Tracking Genomic Cancer Evolution for Precision Medicine: The Lung TRACERx Study

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Tracking Genomic Cancer Evolution for Precision Medicine: The Lung TRACERx Study

Mariam Jamal-Hanjani1,2, Alan Hackshaw3, Yenting Ngai3, Jacqueline Shaw4, Caroline Dive5, Sergio Quezada6, Gary Middleton7, Elza de Bruin1, John Le Quesne4, Seema Shafi1, Mary Falzon8, Stuart Horswell9, Fiona Blackhall10, Iftekhar Khan3, Sam Janes11, Marianne Nicolson12, David Lawrence13, Martin Forster2, Dean Fennell4,14, Siow-Ming Lee2, Jason Lester15, Keith Kerr16, Salli Muller17, Natasha Iles3, Sean Smith3, Nirupa Murugauaesu1,2, Richard Mitter9, Max Salm9, Aengus Stuart9, Nik Matthews18, Haydn Adams19, Tanya Ahmad2, Richard Attanoos20, Jonathan Bennett21, Nicolai Juul Birkbak22, Richard Booton23, Ged Brady24, Keith Buchan25, Arrigo Capitano8, Mahendran Chetty26, Mark Cobbold27, Philip Crosbie28, Helen Davies29, Alan Denison30, Madhav Djeorman31, Jacki Goldman32, Tom Haswell33, Leena Joseph34, Malgorzata Kornaszewska35, Matthew Krebs3, Gerald Langman36, Mairead MacKenzie33, Joy Millar36, Bruno Morgan4, Babu Naidu37, Daisuke Nonaka38,39, Karl Peggs6, Catrin Pritchard39, Hardy Remmen25, Andrew Rowan40, Rajesh Shah41, Elaine Smith42, Yvonne Summers38,43, Magali Taylor44, Selvaraju Veeriah1, David Waller45, Ben Wilcox46, Maggie Wilcox33, Ian Woolhouse47, Nicholas McGranahan40, Charles Swanton1,2,40

1 Translational Cancer Therapeutics Laboratory, University College London Cancer Institute, London, United Kingdom, 2 Department of Medical Oncology, University College London Hospitals, London, United Kingdom, 3 Cancer Research UK & UCL Cancer Trials Centre, London, United Kingdom, 4 Cancer Studies and Molecular Medicine, University of Leicester, Leicester, United Kingdom, 5 Cancer Research UK Manchester Institute, Manchester, United Kingdom, 6 Immune Regulation and Tumour Immunotherapy Laboratory, University College London Cancer Institute, London, United Kingdom, 7 Department of Medical Oncology, Birmingham Heartlands Hospital, Birmingham, United Kingdom, 8 Department of Pathology, University College London Hospitals, London, United Kingdom, 9 Department of Bioinformatics and BioStatistics, Cancer Research UK, London Research Institute, London, United Kingdom, 10 Institute of Cancer Studies, University of Manchester and The Christie Hospital, Manchester, United Kingdom, 11 Department of Respiratory Medicine, University College London Hospitals, London, United Kingdom, 12 Department of Medical Oncology, Aberdeen University Medical School & Aberdeen Royal Infirmary, Aberdeen, Scotland, United Kingdom, 13 Department of Cardiothoracic Surgery, Heart Hospital, London, United Kingdom, 14 Department of Medical Oncology, University of Leicester & Leicester University Hospitals, Leicester, United Kingdom, 15 Department of Clinical Oncology, Velindre Hospital, Cardiff, Wales, United Kingdom, 16 Department of Pathology, Aberdeen University Medical School & Aberdeen Royal Infirmary, Aberdeen, Scotland, United Kingdom, 17 Department of Pathology, University of Leicester & Leicester University Hospitals, Leicester, United Kingdom, 18 The Advanced Sequencing Facility, London Research Institute, London, United Kingdom, 19 Department of Radiology, University Hospital Llandough, Cardiff, Wales, United Kingdom, 20 Department of Pathology, University Hospital Llandough, Cardiff, Wales, United Kingdom, 21 Department of Respiratory Medicine, University of Leicester & Leicester University Hospitals, Leicester, United Kingdom, 22 Department of Systems Biology, Technical University of Denmark, Kongens Lyngby, Denmark, 23 Department of Respiratory Medicine, University Hospital of South Manchester, Manchester, United Kingdom, 24 Cancer Research UK Manchester Institute, Manchester, United Kingdom, 25 Department of Cardiothoracic Surgery, Aberdeen University Medical School & Aberdeen Royal Infirmary, Aberdeen, United Kingdom, 26 Department of Respiratory Medicine, University Hospital Llandough, Cardiff, Wales, United Kingdom, 27 Department of Clinical Immunology, University of Birmingham, Birmingham, B15 2TT, 28 North West Lung Centre, University Hospital of South Manchester, Manchester, United Kingdom, 29 Department of Respiratory Medicine, University Hospital Llandough, Cardiff, Wales, United Kingdom, 30 Aberdeen Biomedical Imaging Centre, University of Aberdeen, Aberdeen, United Kingdom, 31 Department of Radiology, Birmingham Heartlands Hospital, Birmingham, United Kingdom, 32 Department of IT, London Research Institute, London, United Kingdom, 33 Independent Cancer Patient’s Voice, London, united kingdom, 34 Department of Pathology, University Hospitals of South Manchester, Manchester, 35 Department of Cardiothoracic Surgery, University Hospital Llandough, Cardiff, Wales, United Kingdom, 36 Department of Cellular Pathology, Birmingham Heartlands Hospital, Birmingham, United Kingdom, 37 Department of Thoracic Surgery, Birmingham Heartlands Hospital, Birmingham, United Kingdom, 38 The Christie Hospital, Manchester, United Kingdom, 39 Department of Biochemistry, University of Leicester, Leicester, United Kingdom, 40 Translational Cancer Therapeutics Laboratory, London Research Institute, London, United Kingdom, 41 Department of Cardiothoracic Surgery, University Hospitals of South Manchester, Manchester, United Kingdom, 42 Department of Radiology, University Hospitals of South Manchester, Manchester, United Kingdom, 43 Department of Medical Oncology, University Hospital of South Manchester, Manchester, United Kingdom, 44 Department of Radiology, University College London Hospitals, London, United Kingdom, 45 Department of Cardiothoracic Surgery, University of Leicester & Leicester University Hospitals, Leicester, United Kingdom, 46 School of Cancer Sciences, University of Birmingham, Birmingham, United Kingdom, 47 Department of Respiratory Medicine, Birmingham Heartlands Hospital, Birmingham, United Kingdom
Introduction

Each patient’s cancer has a unique genomic landscape, often comprised of populations of genetically distinct, separated subclones with the potential to undergo dynamic evolutionary processes throughout the disease course [1,2]. One of the major challenges in achieving the goal of precision medicine lies in obtaining an accurate view of this genomic landscape, in order to choose the appropriate therapeutic regimen [3]. Intratumour heterogeneity poses a challenge in that a single tumour biopsy may not fully capture the current or future tumour landscape and merely represents a “snapshot” of the disease in space and time. Several studies have demonstrated branched evolution in different tumour types, including breast [4,5], pancreatic [6], kidney [7], colorectal [8], and prostate [9] cancers, as well as haematological malignancies such as chronic lymphoblastic leukaemia [1] and acute lymphoblastic leukaemia [10]. Understanding how tumour clonal heterogeneity impacts upon clinical outcome, and how cancer subclones compete, adapt, and evolve through the disease course in relation to therapy, is an area of unmet clinical and scientific need. Lung TRACERx (TRAcking non-small cell lung Cancer Evolution through therapy [Rx]), a prospective study of patients with primary non-small cell lung cancer (NSCLC), aims to define the evolutionary trajectories of lung cancer in both space and time through multiregion and longitudinal tumour sampling and genetic analysis. By following cancers from diagnosis to relapse, tracking the evolutionary trajectories of tumours in relation to therapeutic interventions, and determining the impact of clonal heterogeneity on clinical outcomes, TRACERx may help to identify novel therapeutic targets for NSCLC and may also serve as a model applicable to other cancer types.

Abstract: The importance of intratumour genetic and functional heterogeneity is increasingly recognised as a driver of cancer progression and survival outcome. Understanding how tumour clonal heterogeneity impacts upon therapeutic outcome, however, is still an area of unmet clinical and scientific need. Lung TRACERx (TRAcking non-small cell lung Cancer Evolution through therapy [Rx]), a prospective study of patients with primary non-small cell lung cancer (NSCLC), aims to define the evolutionary trajectories of lung cancer in both space and time through multiregion and longitudinal tumour sampling and sequencing, aiming to define the genomic landscape of NSCLC and to understand the impact of tumour clonal heterogeneity upon therapeutic and survival outcome.

Overview of Lung TRACERx

Lung TRACERx incorporates longitudinal sample collection from diagnosis to relapse in order to investigate how each cancer responds to treatment, the potential mutational processes and mechanisms involved in drug resistance, and development of metastatic disease. Although here we discuss TRACERx in NSCLC, the proposed longitudinal sample collection and study template is also relevant to other tumour types. TRACERx, conducted across six sites in the United Kingdom (London, Leicester, Manchester, Aberdeen, Birmingham, and Cardiff), will enrol 842 patients with primary NSCLC stages I-IIIA over an accrual period of four years with a total 5-year follow-up per patient. Primary surgically resected NSCLC tumours and associated lymph nodes, surplus to diagnostic requirements, will be subject to multiregion sampling and subsequent whole-exome and/or whole-genome sequencing. In patients suffering disease recurrence, consent will be obtained for a further biopsy to assess how the tumour clonal structure has changed through therapy and disease progression. The primary objectives of TRACERx are to determine the relationship between intratumour heterogeneity and clinical outcome (disease-free survival [DFS] and overall survival [OS]), and to establish the impact of adjuvant platinum-containing regimens on intratumour heterogeneity in relapsed disease. The secondary objectives include developing and validating an intratumour heterogeneity index as a prognostic or predictive biomarker and identifying drivers of genomic instability, metastatic progression, and drug resistance by identifying and tracking the dynamics of somatic mutational heterogeneity. TRACERx also aims to define clonally dominant drivers of disease to address the role of clonal driver dominance in targeted therapeutic response, and to guide lung cancer treatment stratification. The sample collection per patient and overall study scheme are summarised in Figure 1 and Figure 2, respectively.

Spatial Heterogeneity and Branched Evolution in NSCLC

Previous efforts to characterise the cancer genome of NSCLC have involved the analysis of copy number alterations [11,12], targeted sequencing of candidate cancer genes [13,14] and next-generation sequencing of genomes and/or exomes [15–18]. By interrogating the mutational spectrum of tumours, these studies have demonstrated its complex and heterogeneous genomic landscape from point mutations to large structural variants, and the high mutational burden of smoking-related NSCLC. However, few studies in NSCLC have investigated the clonal and subclonal architecture of lung cancer tumours and their evolution through disease progression. The TRACERx consortium has developed methods to analyse the dynamics of genetic intratumour heterogeneity within individual tumours over time [7]. Distance-based phylogenetic trees will be inferred from the variants, insertions and deletions (INDELS), and
structural variations observed in multi-region exome sequence datasets from a single tumour, allowing the discrimination of conserved early genetic mutations present at all sites of the primary tumour from later somatic events present in parts of the tumour and/or metastatic sites. This estimated temporal ordering will give insight into the potential relationships of such changes with ploidy shifts, chromosomal instability, and mutational processes that may change during the course of tumour progression.

**Histological Heterogeneity in NSCLC**

Lung cancer is a histologically highly heterogeneous disease. Mixed lung tumours containing more than one histological type, such as adenosquamous tumours, combined small-cell tumours (small-cell combined with NSCLC), or tumours with areas of histological dedifferentiation are not uncommon. Within adenocarcinomas, histological variety is the rule, with most tumours showing a mixture of patterns, the commonest being lepidic/in situ, acinar, solid, papillary, and micropapillary. Solid and micropapillary patterns are associated with worse outcome [19–21]. Some patterns show associations with known driving mutations [22,23], although these relationships are incompletely described at present. Furthermore, nuclear grade, which is not currently routinely assessed, often shows heterogeneity and is itself related to outcome [24,25]. It is not known to what extent this spatial histological heterogeneity reflects genomic heterogeneity as opposed to epigenetic or microenvironmental influences.

TRACERx aims to correlate histological heterogeneity with genomic heterogeneity and potentially improve the predictive and prognostic value of histological appearances in NSCLC.

**Tumour Heterogeneity, Outcome, and Impact of Platinum Chemotherapy in NSCLC**

It is unclear why adjuvant chemotherapy following surgery for primary NSCLC is effective in some patients but not in others. An increasing body of evidence supports the association of patterns of intratumour heterogeneity, in multivariate analyses, with poor survival outcome in NSCLC and other solid tumours [26]. Indeed, work from us and others has shown that chromosomal instability, a driver of intratumour heterogeneity, is associated with cancer drug resistance, and numerous studies have documented the association of chromosomal instability with poor outcome in NSCLC [26–31]. The impact of intratumour heterogeneity on evolutionary fitness, together with the documented relationship of heterogeneity with drug resistance, supports the potential predictive nature of this candidate biomarker. Cytotoxic therapies have also been shown to influence the genomic landscape of drug-resistant diseases [32,33], which raises the concern that increased genomic complexity in cytotoxic refractory tumours may potentiate tumour adaptation. However, studies to date are based on the analysis of small retrospective cohorts such that the true relationship between intratumour heterogeneity and clinical outcome, as well as the impact of platinum-based chemotherapy on the tumour genomic landscape, is currently unknown. TRACERx will prospectively assess whether an intratumour heterogeneity index can predict response to adjuvant therapy, and attempt to validate intratumour heterogeneity as an effective prognostic and predictive biomarker independent of known factors, such as tumour stage.

**Defining Drivers of Intratumour Heterogeneity and Drug Resistance**

Deep sequencing analyses are revealing vast clonal heterogeneity present in solid tumours, including NSCLC, and the spatial and temporal dynamics of cancer subclones that emerge during the disease course and following acquired drug resistance [34,35]. We have shown that drivers of intratumour heterogeneity can be defined in vivo and that one mechanism driving tumour heterogeneity in colorectal cancer, DNA replication stress, may be targetable [36]. Defining such processes in longitudinal solid tumour cohorts may have therapeutic relevance in attempting to limit tumour heterogeneity, adaptation, and cancer evolution [37]. TRACERx aims to develop an improved understanding of the relationship between phenotypic and genetic intratumour heterogeneity with cancer evolution, and identify further drivers of genomic instability. Ultimately it is hoped that this will support the development of novel therapeutic approaches to limit relapse and improve outcomes in NSCLC.

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**Figure 1. Sample collection in TRACERx.**

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Impact of Intratumour Heterogeneity on Host Immunity and Tumour Neo-Antigenic Repertoire

Whilst evidence suggests that intratumour heterogeneity may significantly limit the antitumour activity of targeted therapeutics [38], its overall effect on the anticancer immune response may be beneficial, since high levels of intratumoural mutational diversity may generate neo-antigens perceived by the immune system as non-self, thus providing relevant targets for immune-based therapies [38–40]. TRACERx aims to provide a resource to define the impact of intratumour heterogeneity on cancer immunity throughout tumour evolution and therapy. Through the integration of clinical and tumour multiregion sequencing data with immunological analysis, the consortium will assess various aspects of tumour immunobiology, including the overall impact of distinct drivers of intratumour heterogeneity on immune infiltration and function, the proportion of tumour infiltrating lymphocytes with the ability to recognise neo-antigens, and whether novel T cell receptors that recognise phosphopeptides preferentially expressed by tumour cells can be identified in patients, with NSCLC serving as a platform for the development of future immunotherapeutic strategies.

Development of Minimally Invasive Methods to Study Tumour Evolution

Primary and metastatic tumours will be genetically profiled to identify clonal and subclonal driver mutations. However, our analysis of the primary tumour is limited to tissue surplus to diagnostic requirement, albeit multiregional, and our analysis of metastatic sites is likely to be restricted to one location, emphasising the need to develop less invasive approaches to follow tumour evolution. Circulating biomarkers have the potential to monitor minimal residual disease, forecast early progression, and document subclonal evolution through therapy and acquired drug resistance [41]. Here we propose to extend the TRACERx consortium’s expertise in minimally invasive biomarker approaches to monitor tumour subclonal evolution through serial analysis of circulating-free tumour DNA (cfDNA) and circulating tumour cells (CTCs) before surgery and throughout the disease course. We have shown that cfDNA analysis is technically
straightforward with limited cost and has demonstrable utility in disease monitoring [35,42], and that CTC number in NSCLC is an independent prognostic biomarker [43]. TRACERx aims to address how intratumour heterogeneity is manifested in circulating biomarkers and the extent to which the genetic landscape of the primary and metastatic tumour is reflected in CTCs and cfDNA. This comparison will take into account the limitations in tumour sampling and therefore the potential to identify genetic aberrations in CTCs and cfDNA not detected in the tumour tissue. By comparing serial samples, TRACERx will determine whether cfDNA can detect residual disease following surgery and predict tumour recurrence, whether CTCs and cfDNA detected genetic heterogeneities in advanced metastatic disease can represent further selection of subclones over time, and whether CTCs and cfDNA can provide insight into drug resistance mechanisms.

**Clonal Dominance and Clinical Outcome**

There is a pressing need to define early driver events suitable for clinical drug trial stratification and to assess prospectively the role of drug target intratumour heterogeneity in the early emergence of resistance and poor DFS outcomes. Until recently, the term “actionable mutation” was used to define the presence of a somatic mutation or copy number event in a single tumour biopsy that might suggest a targeted therapeutic approach. However, emerging evidence for intratumour heterogeneity in breast cancer [44], renal cell carcinoma [7], glioblastoma [45], pancreatic cancer [6,46], and medulloblastoma [47]. Longitudinal sample collection and genomic analysis from the primary tumour through disease progression and at the time of death has the potential to identify the molecular features and subclonal origin of the metastatic process. In an interesting case of prostate cancer, Haffner and colleagues correlated whole-genome sequencing data from a primary tumour with three sites of metastases collected at autopsy 17 years after presentation [9]. Despite genetic heterogeneity among metastases, there were many shared events suggesting a monoclonal origin. Through historical assessment, alongside sequencing, they identified the lethal metastatic clone originating from the primary tumour. Patients who develop terminal metastatic NSCLC in TRACERx will be asked to consider enrolling in an autopsy programme that will be open nationally. For each patient, TRACERx will have accumulated an unprecedented amount of genetic data, and accessing tissue from multiple sites of disease after death would give some insight into the evolving constellation of genetic aberrations and a potential model for the metastatic process. Circulating biomarkers collected at this point may add to this model, although as previously mentioned, the extent to which these biomarkers reflect tumour genomics in NSCLC is yet to be fully determined.

**Conclusions**

The importance of intratumour heterogeneity is increasingly recognised as a driver of tumour progression, drug resistance and treatment failure in solid tumours [5,6,27,44,47,50–52]. The presence of subclonal driver events may prove a significant challenge to biomarker development and drug target discovery efforts, and contribute to drug resistance and poor survival outcome [10,44,53,54]. Despite the impressive developments of international large-scale sequencing consortia, the spatial separation of tumour subclones, the changing nature of the disease over time, and the impact of such diversity upon outcome are yet to be addressed [5]. Lung TRACERx is a large-scale study integrating complex genomic data with phenotypic clinical annotation and outcome in order to decipher the heterogeneity of the cancer genome and mutational pathways involved in NSCLC pathogenesis. It aims to develop clinically meaningful measures of intratumour heterogeneity to guide patient management and treatment stratification [55] and to prospectively define thresholds of tumour heterogeneity for clinical risk stratification. With increasing awareness of the need to obtain tissue and genetically profile cancers in order to stratify treatment, the concept of longitudinal tissue collection and analysis has become more acceptable in oncological practice. In following cancers from diagnosis to relapse, tracking the evolutionary trajectories of tumours in relation to therapeutic interventions, and determining the impact of clonal heterogeneity on clinical outcomes, TRACERx will also serve as a model applicable to other cancer types.

TRACERx is not without its limitations. In determining the full extent of intratumour heterogeneity, we are reliant on tissue collected surplus to diagnostic requirements, and therefore entire tumours are not sequenced. However, with deep sequencing and multiregion sampling, together with retrospective genomics analysis of residual surplus tumour tissue guided by the metastatic sample datasets, we hope to achieve significant coverage of the relevant tumour genomic landscape within each patient. Analysing circulating biomarkers, such as cfDNA and CTCs, may further complement the tumour sequencing data and identify additional genetic aberrations not detected by primary or metastatic tumour sequencing. We anticipate that a biopsy of a metastatic site may not be appropriate in all patients, but having taken into account expected rates of attrition, we will have a sufficient number of cases to meet the study outcome objectives. Finally, our ability to detect subclonal somatic events occurring at low variant allele frequencies is limited by the power of our existing methods, but as sequencing and bioinformatics methods advance, TRACERx will
adapt to incorporate such improvements in technologies, including the use of deep whole-genome sequencing datasets in some cases with no clear genetic driver events. Overall, TRACERx aims to develop a comprehensive understanding of the genomic landscape of NSCLC through the disease course and the biological role of underlying genetic events that might contribute to disease progression.

Optimising understanding of NSCLC evolutionary processes may help to identify novel therapeutic targets to improve clinical outcomes. As the cost of sequencing decreases and informatics techniques advance, such large-scale longitudinal genomic studies may become a central component to the delivery of precision cancer medicine.

References


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