

Quantitative Detection of *EGFR* Mutations in Circulating Tumor DNA Derived from Lung Adenocarcinomas

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Abstract

Purpose: Examination of somatic epidermal growth factor receptor (*EGFR*) mutations is now a diagnostic routine for treatment of cancer using *EGFR* tyrosine kinase inhibitors (*EGFR*-TKI). Circulating tumor DNA is a promising target for noninvasive diagnostics. We evaluated its utility by quantitatively detecting activating and resistant mutations, which were measured with BEAMing (beads, emulsion, amplification, and magnetics).

Experimental Design: Twenty-three patients with lung cancer with progressive disease after *EGFR*-TKI treatment and 21 patients who had never been treated with *EGFR*-TKIs were studied. Their primary tumors were confirmed to have activating mutations. In the plasma DNA of each patient, the activating mutation found in the corresponding primary tumor and the T790M resistance mutation were quantified by BEAMing.

Results: In 32 of 44 patients, activating mutations were detected in the plasma DNA [72.7%; 95% confidence interval (CI), 58.0%–83.6%]. The T790M mutation was detected in 10 of 23 patients in the first group (43.5%; 95% CI, 25.6%–53.4%). The ratio of T790M to activating mutations ranged from 13.3% to 94.0%. The peak of the distribution of the mutation allele fraction in the plasma DNA was in the 0.1% to 1% range.

Conclusions: The major advantage of BEAMing is its ability to calculate the fraction of T790M-positive alleles from the alleles with activating mutations. This feature enables the detection of increases and decreases in the number of T790M mutations in cancer cells, regardless of normal cell DNA contamination, which may be useful for monitoring disease progression. Circulating tumor DNA could potentially be used as an alternative method for *EGFR* mutation detection. *Clin Cancer Res*; 17(24); 7808–15. ©2011 AACR.

Introduction

The strong effects of epidermal growth factor receptor (*EGFR*) tyrosine kinase inhibitors (*EGFR*-TKI; i.e., gefitinib and erlotinib) on non-small cell lung cancer (NSCLC) are correlated with activating somatic mutations in the epidermal growth factor receptor (*EGFR*; refs. 1–3). Patients subjected to these drugs are currently selected on the basis of the presence of these activating mutations. In addition, a mutation known as T790M has been identified as a cause of gefitinib resistance (4, 5). The T790M mutation appears in about half of the cases of acquired resistance to *EGFR*-TKIs. Detection of T790M may have prognostic value in the

patients with acquired resistance to *EGFR*-TKIs, because the presence of T790M defines a clinical subset with a relatively favorable prognosis and more indolent progression (6).

Detecting *EGFR* mutations using tumor tissues obtained via a biopsy or surgical resection is now routinely used to diagnose NSCLC. Because a biopsy is an invasive procedure, it is desirable to replace it with a noninvasive procedure. In particular, noninvasive tests allow the frequent monitoring of disease progression in patients with the T790M mutation (7).

For some time, circulating nucleic acids in the plasma or serum have been considered to be candidates for noninvasive cancer diagnostics (8, 9). In particular, circulating tumor DNA (ctDNA) has been explored to detect somatic mutations derived from malignant tumors. For example, in 2 studies, somatic mutations in ctDNA were used to monitor disease status with the appearance of target mutations (10, 11). One major problem is that detecting rare mutant alleles is technically difficult. Diehl and colleagues used their proprietary technique called BEAMing (beads, emulsion, amplification and magnetics; ref. 12) to measure somatic mutations in ctDNA and monitor the tumor burden during the course of the disease. In BEAMing, PCR

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Translational Relevance

For therapies using EGFR-TKIs (e.g., gefitinib and erlotinib), it is essential to determine the epidermal growth factor receptor mutation status of lung cancer lesions. Although a biopsy of the primary lesion is indispensable, noninvasive diagnostics are desirable because they allow repeated testing. In particular, it is useful to follow the disease progression by monitoring the T790M status. In contrast to other techniques, beads, emulsion, amplification, and magnetics (BEAMing) can estimate the extent to which the activating mutation alleles have been converted into resistant alleles, regardless of normal DNA contamination. This information should be more suitable for monitoring the disease status. Because BEAMing also detects activating mutations with a moderate success rate, examining the ctDNA may support a diagnosis via a biopsy. It should be noted that BEAMing and next-generation sequencers are based on the same technological principle. With this study, we can predict how next generation sequencers will detect mutations in circulating tumor DNA.

products amplified from a single molecule are fixed to a single magnetic bead using emulsion PCR. The mutation site is labeled with a fluorescent probe or primer extension, and the mutated allele is quantitatively detected by counting the fluorescently labeled beads. Simply by increasing the number of beads that are analyzed, BEAMing can be more sensitive than other PCR-based techniques (13).

In this report, we used BEAMing to detect activating and resistant *EGFR* mutations in ctDNA derived from lung cancer. The results suggest that ctDNA may complement the biopsy of primary lesions as a source of *EGFR* mutation detection. Its major advantage over other techniques is its ability to calculate the fraction of T790M-positive alleles in cancer cells, regardless of normal cell DNA contamination. In particular, this approach would enable the monitoring of disease progression during EGFR-TKI therapy via the T790M mutation.

Materials and Methods

Patient characteristics

Patients with activating *EGFR* mutations in tumor tissues were selected following a biopsy examination between June 2010 and April 2011. We recruited 23 patients with progressive disease (PD) after EGFR-TKI treatment as group 1. PD is defined as the appearance of a new lesion or a 20% increase in tumor size. The duration between the detection of PD and blood sampling for BEAMing was variable. We recruited 21 patients who had never been treated with EGFR-TKIs as group 2. In all of the patients, activating *EGFR* mutations were found in biopsy samples using the PNA-LNA PCR clamp method (14).

Plasma samples and DNA extraction

DNA was purified from plasma obtained from 5 mL of heparin-treated blood using Agencourt Genfind version 2 (Beckman Coulter). The DNA concentration was determined by measuring the copy number of *LINE-1* (15). It should be noted that the calibration was done using intact human genomic DNA, whereas the plasma DNA was in fragments of approximately 200 bp or less. Thus, the deduced measurement may be biased to be too low.

BEAMing

BEAMing was done as described previously (16, 17), except for the use of locked nucleic acids (LNA) as the hybridization probes for single-base substitutions. Primer and probe sequences are shown in Table 1. In the initial PCR step, the target region (~100 bp) was amplified using gene-specific primers with tag sequences. Amplification was done in a 100- μ L reaction mixture containing genomic DNA obtained from 400 μ L of plasma, 600 pmol of primers and 2 units of KOD -Plus- DNA polymerase (Toyobo). The product was purified with a MinElute PCR Purification Kit (Qiagen).

To prepare the magnetic beads for BEAMing, a common oligonucleotide, the sequence of which was identical to the forward primer for emulsion PCR (Table 1), was synthesized using a dual biotin group at the 5' end and a spacer 18 polyethylene glycol between the biotin group and the terminal thymidine (Integrated DNA Technologies). One nanomole of the common oligonucleotide was attached to 100 μ g of MyOne streptavidin-coated magnetic beads (Dyna), as described previously (12). The beads were finally suspended in 100 μ L of TK buffer (20 mmol/L Tris-HCl, pH 8.4, 50 mmol/L KCl). To prepare the emulsifier oil, 7% ABIL WE09 (Degussa), 20% mineral oil (Sigma-Aldrich) and 73% Tegosoft DEC (Degussa) were mixed by vortexing and allowed to settle for 30 minutes.

Emulsion PCR was done as follows. A 150- μ L reaction mixture consisted of 15 pg of the first aforementioned PCR product, 15 μ L of 10 \times KOD buffer, 75 pmol of the forward primer, 12 μ mol of the reverse primer and 6 μ L of the magnetic beads, which were prepared as described above. Next, 0.6 mL of the emulsifier oil and 5-mm Zirconia beads were added to the 150- μ L reaction mixture. A water-oil emulsion was prepared in a 2-mL Eppendorf tube using a Mixer Mill MM 300 (Qiagen) at 15 Hz for 17 seconds. The reaction mixture was divided into 50- μ L aliquots and amplified using the following thermal cycling protocol: 94°C for 2 minutes; 3 cycles of 98°C for 15 seconds, 64°C for 45 seconds, and 72°C for 75 seconds; 3 cycles of 98°C for 15 seconds, 61°C for 45 seconds, and 72°C for 75 seconds; 3 cycles of 98°C for 15 seconds, 58°C for 45 seconds, and 72°C for 75 seconds; and 50 cycles of 98°C for 15 seconds, 57°C for 45 seconds, and 72°C for 75 seconds.

After thermal cycling, the reaction mixture was centrifuged to separate the oil and water. After removing the supernatant, the emulsion was degraded with 400 μ L of breaking buffer (5 mmol/L Tris-HCl, pH 7.5, 1% Triton X-100, 1% SDS, 100 mmol/L NaCl, 1 mmol/L EDTA) and by

Table 1. Primer list

Name	Sequence	Modification	Target
Primers for exon amplification from plasma DNA			
exon19	Tag119del TCCCCGGAAATTAATACGCAAGTTAAAAATCCCGTCGCTATC		
	Tag219del GCTGGAGCTCTGCAGCTAGACCCACACAGCAAAG		
exon20	Tag1T790M TCCCCGGAAATTAATACGCAAGTTAAAAATCCCGTCGCTATC		
	Tag2T790M GCTGGAGCTCTGCAGCTAGACCCACACAGCAAAG		
exon21	Tag1L858R TCCCCGGAAATTAATACGCAAGTTAAAAATCCCGTCGCTATC		
	Tag2L858R GCTGGAGCTCTGCAGCTAGACCCACACAGCAAAG		
Primers for emulsion PCR			
	Tag1 (forward) TCCCCGGAAATTAATACGCAAGTTAAAAATCCCGTCGCTATC		
	Tag2 (reverse) GCTGGAGCTCTGCAGCTAGACCCACACAGCAAAG		
Hybridization probes for detection of beads with successful amplification			
exon19	19del_BEAM_PE_b AGCAAAGCAGAAATCAGCATC	5' biotin	
exon20	T790M_BEAM_PE_b CGGACATAGTCCAGGAG	5' biotin	
exon21	L858R_BEAM_PE_b ATGCCTCCTTCTGCATGGTAT	5' biotin	
Hybridization probe for BEAMing			
exon19	19del_35_49_647 GGAGATGTTTTGATAGCG	5' Alexa647	exon 19 E746-A750del
	19del_36_50_647 CGGAGATGCTTTGATAGC	5' Alexa647	exon 19 E746-A750del
	19del_40_57_647 TGGCTTTCGATTCCCTTGA	5' Alexa647	exon 19 L747-S752del.P753S
	19del_AATTCC_647 TGTTGCTTCTCTGGAAAT	5' Alexa647	exon 19 E746-L747del.IP
	19del_36_55_T_647 GCTTTCGGAACCTTGATAG	5' Alexa647	exon 19 L747-S752del. E746V
	19del_35_53_ACT_647 GGAGAAAGTTTTGATAGCG	5' Alexa647	exon 19 K745-E749del.A750K
	19del_39_56_CAG_647 TTTCGGCTGTTCCCTTGTAT	5' Alexa647	exon 19 L747-T751del.S752Q
	19del_39_48_C_647 GAGATGTTGGTTCCTTGTAT	5' Alexa647	exon 19 L747-E749del.A750P
	19del_WT_488 TGTTGCTTCTCTTAATTCC	5' Alexa488	exon 19 wild-type control
exon20	T790M_Mut_BNA_647 atgagctgcAtgatgag	5' Alexa647	T790M mutation
	T790M_WT_BNA_488 tgagctgcGtgatgag	5' Alexa488	Wild-type control for T790M
exon21	L858R_Mut_LNA_647 gtttggccCgccccaaaat	5' Alexa647	L858R mutation
	L858R_WT_LNA_488 gtttggccAgccccaaaat	5' Alexa488	Wild-type control for L858R
	T2582A_Mut_647 caccacagCtgttggcc	5' Alexa647	T2582A mutation
	T2582A_WT_488 caccacagCggtttggcc	5' Alexa488	Wild-type control for T2582A

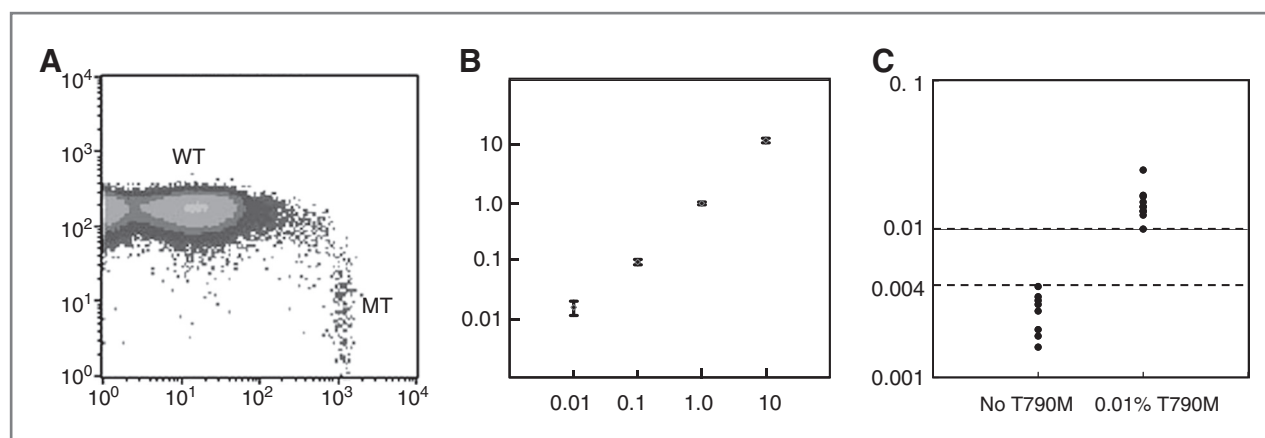


Figure 1. A, flow cytometric profile of BEAMing. The wild-type *EGFR* fragment was mixed with 0.1% of the T790M *EGFR* fragment, and BEAMing was done after PCR amplification. Horizontal axis, the fluorescence intensity of Alexa 647; vertical axis, the fluorescence intensity of Alexa 488. WT, signals from the wild-type *EGFR* fragment; MT, signals from the T789M fragment. B, linear correlation between the inoculated amount of the T790M *EGFR* fragment and the BEAMing measurement. Horizontal axis, the fraction of the T790M fragment inoculated into the wild-type fragment; vertical axis, the fraction of the T790M-positive allele measured using BEAMing. C, repeated measurements of the samples with 0.01% of the T790M fragment and those with no T790M fragment. The vertical axis indicates the fractions of the T790M-positive allele detected using BEAMing.

vortexing. After centrifugation and removal of the supernatant, the beads were washed once. Next, the DNA on the beads was denatured by 2 minutes of incubation at room temperature with 500 μ L of 0.1 mol/L NaOH. After washing twice, the beads were suspended in 30 μ L of distilled water.

The mutation loci were detected using allele-specific hybridization probes that consisted of locked nucleic acids and were fluorescence-labeled at their 5' ends. Alexa 647 and Alexa 488 fluorescent dyes were used for the mutated and wild-type alleles, respectively. A hybridization probe complementary to common sequences in the mutated and wild-type alleles was manufactured via 5' biotinylation. The hybridization reactions were carried out in a 100- μ L reaction mixture consisting of 3 mol/L tetramethylammonium chloride, 50 mmol/L Tris-HCl (pH 7.5), 4 mmol/L EDTA, and 5 pmol each of the aforementioned hybridization probes. The reaction mixture was divided into 50 μ L aliquots, incubated at 70°C for 10 seconds, then at 35°C for 2 minutes after cooling down at a rate of 0.1°C/s, and additionally cooled down to room temperature using the GeneAmp PCR System 9700 Thermal Cycler (Applied Biosystems). After removing the supernatant, the beads were incubated at room temperature for 10 minutes in 20 μ L of binding buffer (5 mmol/L Tris-HCl, pH 7.5, 1 mol/L NaCl, 1 mmol/L EDTA) containing 2 μ g of streptavidin-conjugated phycoerythrin (PE; Invitrogen). After washing, the beads were suspended in 100 μ L of TK buffer. Flow cytometric analysis was conducted with FACSCalibur (BD Bioscience) according to the manufacturer's protocol.

Results

Quantitation of the accuracy and sensitivity of BEAMing

We examined the measurement's accuracy and sensitivity using T790M as an example. We prepared normal *EGFR*

gene fragments containing the mutated fragment at 10%, 1%, 0.1%, and 0.01%. These preparations were subjected to emulsion PCR. A typical example of a flow cytometric profile separating 1% T790M from the wild-type allele is shown in Fig. 1A. In BEAMing, the fractions of the mutated fragment are estimated by the ratio of the numbers of beads labeled with Alexa 647 (mutant) and those labeled with Alexa 488 (wild-type). There is a good linear correlation between the ratio deduced from the numbers of beads and the fraction of mutated fragments in the initial preparations (Fig. 1B). To determine the detection limit of BEAMing, samples without the T790M mutation and samples with 0.01% T790M mutations were analyzed repeatedly. The measurements of these 2 groups did not overlap (Fig. 1C). To confirm this result in a real experimental setting, we measured exon 19 deletion, L858R, and T790M mutations in the plasma DNA purified from 20 normal individuals. The mutation rates ranged from 0 to 0.0094 (average, 0.0021; 95% CI, 0.0012–0.0030), from 0.0009 to 0.0074 (average, 0.0025; 95% CI, 0.0019–0.0031) and from 0.0011 to 0.0097 (average, 0.0042; 95% CI 0.0030–0.0054), respectively. Thus, we set the detection limit of BEAMing as 1 in 10,000.

Activating and resistant *EGFR* mutations in plasma DNA

Plasma obtained from 44 patients was analyzed by BEAMing for the T790M mutation, and activating mutations were determined via a tumor biopsy. The results are shown in Table 2. In group 1, which consisted of patients who developed PD after EGFR-TKI treatment, the detection of activating and T790M mutations can be evaluated. In group 2, which consisted of patients who were never treated with EGFR-TKI, only those with activating mutations were evaluated. Most of the cases were in stage IV when their plasma DNA was obtained. In 32 of 44 patients, activating

Table 2. Allele frequency of activating and resistant *EGFR* mutations

Patient	Age, y	Sex	Histology	Stage	T790M, %	Activating mutation, %	T790M/activating mutation, %	Activating mutation type
A. Group 1 (patients with PD after EGFR-TKI treatment)								
1	56	M	adeno	4	0.029	0.058	50.8	L861Q
2	58	F	adeno	4	0.26	0.28	94.0	L858R
3	70	F	adeno	4	2.61	7.39	35.3	L858R
4	78	M	adeno	3A	0.08	0.13	65.0	L858R
5	65	M	Adeno + Sq	4	0.63	1.10	57.6	L858R
6	20	M	Adeno	4	0.14	1.03	13.3	exon 19 E746-A750del
7	41	F	adeno	4	4.28	10.3	41.6	exon 19 E746-A750del
8	59	F	adeno	4	9.54	42.7	22.3	exon 19 E746-A750del
9	53	M	adeno	4	0.16	0.19	83.6	exon 19 E746-A750del
10	49	F	adeno	4	ND	0.12	0.0	L861Q
11	75	F	adeno	4	ND	2.03	0.0	L858R
12	34	M	adeno	4	ND	0.33	0.0	L858R
13	64	M	adeno	4	ND	12.2	0.0	L858R
14	73	F	adeno	4	ND	0.046	0.0	L858R
15	66	F	adeno	4	ND	0.28	0.0	exon 19 L747-S752del.P753S
16	70	M	adeno	4	ND	11.5	0.0	exon 19 L747-S752del.P753S
17	44	F	adeno	4	ND	0.09	0.0	exon 19 L747-E749del.A750P
18	52	M	adeno	4	ND	0.74	0.0	exon 19 L747-E749del.A750P
19	74	F	adeno	4	ND	0.33	0.0	exon 19 E746-A750del
20	63	F	adeno	4	ND	ND	NA	L858R
21	65	F	adeno	4	0.10	ND	NA	exon 19 E746-A750del
22	51	F	adeno	4	ND	ND	NA	exon 19 E746-A750del
23	62	F	adeno	4	ND	ND	NA	exon 19 E746-A750del
B. Group 2 (patients not treated with EGFR-TKI)								
24	68	M	adeno	4	ND	0.17	0.0	L858R
25	45	F	adeno	4	ND	0.23	0.0	L858R
26	85	F	adeno	2B	ND	0.25	0.0	L858R
27	67	F	adeno	4	ND	0.079	0.0	L858R
28	58	F	adeno	4	ND	0.013	0.0	L858R
29	39	F	adeno	3B	ND	36.4	0.0	L858R
30	36	F	adeno	4	ND	0.11	0.0	exon 19 L747-S752del.E746V
31	56	M	adeno	4	ND	6.47	0.0	exon 19 L747-T751del.S752Q
32	55	F	adeno	3A	ND	6.24	0.0	exon 19 L747-E749del.A750P
33	65	F	adeno	3B	ND	11.8	0.0	exon 19 E746-A750del
34	76	F	adeno	4	ND	1.06	0.0	exon 19 E746-A750del
35	63	F	Sq	4	ND	0.73	0.0	exon 19 E746-A750del
36	63	M	adeno	4	ND	0.030	0.0	exon 19 E746-L747del.IP
37	72	F	adeno	4	ND	ND	NA	L858R
38	70	F	adeno	4	ND	ND	NA	L858R
39	63	M	adeno	4	ND	ND	NA	L858R
40	80	F	adeno	4	ND	ND	NA	L858R
41	70	F	adeno	4	ND	ND	NA	L858R
42	72	M	adeno	4	0.03	ND	NA	exon 19 L747-S752del.P753S
43	47	M	adeno	4	ND	ND	NA	exon 19 E746-A750del
44	54	F	adeno	4	ND	ND	NA	exon 19 E745-E749del.A750K

Abbreviations: NA, not applicable; ND, not detected.

mutations were detected in the plasma DNA (72.7%; 95% CI, 58.0–83.6%). The detection rate was higher in group 1 (group 1, 82.6%; group 2, 61.9%), but this difference was not statistically significant (the Fischer exact test, $P = 0.18$).

The detection rates of L858R/L861Q and exon 19 deletion were identical (72.7%). The T790M mutation was detected in 10 of 23 patients in group 1 (43.5%; 95% CI, 25.6%–53.4%). Because T790M accounted for about half of the

being planned to validate present observations. It should be noted that specificity, that is, absence of pseudopositive, is most important for new noninvasive diagnostics. The validation study should also be focused on this point as well.

As suggested by a recent review (26), the most problematic aspect of ctDNA analysis is the difficulty in purifying DNA from the blood. As described above, the amount of plasma DNA varies by 2 orders of magnitude. The cause of this variation (i.e., whether it is due to true variation or the low reproducibility of the purification procedure) is unknown. However, it should be noted that unsuccessful mutation detection was not necessarily frequent in the cases with low DNA recovery and that unsuccessful mutation detection was still found among those with abundant DNA recovery. Some cases of low DNA recovery contained the minimum number of *EGFR* copies for detection. In such cases, whole-genome amplification is beneficial for sound PCR and may enhance the detection rate, as seen in a previous study (19).

This study focused on advanced lung cancer (mainly stage IV lung cancer). If ctDNA analysis is effective for early lung cancer, then it may be applicable to early cancer detection. Because ctDNA is also easily detected in the early stages of colorectal cancer (27), it is worthwhile to test ctDNA analysis for early lung cancer.

BEAMing uses the template preparation step of massively parallel sequencers (so-called next-generation sequencers; ref. 28). Therefore, we can predict the outcome when massively parallel sequencers are applied to this problem. The recent development of a new sequencer (29) has addressed the shortcomings of currently available sequencers (i.e., a long runtime for a single assay and high operating costs), and would be suitable for diagnostic purposes.

References

- Lynch TJ, Bell DW, Sordella R, Gurubhagavatula S, Okimoto RA, Brannigan BW, et al. Activating mutations in the epidermal growth factor receptor underlying responsiveness of non-small-cell lung cancer to gefitinib. *N Engl J Med* 2004;350:2129–39.
- Paez JG, Janne PA, Lee JC, Tracy S, Greulich H, Gabriel S, et al. *EGFR* mutations in lung cancer: correlation with clinical response to gefitinib therapy. *Science* 2004;304:1497–500.
- Rosell R, Moran T, Queralt C, Porta R, Cardenal F, Camps C, et al. Screening for epidermal growth factor receptor mutations in lung cancer. *N Engl J Med* 2009;361:958–67.
- Kobayashi S, Boggon TJ, Dayaram T, Janne PA, Kocher O, Meyerson M, et al. *EGFR* mutation and resistance of non-small-cell lung cancer to gefitinib. *N Engl J Med* 2005;352:786–92.
- Pao W, Miller VA, Politi KA, Riely GJ, Somwar R, Zakowski MF, et al. Acquired resistance of lung adenocarcinomas to gefitinib or erlotinib is associated with a second mutation in the *EGFR* kinase domain. *PLoS Med* 2005;2:e73.
- Oxnard GR, Arcila ME, Sima CS, Riely GJ, Chmielecki J, Kris MG, et al. Acquired resistance to *EGFR* tyrosine kinase inhibitors in *EGFR*-mutant lung cancer: distinct natural history of patients with tumors harboring the T790M mutation. *Clin Cancer Res* 2011;17:1616–22.
- Kosaka T, Yatabe Y, Endoh H, Yoshida K, Hida T, Tsuboi M, et al. Analysis of epidermal growth factor receptor gene mutation in patients with non-small cell lung cancer and acquired resistance to gefitinib. *Clin Cancer Res* 2006;12:5764–9.
- Goebel G, Zitt M, Zitt M, Muller HM. Circulating nucleic acids in plasma or serum (CNAPS) as prognostic and predictive markers in patients with solid neoplasias. *Dis Markers* 2005;21:105–20.
- Vlassov VV, Laktionov PP, Rykova EY. Circulating nucleic acids as a potential source for cancer biomarkers. *Curr Mol Med* 2010;10:142–65.
- Diehl F, Schmidt K, Choti MA, Romans K, Goodman S, Li M, et al. Circulating mutant DNA to assess tumor dynamics. *Nat Med* 2008;14:985–90.
- Shinozaki M, O'Day SJ, Kitago M, Amersi F, Kuo C, Kim J, et al. Utility of circulating B-RAF DNA mutation in serum for monitoring melanoma patients receiving biochemotherapy. *Clin Cancer Res* 2007;13:2068–74.
- Dressman D, Yan H, Traverso G, Kinzler KW, Vogelstein B. Transforming single DNA molecules into fluorescent magnetic particles for detection and enumeration of genetic variations. *Proc Natl Acad Sci U S A* 2003;100:8817–22.
- Pao W, Ladanyi M. Epidermal growth factor receptor mutation testing in lung cancer: searching for the ideal method. *Clin Cancer Res* 2007;13:4954–5.
- Nagai Y, Miyazawa H, Huqun, Tanaka T, Udagawa K, Kato M, et al. Genetic heterogeneity of the epidermal growth factor receptor in non-small cell lung cancer cell lines revealed by a rapid and sensitive detection system, the peptide nucleic acid-locked nucleic acid PCR clamp. *Cancer Res* 2005;65:7276–82.
- Rago C, Huso DL, Diehl F, Karim B, Liu G, Papadopoulos N, et al. Serial assessment of human tumor burdens in mice by the analysis of circulating DNA. *Cancer Res* 2007;67:9364–70.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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16. Diehl F, Schmidt K, Durkee KH, Moore KJ, Goodman SN, Shuber AP, et al. Analysis of mutations in DNA isolated from plasma and stool of colorectal cancer patients. *Gastroenterology* 2008;135:489–98.
17. Li M, Chen WD, Papadopoulos N, Goodman SN, Bjerregaard NC, Laurberg S, et al. Sensitive digital quantification of DNA methylation in clinical samples. *Nat Biotechnol* 2009;27:858–63.
18. Kimura H, Kasahara K, Kawaishi M, Kunitoh H, Tamura T, Holloway B, et al. Detection of epidermal growth factor receptor mutations in serum as a predictor of the response to gefitinib in patients with non-small-cell lung cancer. *Clin Cancer Res* 2006;12:3915–21.
19. Kuang Y, Rogers A, Yeap BY, Wang L, Makrigiorgos M, Vetrand K, et al. Noninvasive detection of EGFR T790M in gefitinib or erlotinib resistant non-small cell lung cancer. *Clin Cancer Res* 2009;15:2630–6.
20. Brevet M, Johnson ML, Azzoli CG, Ladanyi M. Detection of EGFR mutations in plasma DNA from lung cancer patients by mass spectrometry genotyping is predictive of tumor EGFR status and response to EGFR inhibitors. *Lung Cancer* 2011;73:96–102.
21. Bai H, Mao L, Wang HS, Zhao J, Yang L, An TT, et al. Epidermal growth factor receptor mutations in plasma DNA samples predict tumor response in Chinese patients with stages IIIB to IV non-small-cell lung cancer. *J Clin Oncol* 2009;27:2653–9.
22. Inukai M, Toyooka S, Ito S, Asano H, Ichihara S, Soh J, et al. Presence of epidermal growth factor receptor gene T790M mutation as a minor clone in non-small cell lung cancer. *Cancer Res* 2006;66:7854–8.
23. Soh J, Toyooka S, Ichihara S, Suehisa H, Kobayashi N, Ito S, et al. EGFR mutation status in pleural fluid predicts tumor responsiveness and resistance to gefitinib. *Lung Cancer* 2007;56:445–8.
24. Giaccone G, Wang Y. Strategies for overcoming resistance to EGFR family tyrosine kinase inhibitors. *Cancer Treat Rev* 2011;37:456–64.
25. Ercan D, Zejnullahu K, Yonesaka K, Xiao Y, Capelletti M, Rogers A, et al. Amplification of EGFR T790M causes resistance to an irreversible EGFR inhibitor. *Oncogene* 2010;29:2346–56.
26. Schwarzenbach H, Hoon DS, Pantel K. Cell-free nucleic acids as biomarkers in cancer patients. *Nat Rev Cancer* 2011;11:426–37.
27. Diehl F, Li M, Dressman D, He Y, Shen D, Szabo S, et al. Detection and quantification of mutations in the plasma of patients with colorectal tumors. *Proc Natl Acad Sci U S A* 2005;102:16368–73.
28. Margulies M, Egholm M, Altman WE, Attiya S, Bader JS, Bembien LA, et al. Genome sequencing in microfabricated high-density picolitre reactors. *Nature* 2005;437:376–80.
29. Rothberg JM, Hinz W, Rearick TM, Schultz J, Mileski W, Davey M, et al. An integrated semiconductor device enabling non-optical genome sequencing. *Nature* 2011;475:348–52.
30. Kinde I, Wu J, Papadopoulos N, Kinzler KW, Vogelstein B. Detection and quantification of rare mutations with massively parallel sequencing. *Proc Natl Acad Sci U S A* 2011;108:9530–5.