for RET and ROS1 fusions are in preclinical and clinical trials and ROS1 inhibitors might also be effective on patients with activating ROS1 mutations.

3. Targeted therapies currently in use

Specific aberrations in genes or pathways can lead to increased protein levels, and/or pre-active protein kinases that stimulate tumor cell growth. These aberrations can be targeted with small molecules such as TKIs (administered orally) and/or with monoclonal antibodies that are administered intravenously. At the moment, more clinical targets have been discovered in AC than in SQCC. Commonly used therapies in AC target the tyrosine kinase part of EGFR, HER2, VEGFR and ALK protein [33]. In addition, a number of novel drugs against KRAS (AC/SQCC), BRAF (AC/SQCC), ROS1 (AC), RET (AC), FGFR1 (SQCC), PIK3CA (AC/SQCC) and DDR2 (SQCC) are being evaluated in clinical trials or soon will be [34]. The known target genes, the kinase inhibitors used, and clinical outcomes in non-SQCC clinical trials phase III are summarized in Table 1. No phase III study has been performed in SQCC yet. Therefore, we only focus on non-SQCC. Frequencies of hotspot mutations, fusion genes and possible resistance mechanisms are summarized in Tables 2 and 3.

3.1. EGFR inhibitors

TKIs, such as erlotinib, gefitinib, and afatinib, are currently registered for treatment of EGFR mutant non-SQCC patients. Patients with activating EGFR mutations, such as exon 19 insertions/deletions, and nonsynonymous mutations such as G719X in exon 18, or L858R and L861Q in exon 21, are sensitive to erlotinib and gefitinib, with a tumor response of about 75%. Patients with such mutations show an increased progression-free survival (PFS) after targeted treatment compared to treatment with chemotherapy [35]. This effect was observed in both first and second line treatment. Hazard ratios for progression-free survival varied between 0.43 and 0.25. Most pivotal studies of first-line EGFR-TKI were limited to lung cancer patients carrying EGFR exon 19 deletions or L858R point mutations. Only patients with EGFR exon 19 deletions showed an overall survival benefit with afatinib.

The effect of EGFR-TKI in patients with rare EGFR mutations has not been defined but seems less striking [36]. A meta-analysis revealed a significant association between increased EGFR copy number and improved survival outcome [37]. In NSCLC, EGFR mutation screening is the best method to predict tumor response to TKIs compared to fluorescence in situ hybridization (FISH) and immunohistochemistry [38]. In almost 25% of patients tumor growth is enhanced when EGFR treatment is ended, indicating that the tumor remains at least partly dependent on the EGFR signaling [39].

3.2. Mechanisms of resistance to EGFR inhibitors

After 9 to 12 months of treatment with an EGFR-TKI, the tumor appears to become resistant due to a spectrum of mechanisms. In about 50% of cases, an originally low-frequency TKI-resistant mutation, the T790M (gatekeeper) mutation, can increase to detectable and clinically relevant frequencies upon treatment with a TKI. In addition, amplification of MET or HER2, mutations in PIK3CA or BRAF, activation of the AXL kinase, and transformation to small cell lung cancer are the most prominently induced resistance mechanisms to TKI treatment [34,40]. These last two mechanisms have been proven in cell lines, xenografts or tumors of patients, and can therefore be considered as truly causative in relation to the resistance [41-43]. Some authors proposed that new mutations developing in EGFR (like the T790M gatekeeper mutation) are associated with resistance in patients treated with EGFR-TKI [40], but also mutations in other genes such as GAS6, VIM, NF-kB, ADAM17 and NOTCH1 have been found in tumors of patients who became resistant to EGFR-TKI [43-45]. Finally, in studies using cell lines, mutations in COL6A1, IGF1, TGFβ or mTOR genes or mutations affecting the Hedgehog, pp.53, Wnt pathways were found to be associated with resistance mechanisms [43]. A true causal relation needs to be proven for these mechanisms.

3.3. BRAF inhibitors

BRAF is a serine/threonine kinase that is activated by RAS and signals its proliferative actions through MEK kinase. BRAF mutations are more common in lung ACs but are observed in less than 1% of NSCLC tumors [46]. In a study of 697 lung AC patients, BRAF mutations were present in 18 patients (3%), half were V600E (50%), the other most common mutations were G469A (39%) and D594G (11%) [47]. NSCLC patients with
the BRAF V600E mutation have a shorter disease-free survival and overall survival after chemotherapy than patients without such mutations. At the moment, vemurafenib and dabrafenib are the two BRAF inhibitors that are clinically available. There are two case reports of lung AC patients with a V600E mutation who responded to treatment with vemurafenib [48,49]. The first, still ongoing, experience with dabrafenib in advanced NSCLC showed a tumor response rate of 40% [50]. Preclinical data suggest that non-V600E-mutated BRAF kinases are resistant to vemurafenib. In addition, BRAF mutations may predict sensitivity of NSCLC cells to MEK inhibitors [51].

3.4. Mechanisms of resistance to BRAF inhibitors

Different resistance mechanisms have been found in preclinical studies. A switch of full-length BRAF to aberrant BRAF (p61VE) has been shown in treated cell lines becoming resistant to BRAF inhibitors. Another mechanism that has been described in cell lines is upregulation of the EGFR protein due to loss of the c-Jun feedback loop [52]. A single lung cancer patient with a BRAF mutation and treated with dabrafenib showed a KRAS mutation in a re-biopsy at tumor progression. The hypothesis was therefore put forward that the cause of resistance was due to a G12D KRAS mutation [53]. Other mechanisms that have been described mostly in melanoma are MAPK-dependent mechanisms, like NRAS or CRAF upregulation, BRAF upregulation and MEK mutations. MAPK-independent mechanisms, like PTEN loss and upregulation of PDGFR-β and IGF-1 R, have also been described [54].

3.5. ALK inhibitors

EML4-ALK is a fusion gene generated by an inversion of a segment of chromosome 2. It was the first targetable fusion onco-kinase identified in NSCLC [34]. It is most often observed in young, light- or never smoking patients, occurring equally in males and females [55]. It can be detected in up to 4% of NSCLC patients [34] and 3–6% of patients with lung AC [56]. ALK fusion genes rarely coexist with KRAS or EGFR mutations in lung cancer patients [57]. The EML4-ALK fusion protein results in enhanced ALK kinase activity [55]. Crizotinib was the first registered ALK inhibitor used in clinical practice (Table 1). It was originally designed for inhibition of the c-MET protein but it turned out to have an inhibitory effect on ALK kinase as well [58]. The overall response rate in a FISH-based ALK-positive NSCLC group treated with crizotinib was 65% (95% confidence interval [CI]; 58–72) versus 20% (95% CI; 14–26) in the chemotherapy group. In a phase III study, the median PFS for crizotinib was 7.7 months. In the chemotherapy group PFS was 3.0 months [59].

Ceritinib and alectinib are also two potent second-generation ALK-TKIs [60] that can be used in crizotinib resistant patients [61,62]. In a phase I clinical trial, Shaw and colleagues treated ALK-positive patients with ceritinib. Majority of the patients had been pretreated with crizotinib. The overall response rate with ceritinib was 58% (95% CI; 48–67), median PFS was 7 months in those who received 4400 mg daily. Moreover, they observed tumor responses in patients with different ALK resistance mutations (L1196M, G1269A and S1206Y) as well as the patients without any detectable ALK mutation [61]. Treatment of an AC patient with alectinib
Both drugs are also effective for brain metastasis.

### 3.6. Mechanisms of resistance to ALK inhibitors

ALK-positive patients develop tumor resistance to targeted therapy. This resistance can be due to gatekeeper mutations in the kinase domain of the ALK gene (L1196M and G1269A), copy number gain of the EML4-ALK fusion gene, and mutations in EGFR and KRAS [63]. Other reported ALK mutations linked to resistance are V1135E, L1152R, C1156Y, F1174L, L1198P, G1202R, D1203N, S1206Y, G1269S, G1269A and L1318M. Targeted NGS showed an association between the development of resistance to crizotinib in two patients and new nonsynonymous mutations outside the ALK kinase domain [15, 63–65]. The observation of different nonsynonymous mutations in MET could be important because crizotinib also is a potent MET inhibitor [66]. And lastly, mutations in pathways of AXL and the development of epithelial-mesenchymal transition (EMT) have been described as factors that contribute to ALK-TKI resistance [67].

### 3.7. ROS1 inhibitors

In about 1–2% of patients with NSCLC, a translocation of ROS1, which is located on chromosomal region 6q22, has been found with different fusion partners (SLC34A2, SDC4, CD74, EZR). Preclinical studies and case reports show that ROS1 kinase activity is inhibited by crizotinib. ROS1 fusions occur more often in younger patients and in the AC subtype [68, 69]. Crizotinib is a potent inhibitor of cell growth in cell lines as well as in patients with a ROS1 fusion [70]. A phase I clinical trial by Shaw and colleagues on fifty ROS1-positive patients with AC subtype treated with crizotinib showed an overall response rate of 72% (95% CI; 58–84) and the median PFS of 19.2 months [71]. Another study with thirty two AC patients with ROS rearrangement treated with crizotinib showed an overall response rate of 80% and median PFS was 9.1 months [72]. No randomized studies have been published yet.

### 3.8. Mechanisms of resistance to ROS1 inhibitors

A G2032R mutation of ROS1 was found in a crizotinib-resistant patient. Foretinib (a MET and VEGFR inhibitor) seems to be a potent compound to overcome this resistance [73]. In the search for resistance mechanisms in cell lines, a switch in signaling from ROS1 to EGFR was observed, when ROS1 was inhibited by crizotinib [74]. The same study

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**Table 2** Frequencies of mutation and fusion partners of therapeutic targets in non-SQCC.

<table>
<thead>
<tr>
<th>Target</th>
<th>Mutation</th>
<th>Fusion partner</th>
<th>Frequency</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGFR</td>
<td>Exon 18</td>
<td>G719C/S/A</td>
<td>7%</td>
<td>[91]</td>
</tr>
<tr>
<td></td>
<td>Exon 19</td>
<td>E746_A750del</td>
<td>37%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Exon 20</td>
<td>V769M</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>other</td>
<td></td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L833F</td>
<td></td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A840T</td>
<td></td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L858R</td>
<td></td>
<td>26%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>other</td>
<td></td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EML4</td>
<td></td>
<td>89%</td>
<td>[34]</td>
</tr>
<tr>
<td>ALK</td>
<td>KIF5B</td>
<td></td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>KLC1</td>
<td></td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TFG</td>
<td></td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PTPN3</td>
<td></td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>ROS1</td>
<td>SLC34A2</td>
<td></td>
<td>40%</td>
<td>[69, 70]</td>
</tr>
<tr>
<td></td>
<td>CD74</td>
<td></td>
<td>40%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SDC4</td>
<td></td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EZR</td>
<td></td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>RET</td>
<td>KIF5B</td>
<td></td>
<td>69%</td>
<td>[77, 78]</td>
</tr>
<tr>
<td></td>
<td>CCDC6</td>
<td></td>
<td>15%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NCOA4</td>
<td></td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TRIM33</td>
<td></td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3** Proposed resistance mechanisms in targetable mutations and translocations in non-SQCC.

<table>
<thead>
<tr>
<th>Protein</th>
<th>Resistance mechanisms</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGFR</td>
<td>AXL/GAS6 axis activation</td>
<td>[43]</td>
</tr>
<tr>
<td></td>
<td>Small cell transformation</td>
<td>[41, 42]</td>
</tr>
<tr>
<td></td>
<td>T790M mutation</td>
<td>[40]</td>
</tr>
<tr>
<td></td>
<td>KRAS mutation</td>
<td>[40]</td>
</tr>
<tr>
<td></td>
<td>MET/HER2 amplification</td>
<td>[40]</td>
</tr>
<tr>
<td></td>
<td>Mutations in NF-kB/ADAM17/NOTCH1/VIM</td>
<td>[43-45]</td>
</tr>
<tr>
<td></td>
<td>Mutations in COL6A1/IGFR1/Hedgehog/ TGFβ/ p53/ Wnt/mTOR pathways</td>
<td>[40, 43]</td>
</tr>
<tr>
<td>BRAF</td>
<td>NRAS/BRAF upregulation</td>
<td>[54]</td>
</tr>
<tr>
<td>MEK</td>
<td>mutations</td>
<td>[54]</td>
</tr>
<tr>
<td>PTEN</td>
<td>loss</td>
<td>[54]</td>
</tr>
<tr>
<td>EGFR</td>
<td>upregulation</td>
<td>[54, 52]</td>
</tr>
<tr>
<td>IGF-1R</td>
<td>upregulation</td>
<td>[54]</td>
</tr>
<tr>
<td>PDGFR-β</td>
<td>upregulation</td>
<td>[54]</td>
</tr>
<tr>
<td>ALK</td>
<td>ALK mutation</td>
<td>[15, 63–64]</td>
</tr>
<tr>
<td></td>
<td>ALK copy number gain</td>
<td>[63]</td>
</tr>
<tr>
<td></td>
<td>KRAS/EGFR mutations</td>
<td>[64]</td>
</tr>
<tr>
<td></td>
<td>KIT amplification</td>
<td>[92]</td>
</tr>
<tr>
<td></td>
<td>AXL overexpression</td>
<td>[67]</td>
</tr>
<tr>
<td></td>
<td>EMT</td>
<td>[67]</td>
</tr>
<tr>
<td>ROS1</td>
<td>ROS1 mutations</td>
<td>[73, 75]</td>
</tr>
<tr>
<td></td>
<td>Signaling switch to EGFR</td>
<td>[74]</td>
</tr>
<tr>
<td></td>
<td>KRAS/NRAS mutations</td>
<td>[76]</td>
</tr>
<tr>
<td></td>
<td>KRAS overexpression</td>
<td>[76]</td>
</tr>
</tbody>
</table>
also reported that treatment with an EGFR inhibitor in combination with a ROS1 inhibitor was effective in cell lines resistant to ROS1 inhibitors. In another study, a new mutation, L2155S, was found in a ROS1-positive NSCLC cell line resistant to crizotinib. Authors also showed that L2155S and G2032R mutations can induce resistance to crizotinib in Ba/F3 cells [75]. KRAS/NRAS mutations or KRAS overexpression have been shown as other possible resistance mechanisms to crizotinib in HCC78-crizotinib resistant cell line [76].

3.9. RET inhibitors

A translocation of the rearranged during transfection (RET) gene located at chromosome 10 can be identified in about 1% of non-smoking patients with lung ACs. KIF5B, CCDC6, TRIM33 and NCOA4 serve as fusion partners [77,78]. As a result of this fusion, the normally low expression level of RET is increased in lung AC cells [79]. Over 12 drugs have been described wit RET inhibitory properties [80]. Most potent were cabozantinib (IC50 4 nM), alectinib (IC50 4.8 nM) and ponatinib (IC50 7 nM) [80,81]. Vandetanib, sunitinib, sorafenib and cabozantinib are all multikinase inhibitors, and the first three show in vitro activity against RET expressing NIH3T3 and Ba/F3 cell lines [17]. It has been shown that alectinib can inhibit cell growth by suppressing phosphorylated RET both in cell line and RET-positive mouse model [81]. A case report confirmed the anti-tumor effects of vandetanib in a NSCLC patient [82]. In a phase II clinical trial, cabozantinib was tested on three RET-positive patients. Two of the patients showed partial response, while the other one remained with stable disease [78].

3.10. HER2 and cMET

HER2 is mutated (mostly exon 20) in approximately 2% of NSCLC patients [83]. Activating mutations in HER2 will result in activation of downstream signaling pathways (AKT and MEK) leading to cell proliferation and survival [84]. Blocking HER2 in HER2-mutated cell line resulted in cell cycle arrest and cell death [85]. Treatment of sixteen NSCLC patients with different combination of HER2 inhibitors showed a median PFS of 5.1 months [83].

cMET is a tyrosine kinase receptor (TKR) which is coded by MET proto-oncogene and it is widely expressed by cells with epithelial-endothelial origin [86]. Different mechanisms can lead to aberrant activation of MET such as MET gene mutation or amplification and cMET/HGF overexpression [87]. Preclinical studies revealed inhibition of cell growth by crizotinib in MET dependent lung cancer cell lines, while tivantinib is independent of MET signaling and results in apoptosis [88]. A phase I clinical trial showed that tivantinib in combination with erlotinib was well tolerated in advanced NSCLC patients based on CYP2C19 genotype [89]. A phase II study showed a median PFS of 3.8 months in erlotinib plus tivantinib group compared to erlotinib or tivantinib plus placebo group [90]. Several clinical trials are still ongoing.

4. Conclusion

Nowadays, more and more somatic mutations and fusion genes can be considered as potential targets for treatment of NSCLC. At the moment, we only have a few gene mutations and fusion genes that can be targeted with TKIs, although many other specific TKIs are under investigation. A striking and common feature is that tumor resistance develops after about one year of targeted treatment. Therefore, the search for different resistance mechanisms is important so that treatment regimens can be adapted at an early enough stage. At the moment, most resistance mechanisms are described on the basis of their associations with newly detected mutations observed at disease progression. We need to put more effort into functional studies to discover the role of mutations in new and known cancer genes and to define novel therapeutic drivers, which may even be genes with mutations at low frequencies. This is important, because even a gene with a low mutation frequency can save a considerable number of patients with NSCLC.

In the future, we need to integrate the NGS results with epigenetic, transcriptome, copy number and proteomic analyses. This should preferably be done in primary tumors, metastases and the subsequent relapses with developing resistance to gain a good insight into the tumor cell evolution and to help design strategies to treat lung cancer patients optimally. Moreover, complete overviews of the mutational landscape of each patient's tumor will aid providing personalized therapy to patients and allow a timely switch to drugs that attack or work round resistance.

Combination therapies of different targeting drugs that are based on this mutational landscape will probably be more effective in prolonging the survival of patients and increasing their quality of live. Nowadays, the treatment of cancer patients should be based more on their genetic profiles and less on traditional organ- or cancer subtype-based strategies.

Three kinds of lung cancer patient groups may emerge in the future. In the first group are younger patients - mainly past, light or non-smokers - with limited somatic genomic instabilities that have one or two driver genomic aberration(s) that can be targeted with small molecules or combinations of these drugs. In the second group, smoking patients with SQCC usually have many somatic genomic alterations. These genomic changes might result in many abnormal peptides or proteins that can be recognized by the immune system and may induce an immune response. These patients will profit from immunotherapy. The third group still needs chemotherapy.

Conflict of interest

None.

Disclosure of funding

None.

References

Genomic aberrations guiding treatment of non-small cell lung cancer patients


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