Environmental and Nutritional Factors That Affect Growth and Metabolism of the Pneumococcal Serotype 2 Strain D39 and Its Nonencapsulated Derivative Strain R6

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Abstract

Links between carbohydrate metabolism and virulence in Streptococcus pneumoniae have been recurrently established. To investigate these links further we developed a chemically defined medium (CDM) and standardized growth conditions that allowed for high growth yields of the related pneumococcal strains D39 and R6. The utilization of the defined medium enabled the evaluation of different environmental and nutritional factors on growth and fermentation patterns under controlled conditions of pH, temperature and gas atmosphere. The same growth conditions impacted differently on the nonencapsulated R6, and its encapsulated progenitor D39. A semi-aerobic atmosphere and a raised concentration of uracil, a fundamental component of the D3 capsule, improved considerably D39 growth rate and biomass. In contrast, in strain R6, the growth rate was enhanced by strictly anaerobic conditions and uracil had no effect on biomass. In the presence of oxygen, the difference in the growth rates was mainly attributed to a lower activity of pyruvate oxidase in strain D39. Our data indicate an intricate connection between capsule production in strain D39 and uracil availability. In this study, we have also successfully applied the in vivo NMR technique to study sugar metabolism in S. pneumoniae R6. Glucose consumption, end-products formation and evolution of intracellular metabolite pools were monitored online by 13C-NMR. Additionally, the pools of NTP and inorganic phosphate were followed by 31P-NMR after a pulse of glucose. These results represent the first metabolic profiling data obtained non-invasively for S. pneumoniae, and pave the way to a better understanding of regulation of central metabolism.

Introduction

Streptococcus pneumoniae is a commensal organism of the human nasopharynx, and an opportunistic bacterium that can cause a number of serious diseases such as pneumonia, meningitis and septicemia (reviewed in [1]). According to the World Health Organization (WHO), diseases caused by S. pneumoniae constitute a major global public health problem, leading to an estimated 1 million deaths per year in children under the age of five (http://www.who.int/nuvi/pneumococcus/en/). This high mortality is exacerbated by the rate at which the organism acquires resistance to traditional antibiotics. Therefore, it is urgent to find new targets for the development of novel therapeutic and preventive drugs.

As a strictly fermentative bacterium, carbohydrates are most likely the only nutrients from which the pneumococcus can obtain sufficient energy to support growth. This view is strengthened by the large portion of the pneumococcal genome that is devoted to carbohydrate uptake and metabolism [2–4]. Genes involved in central metabolic processes, namely carbohydrate transport and utilization, recurrently appear in genome-wide studies aimed at identifying genes essential for virulence [5]. Growing evidence adds to these findings by showing that carbohydrate transport systems, metabolic enzymes and a global regulator of carbon metabolism (CcpA) directly contribute to S. pneumoniae colonization and disease [6–14]. These studies linked virulence with carbohydrate metabolism, denoting a far greater importance of basic metabolic physiology than previously imagined. Recently, it was recognized that a true understanding of metabolism is perhaps more difficult to attain than that of any other cellular system [15], because metabolism is influenced by a vast number of regulatory networks. In accordance, lack of correlation between metabolic behaviors and changes in transcript levels [16–18], emphasize the importance of examining metabolic operation in detail. Capturing the essence of complex regulatory mechanisms as those involved in carbohydrate metabolism demands the use of well-defined physiological conditions.

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A powerful technique for studying metabolism in a non-invasive way is in vivo NMR spectroscopy. This methodology provides real time information on the pools of intracellular metabolites and metabolic fluxes and can also be used to identify metabolic bottlenecks and regulatory sites [reviewed in [19]]. The application of NMR to study metabolism is largely facilitated by the use of a proper chemically defined medium (CDM) for growth [20]. In CDM all the components and respective concentrations are defined, facilitating data interpretation and improving reproducibility between experiments [21,22]. CDM formulations for S. pneumoniae are available, but the maximal pneumococcal biomass formed in these media is generally below an optical density value of 1 [23–25]. Low biomass yields are inadequate when in vivo NMR is to be used for metabolic studies, as this technique requires the utilization of dense cell suspensions. Furthermore, paramagnetic ions (e.g. Mn²⁺, Fe²⁺), which are well known for lowering the sensitivity of NMR spectroscopy (reviewed in [19]), are generally present at relatively high concentrations in the defined media for the pneumococcus.

Most cultivation optimizations for streptococcal growth have been performed in complex media with the goal of producing capsular polysaccharide on a large-scale for industrial application [4]. Growth and fermentation profiles in the improved CDM were obtained by ³¹P-NMR. The application of this technique to pneumococci (e.g. S. pneumoniae strain R6 and its acapsular derivative R6) is expected to extend the use of ³¹P-NMR spectroscopy to other human pathogens.

Results and Discussion

Chemo-taxonomically defined CDMs are useful because they support high yields of pneumococcal biomass [3]. In the present study, we optimized the growth conditions of S. pneumoniae using various CDM formulations and determined their effect on the growth physiology of the two strains. A simplification and optimization of the medium was achieved by designing a proper chemically defined medium (CDM) for growth [20]. In accordance to our hypothesis R6 cultures grown at 60 mM of glucose as the carbon source, choline-HCl and pyruvate (Table 1) are chemicals generally used in CDM for S. pneumoniae growth [23–25]. The growth dependency of S. pneumoniae on exogenous choline, which is used to decorate its unusual teichoic acids, is well known [29], and was confirmed in our conditions (data not shown). Furthermore, we verified that increasing the choline-HCl concentration from 5 to 10 mg l⁻¹ increased the final biomass by 30%. Sodium pyruvate (0.1 g l⁻¹), the only amino acid not present in the lactococcal CDM, showed no effect. Interestingly, complex nitrogenous sources (soytone and caserin EH) improved the final biomass by about 50%. The latter result might indicate a preference of S. pneumoniae for oligopeptides over single amino acids, as tripling the concentration of all the amino acids in the medium did not improve growth (data not shown). For streptococcal cultivation conditions obtained under semi-aerobic conditions (standing rubber-stoppered bottles, cultivation conditions as in Materials and Methods) for strains R6 and D39 are shown in Fig. 1A.

Batch Cultivations Under Controlled Environmental Conditions

S. pneumoniae is a strictly fermentative organism that relies on the energy obtained during the conversion of sugars into pyruvate for growth. To fulfill the redox balance, the NAD⁺ consumed in glycolysis is primarily recycled through reduction of pyruvate to lactate, causing acidification of the medium and ultimately growth arrest. It is well established that increasing acidities progressively inhibit growth of Streptococcaceae [31,32]. Thus, we hypothesized that biomass production could be improved by maintaining the medium pH at 6.5, a value determined in independent experiments to be beneficial for growth of S. pneumoniae (data not shown).

To circumvent medium acidification high performance bioreactors were used for batch cultivations of S. pneumoniae. Bioreactors allow for the tight control of pH, as well as other growth parameters, such as gas atmosphere and temperature, and provide increased working volumes. Hence, strain R6 was grown in a 2-L fermentor vessel under controlled conditions of pH (6.5), temperature (37°C) and gas atmosphere (semi-aerobiosis), and the effect of pH control was examined in CDM supplemented with 60 mM glucose.

(i) Effect of pH control on growth of S. pneumoniae R6. In accordance to our hypothesis R6 cultures grown at constant pH of 6.5, under semi-aerobic conditions (Fig. 1B), showed a 2-fold increase in maximal biomass (OD₅₆₀ Max 3.6 as
compared to 1.7–1.9 in cultures without pH control) and identical growth rate (Fig. 1B and Fig. 1A). Thus, pH is a key parameter to control when high biomass yields are to be obtained.

(ii) Growth and fermentation profiles of S. pneumoniae D39 at constant pH of 6.5. Considering the genomic relatedness of strains R6 and D39 [4], we expected a positive effect on growth under constant pH of 6.5. To our surprise, however, strain D39 reached an OD$_{\text{Max}}$ value of 1.3±0.1, slightly lower than that under non-controlled pH conditions (1.6±0.2), and reduced by 64% when compared to OD$_{\text{Max}}$ value of strain R6 (3.6±0.2) (Fig. 1B and Fig. 1A). The growth rate was independent of pH control, and higher than that of strain R6 by about 15% (Fig. 1B and Fig. 1A, compare μ values). Intrigued by these results we questioned whether the dissimilar growth profiles could be due to an altered central metabolism. Accordingly, we examined substrate consumption and the pattern of end-products resulting from the fermentation of glucose (for a metabolic scheme see Fig. 2). Under controlled pH conditions, strain R6 stopped growing due to glucose limitation (glucose was totally consumed in the early-stationary phase after 9 h of growth, Fig. 1B and Table 2). A similar behaviour had previously been reported for L. lactis grown under constant pH in the CDM improved for NMR [20], and is common among the Streptococcaceae. In contrast, growth arrest in D39 cultures occurred at time-point 5 h while glucose was still abundant in the medium (Fig. 1B and Table 2), suggesting that a factor (nutritional or environmental) other than the carbon substrate is limiting growth. Both strains showed, however, typical homolactic fermentation, lactate being by far the major end-product. Minor amounts of mixed-acid fermentation products were also detected in supernatants of both strains, but pyruvate accumulation was only observed for strain D39 (Table 2). Accumulation of pyruvate in the medium suggests impairment of the activities at the pyruvate node. To our knowledge, in S. pneumoniae three competing enzymes, lactate dehydrogenase, pyruvate formate-lyase and pyruvate oxidase, can possibly catalyze the conversion of pyruvate to end-products (Fig. 2). The pyruvate dehydrogenase complex has been postulated (grey lines in scheme portrayed in Fig. 2), but its occurrence remains to be proved [33,34]. In view of the fermentation type exhibited by S. pneumoniae (Table 2), the most obvious candidate to be affected is lactate dehydrogenase (LDH). However, the activity values determined for LDH in cell extracts of strains D39 and R6 (Table 3) were in
the same range, indicating a similar expression of LDH in both strains. The \textit{in vivo} activity could, however, be directly influenced by metabolic regulation. In view of the higher glucose consumption rate of strain D39 relative to strain R6, it is reasonable to hypothesize dissimilar accumulation of intracellular metabolites, potentially involved in metabolic regulation (Table 2). Considering that LDH activity does not seem to be in great excess, since a lactate flux of 1.5 \text{ mmol min}^{-1} \text{ mg}^{-1} \text{prot} can be estimated from a maximal glucose consumption rate of 0.92 \text{ mmol min}^{-1} \text{ mg}^{-1} \text{prot} and a lactate yield of 1.63, direct modulation could easily explain the pyruvate accumulation. To the best of our knowledge a thorough biochemical characterization of the pneumococcal LDH is not available and, hence, potential activity inhibitors and/or activators unknown.

The gene encoding pyruvate oxidase, \textit{spxB}, is among the 81 allelic variants in strain R6 and D39 [4]. A major consequence of this genetic variation is the different pyruvate oxidase activity values reported in the literature for D39 and R6 strains [35,36], and fully corroborated by our own activity measurements in fresh lysates of cells grown aerobically (Table 3). Furthermore, the detection of H$_2$O$_2$ in the cultivation medium of strain D39 grown semi-aerobically is indicative of \textit{in vivo} activity under the conditions studied (Table 2). Thus, the lower pyruvate oxidase activity of strain D39 could in part explain the higher accumulation of pyruvate in the growth medium. In addition, this metabolic trait is likely reinforced in strain D39 by the higher NADH oxidase activity (Table 3), which overcomes the need to regenerate NAD$^+$ through pyruvate reduction (Fig. 2). However, these mechanisms cannot account for the total pyruvate accumulation (0.78±0.08 mM), mainly because under semi-aerobic conditions the oxidase activities are limited by the oxygen in the medium (initial concentration of circa 0.13–0.14 mM), which decreased to undetectable levels in about 60 min for strain D39 (Fig. S1). The rate of oxygen consumption was lower in strain D39 than in R6 (Fig. S1), which is consistent with the lower pyruvate oxidase activity, but not the higher NADH oxidase activity. Considering that the specific pyruvate oxidase activity is lower than that of NADH oxidase, the latter results can only be explained assuming a higher affinity of the pyruvate oxidase for oxygen.

The carbon and redox recoveries were modestly, but consistently lower for strain D39. Based on this observation it is tempting to speculate that in the capsulated strain carbon is being redirected from merely catabolic processes to biosynthesis, \textit{e.g.} capsule production.

**Effect of Oxygen on Growth and Metabolism of \textit{S. pneumoniae} D39 and R6**

Our data under semi-aerobic conditions establishes substantial differences in the growth profiles of strains D39 and R6. The level of oxygenation influences a number of cellular processes in \textit{S. pneumoniae}, including central metabolism and competence [34,37]. Thus, we deemed important to examine the effect of oxygen availability on the growth of strains D39 and R6.

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**Table 1. Composition of CDM used for growth of \textit{S. pneumoniae} in pH-controlled batch cultures.**

| Components                      | Concentration (g l$^{-1}$) | Components                      | Concentration (g l$^{-1}$) |
|---------------------------------|-----------------------------|---------------------------------|-----------------------------|
| **Buffers/Salts**               |                             | **Aminoacids (10$^{-3}$)**      |                             |
| KH$_2$PO$_4$                    | 3.0                         | Alanine                         | 0.24                        |
| K$_2$HPO$_4$                   | 2.5                         | Arginine                        | 0.13                        |
| Na-acetate                      | 1.0                         | Asparagine                      | 0.35                        |
| (NH$_4$)$_2$-citrate            | 0.6                         | Aspartate                       | 0.40                        |
| Na-pyruvate                     | 0.1                         | Cysteine-HCl                    | 0.40                        |
| **Vitamins (10$^{-3}$)**        |                             | Glutamate                       | 0.50                        |
| Choline-HCl                     | 0.01                        | Glutamine                       | 0.39                        |
| Na-p-Aminobenzoate              | 5.0                         | Glycine                         | 0.18                        |
| D-biotin                        | 2.5                         | Histidine                       | 0.15                        |
| Folic acid                      | 1.0                         | Isoleucine                      | 0.21                        |
| Nicotinic acid                  | 1.0                         | Leucine                         | 0.46                        |
| Ca (D$^+$) Pantothenate          | 1.0                         | Lysine                          | 0.44                        |
| Pyridoxamine-HCl                | 2.5                         | Methionine                      | 0.13                        |
| Pyridoxine-HCl                  | 2.0                         | Phenylalanine                   | 0.28                        |
| Riboflavin                      | 1.0                         | Proline                         | 0.68                        |
| Thiamine-HCl                    | 1.0                         | Serine                          | 0.34                        |
| DL-6,8-Thiocitic acid           | 1.5                         | Threonine                       | 0.22                        |
| Vitamin B$_12$                  | 1.0                         | Tryptophane                     | 0.05                        |
| **Nucleobases (10$^{-2}$)**     |                             | Thymine                         |                             |
| Adenine                         | 1.0                         | Valine                          | 0.33                        |
| Uracil                          | 1.0                         | Micronutrients (10$^{-1}$)      |                             |
| Guanine                         | 1.0                         | MgCl$_2$                        | 2.0                         |
| Xanthine                        | 1.0                         | CaCl$_2$                        | 0.4                         |
| **Micronutrients (10$^{-1}$)**  |                             | ZnSO$_4$                        | 0.05                        |

*K$_2$HPO$_4$ is replaced by disodium β-glycerophosphate (21 g l$^{-1}$) for growth without pH control.

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(i) Growth and fermentation profiles of *S. pneumoniae* D39 and R6 under anaerobic conditions. The growth profiles of strains D39 and R6 under strictly anaerobic conditions are depicted in Fig. 1C. The values of OD_{Max} obtained, 1.46±0.2 and 3.76±0.0 for strains D39 and R6, respectively, were similar to those observed in semi-aerobic conditions (Fig. 1C and 1B). Under anoxic conditions, the growth rate of strain D39 was decreased by 30%, but strain R6 showed a modest increase as compared to semi-aerobic conditions (Fig. 1C and 1B). Likewise under semi-aerobic conditions, glucose was still abundant when growth of strain D39 ceased (66% of the initial glucose remained in the culture medium at the time-point of maximal biomass, 8 h, Table 2), whereas strain R6 consumed all the glucose present in the medium (time-point 7 h, Table 2). The distribution of end-products was comparable to that observed under semi-aerobic conditions, except for the accumulation of pyruvate and lactate in strain D39 (Table 2). Under anaerobic conditions, pyruvate catabolism is dependent on the activities of LDH and PFL (Fig. 2), thus the 6.5-fold reduction in concentration (as compared to semi-aerobic conditions) most likely results from the higher pressure to regenerate NAD^+ via the dehydrogenases downstream of this metabolite.

The differences in growth rates between semi-aerobic and anaerobic conditions can tentatively be explained on the basis of metabolic activities. The 30% decline in D39’s growth rate when switching from semi-aerobiosis to anaerobiosis can be due to the decreased glucose consumption rate (0.92±0.04 in semi-aerobiosis as compared to 0.60±0.16 μmol min^{-1} mg^{-1} prot in anaerobiosis) (Table 2), which in turn can be attributed to a lower NAD^+ recycling capacity, as NADH oxidases are inoperative under anoxic conditions. Under semi-aerobic conditions, activity of NADH oxidase presumably enables a faster NAD^+ regeneration, and consequently a higher glucose consumption rate (Table 2). It is worth noting that the activity of NADH oxidase measured in cell extracts of strains R6 and D39 (Table 3) was considerably higher than that found for other related bacteria [38,39]. The lower growth rate of R6 under semi-aerobic conditions can be a direct consequence of the activity of pyruvate oxidase (Table 3), since its enzymatic product, H_2O_2, is known to induce oxidative stress in *S. pneumoniae* [40].

(ii) Growth and fermentation profiles of *S. pneumoniae* D39 in aerobic conditions. We then examined the effect of supplying a constant oxygen tension (continuous supply of 40% air) on the growth of strains D39 and R6. Under aerobic conditions the maximal biomass (OD_{Max}) reached for strains D39 (0.49±0.03) and R6 (0.23±0.02) were, respectively, 3-fold and 16-fold lower than those observed under semi-aerobic conditions (Fig. 1D). This drastic decrease in the OD_{Max} contrasts with the higher growth rates obtained for both strains (around 1 h^{-1}) (Fig. 1D). Noteworthy, at the time-point of transition to stationary conditions, the growth rate of strain D39 decreased by 50%, whereas strain R6 showed a modest increase as compared to semi-aerobic conditions (Fig. 1D).
Table 2. Effect of oxygen and uracil on growth and energetic parameters of strains D39 and R6.

|                        | Semi-aerobic | Anaerobic | Aerobic  |
|------------------------|--------------|-----------|----------|
|                        | Early stationary | Transition phase | Early stationary |
|                        | 10 mg l⁻¹ U | 30 mg l⁻¹ U | 10 mg l⁻¹ U | 10 mg l⁻¹ U |
| Product yields         |              |           |           |              |
| Lactate                | D39          | R6        | D39       | R6            |
| 10 mg l⁻¹ U            | 1.63 ± 0.01  | 1.81 ± 0.10 | 1.62 ± 0.04 | 1.82 ± 0.01 |
| 30 mg l⁻¹ U            | 1.77 ± 0.01  | 1.86 ± 0.04 | 1.78 ± 0.01 | 1.86 ± 0.04 |
| Pyruvate               | D39          | R6        | D39       | R6            |
| 10 mg l⁻¹ U            | 0.04 ± 0.01  | 0.01 ± 0.00 | 0.01 ± 0.00 | 0.01 ± 0.00 |
| Formate                | D39          | R6        | D39       | R6            |
| 10 mg l⁻¹ U            | 0.06 ± 0.01  | 0.06 ± 0.01 | 0.20 ± 0.02 | 0.05 ± 0.00 |
| Acetate                | D39          | R6        | D39       | R6            |
| 10 mg l⁻¹ U            | BDL          | BDL       | BDL       | BDL            |
| Ethanol                | D39          | R6        | D39       | R6            |
| 10 mg l⁻¹ U            | BDL          | BDL       | BDL       | BDL            |
| H₂O₂                   | D39          | R6        | D39       | R6            |
| 10 mg l⁻¹ U            | 10 ± 0       | ND        | ND        | ND            |
| Quantum yield (umol min⁻¹ mg⁻¹ prot) | D39          | R6        | D39       | R6            |
| 10 mg l⁻¹ U            | 0.92 ± 0.04  | 0.76 ± 0.16 | ND        | ND            |
| Consumed substrate (%) | 28 ± 0       | 100 ± 0   | 55 ± 0.4  | 100 ± 0       |
| Redox balance          | D39          | R6        | D39       | R6            |
| 10 mg l⁻¹ U            | 87 ± 1       | 93 ± 5    | 91 ± 1    | 93 ± 1        |
| Biomass yield (g mol⁻¹ Glc) | D39           | R6        | D39       | R6            |
| 10 mg l⁻¹ U            | 26.2 ± 1.0   | 23.1 ± 1.2 | 34.7 ± 0.1 | 22.9 ± 0.2   |
| ATP yield (mol mol⁻¹ Glc) | D39          | R6        | D39       | R6            |
| 10 mg l⁻¹ U            | 1.7 ± 0.0    | 1.9 ± 0.1 | 1.8 ± 0.1 | 1.9 ± 0.1    |
| Yₜₚ (g biomass mol⁻¹ ATP) | D39          | R6        | D39       | R6            |
| 10 mg l⁻¹ U            | 15.0 ± 0.7   | 19.2 ± 0.6 | 19.3 ± 0.6 | 12.1 ± 0.2   |

*Early stationary growth phase (time-point 2 h), strains D39 and R6 consumed only 3.7% and 2.8% of the glucose supplied, respectively (Fig. 3 and Table 2). In both strains, the presence of oxygen (at a concentration of 0.09 mM) shifted the metabolism from lactate to acetate and H₂O₂ production, denoting a high activity of pyruvate oxidase (SpxB) (Fig. 2 and Fig. 3). In strain R6 this shift was more pronounced, as indicated by the higher yields of acetate and H₂O₂ (Table 2). This observation is in good agreement with the high activity of pyruvate oxidase measured for this strain and, possibly, with lower activity of the competing enzyme, NADH oxidase (Table 3 and Fig. 2). In contrast to work by others, in our study, a considerable reduction of NADH oxidase activity was observed in cells grown aerobically relative to semi-aerobically grown cells (Table 3) [41,42]. Under these aeration conditions, formate was not detected in the culture medium, indicating total inhibition of PFL (Fig. 3 and Table 2). Interestingly, growth arrest was observed when the levels of acetate and H₂O₂ in the medium reached values of about 2 mM and 1 mM, respectively (Fig. 3). After the transition to stationary growth phase (time-point 2 h), glucose was not consumed to any significant extent (Fig. 3 and Table 2) and the levels of acetate and H₂O₂ increased at the expense of lactate, showing lactate oxidase (LOX coded by loxO) activity (Fig. 2 and Fig. 3). In accordance, in the early-stationary phase of growth (time-point 3 h) the yields of lactate decreased and the yields of lactate and H₂O₂ increased (Table 2). S. pneumoniae strain GTC13809, when grown aerobically, displayed similar metabolic features [34]. This, however, is not a general mechanism among lactic acid bacteria [39,43,44]. Most commonly, activity of lactate and/or pyruvate oxidase is only apparent after glucose depletion, a phenomenon that allows additional metabolism after glucose starvation [43,44]. The advantage of pyruvate recycling via lactate oxidase is extra generation of ATP in the ensuing conversion to acetate (Fig. 2). Therefore, in accordance with higher acetate production, the higher ATP yields (mol ATP mol⁻¹ glucose) determined for strains D39 and R6 under aerobic conditions were expected (Table 2).

In aerobic conditions, the surplus of ATP produced by S. pneumoniae D39 and R6 led to increased biomass yields (g mol⁻¹ glucose).

Table 3. Enzyme specific activities determined in late-exponential fresh cell lysates or cell-free extracts of the D39 and R6 strains grown in CDM containing 60 mM glucose under semi-aerobic (rubber-stoppered bottles) or aerobic conditions (constant air tension 40%).

| Enzyme                  | Semi-aerobic | Aerobic |
|-------------------------|--------------|---------|
|                         | D39          | R6      | D39       | R6            |
| NADH oxidase            | 1.34 ± 0.00  | 1.02 ± 0.05 | 0.99 ± 0.13 | 0.42 ± 0.01 |
| Pyruvate oxidase        | ND           | ND      | 0.04 ± 0.00 | 0.15 ± 0.00 |
| Lactate dehydrogenase   | 4.75 ± 0.24  | 3.98 ± 0.40 | ND        | ND            |

*Enzyme activities are expressed in micromoles per minute per milligram of protein and are means of at least two independent experiments. Errors are reported as ± SD. ND, not determined.

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glucose) without impacting on the maximal biomass (OD\text{Max}) achieved (Fig. 1D and Table 2). This observation suggests a redirection of ATP from biosynthesis to maintenance of cellular processes, an event that can be triggered by a stressful condition. Considering the controlled pH and the excess of nutrients present in the medium at the time of growth arrest, the most plausible candidate affecting biomass production is H\textsubscript{2}O\textsubscript{2}. In accordance, studies have shown induction of pneumococcal death by H\textsubscript{2}O\textsubscript{2} [36,45]. Moreover, the concentration of H\textsubscript{2}O\textsubscript{2} accumulated at the time-point of growth arrest (Fig. 3), about 1 mM, is in good agreement with the reported minimal inhibitory concentration (MIC) necessary to prevent growth of strain D39 [40]. Therefore, the higher maximal biomass achieved by strain D39 can be explained by the 3-fold lower H\textsubscript{2}O\textsubscript{2} to biomass ratio in this strain as compared to R6 (compare 5.7 ± 0.1 in D39 to 15.5 ± 0.1 nmol H\textsubscript{2}O\textsubscript{2} mg DW\textsuperscript{-1} in R6 at time-point 2 h). A major drawback in the aerobic metabolism of sugars by S. pneumoniae is its poor capacity to break down H\textsubscript{2}O\textsubscript{2}. Indeed, the pneumococcus does not possess the typical defence mechanisms against oxidative stress, such as catalase activity or expression of homologues of the OxyR/PerR transcriptional regulators [2–4]. However, production of H\textsubscript{2}O\textsubscript{2} in the mM range is also a competitive advantage used by S. pneumoniae to kill or inhibit other potential nasopharyngeal flora members, including H. influenzae and N. meningitides [40]. In this context, metabolic activities downstream of pyruvate in S. pneumoniae could have arisen from an evolutionary adaptation to the oxygen-rich environment of the nasopharynx, which is abundantly populated by other competitor microorganisms.

**Manipulation of the Concentration of Nutrients in Culture Medium**

Our data show that both growth and metabolic profiles of strains D39 and R6 are differently affected by oxygen. Semi-aerobiosis (50–60% initial air tension) supported the highest growth parameters (growth rate and biomass) in strain D39. Therefore, this condition was chosen for further studies.

Recently Hathaway and co-workers showed that capsule is a major difference between S. pneumoniae strain D39, serotype 2 capsule is a major virulence factor formed by repeating units of glucose, glucuronic acid and rhamnose in the proportion of 1:2:3 [46]. The precursors of these sugar monomers (UDP-glucose, UDP-glucuronic acid and dTDP-rhamnose) require UTP and dTTP for their synthesis [46]. The sugar moiety in the NDP-sugars derives from the glycolytic intermediate glucose 6-phosphate (Fig. 2). Hence, in addition to ATP generation, glucose is also used for capsule biosynthesis. In our conditions, glucose (~1% wt/vol) is apparently in excess in D39 cultivations, and thereby the nucleobases are the most promising candidates as growth-limiting nutrients. Thus, the effect of varying the nucleobases in the culture medium was assessed. To completely rule out glucose as the limiting nutrient, fermentations at a lower and a higher initial glucose concentration were also performed.

**Manipulation of the Concentration of Nutrients in Culture Medium**

Figure 3. Fermentation profiles of strains D39 and R6 under aerobic conditions. Growth curves, substrate consumption and end-products formed by the D39 (A) and R6 (B) strains growing aerobically as in Fig. 2C. Culture supernatant samples for end-product analysis by HPLC and/or 1H-NMR were harvested during growth. Symbols: (○), Glucose consumption; (■), growth curve; (◆), lactate; (▲), acetate; (●), H\textsubscript{2}O\textsubscript{2}. The error was below 7% for major products (>2 mM) and 25% for minor products (<2 mM).

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concentrations of 2.5% (wt/vol); at an external concentration of 5%, a slight decrease (about 10%) in maximal biomass was observed [47]. Thus, *S. pneumoniae* seems to be more sensitive to high glucose concentrations than the dairy *L. lactis*. A complete explanation for the different behaviours is difficult to put forward, but might relate to the environments sensed in their natural habitats; while the dairy *L. lactis* is continuously exposed to a high sugar concentration in milk (~150 mM lactose), *S. pneumoniae* thrives in the nasopharynx where free sugars, and in particular glucose (<1 mM), are low [3]. Lipid bilayers are impermeable to glucose, thus the inhibitory effect of glucose (3% wt/vol) most likely occurs in the cellular membrane. Since the growth of strains D39 and R6 was not limited or inhibited by 1% (wt/vol) of glucose, this concentration was used in subsequent studies. Furthermore, our data clearly shows that glucose is not the limiting-nutrient in pH-controlled batch cultures of strain D39.

(ii) Effect of nucleobases concentration on growth of *S. pneumoniae* D39 and R6. The nucleobases present in our CDM (Table 1) are the purines adenine, guanine and xanthine, and the pyrimidine uracil. To investigate the effect of this group of nucleobases on the growth of strains D39 and R6, their concentrations were raised simultaneously from 10 to 30 mg l⁻¹ of nucleobases (1.3 %) or (N) 3% (wt/vol) glucose, under controlled conditions of pH (6.5), temperature (37°C) and atmosphere (semi-aerobiosis), in a 2-l bioreactor. The growth rate for each culture is also indicated and the values are averages ± SD.

![Figure 4. Growth profiles of D39 and R6 at different glucose concentrations.](image)

*Figure 4. Growth profiles of D39 and R6 at different glucose concentrations.* Growth of strains D39 (A) and R6 (B) in CDM containing (●) 0.5%, (■) 1% or (○) 3% (wt/vol) glucose, under controlled conditions of pH (6.5), temperature (37°C) and atmosphere (semi-aerobiosis), in a 2-l bioreactor. The growth rate for each culture is also indicated and the values are averages ± SD. doi:10.1371/journal.pone.0058492.g004

(iii) Effect of uracil on growth and glucose fermentation in *S. pneumoniae* D39 and R6. Given the results above, we deemed important to determine if the positive effect of the nucleobases on growth of strain D39 was due to a particular base or the ensemble. Of the four nucleobases present in our CDM (Table 1), uracil is a constituent of UDP-glucose and UDP-glucuronic acid, precursors of D39 serotype 2 capsule repeating units (Fig. 2) [46]. Transporters for uracil are predicted in the genome sequence of strain D39 [4]. Thus, we hypothesized uracil to be the limiting nutrient. Thymine nucleosides are formed from uracil nucleosides in the salvage pathway of pyrimidine biosynthesis, (reviewed in [48]), and to our knowledge transporters for thymine in *Streptococcaceae* have not been described (reviewed in [48]). To test our hypothesis, strain D39 was grown in microtitre plates in CDM containing 0.25% (wt/vol) glucose (initial pH 6.5), and each nucleobase was added individually to a final concentration of 30 mg l⁻¹. Among the nucleobases tested, only an increase in uracil concentration led to improved growth of strain D39 (Fig. S2). Therefore, the effect of uracil per se was investigated. D39 was grown in static rubber-stoppered bottles in CDM containing 1% (wt/vol) glucose, without pH control (initial pH 6.5), and uracil was added to final concentrations of 40, 30, 10, 5, 3.3, 1, 0.67 and 0 mg l⁻¹. Interestingly, incrementing the final concentration of uracil in the culture medium from 0.67 mg l⁻¹ to 30 mg l⁻¹, led to an increase in maximal biomass from about 0.2 to 2.2 of ODMax (Fig. 6A). Notably, this increase was linear from 0.67 mg l⁻¹ to 10 mg l⁻¹ uracil (Fig. 6B). The maximum growth rate (approximately 0.8 h⁻¹) was not significantly affected, except for the lower concentrations of 3.3, 1 and 0.67 mg l⁻¹, which exhibited a rate of about 0.74, 0.53 and 0.48 h⁻¹, respectively. A saturation at around 30 mg l⁻¹ of uracil was found, as increasing the concentration even further, i.e. to 40 mg l⁻¹, did not improve growth (Fig. 6). Strain D39 was able to grow in uracil-free medium, as expected from genome analysis [4], and the growth
profile displayed a lag of 6 h, a growth rate of 0.42 h$^{-1}$ and 1.8 of $\text{OD}_{\text{Max}}$. In lactic acid bacteria, pyrimidine nucleobases are synthesized de novo using bicarbonate ($\text{HCO}_3^-$) or CO$_2$ and amino acids as substrates (reviewed in [48]).

In pH-controlled batch cultivations, a 3-fold increase in the concentration of uracil had a similar effect on growth ($\mu$, 0.80±0.02 h$^{-1}$ and $\text{OD}_{\text{Max}}$ of 3.2±0.1) as that produced when all the four nucleobases were 3 times increased (Fig. 5A), showing that uracil is the sole base stimulating biomass production in the capsulated strain D39. Conversely, incrementing uracil concentration had no effect on the biomass of strain R6. Strain D39 showed a 3-fold higher shift to mixed-acid fermentation in glucose-CDM containing 30 mg l$^{-1}$ uracil (Table 2). Lactate was the major end-product, accounting for 76% of the glucose consumed (Table 2), and formate (6.3±1.3 mM) was produced in a ratio of 2:1:1 relative to ethanol (2.8±1.1 mM) and acetate (3.1±0.4 mM), which is ascribed to PFL activity [11]. The pyruvate accumulated in this condition (circa 0.44 mM) was 2-fold lower than in medium containing 10 mg l$^{-1}$ uracil (Table 2). The levels of acetate accumulated by strain D39 in uracil-enriched medium were at least 2-fold higher than those accumulated in normal CDM. However, the ATP yield (mol ATP mol$^{-1}$ glucose) were similar between both conditions (circa 1.8 and 1.7 in 30 and 10 mg l$^{-1}$ uracil, respectively) and relative to strain R6 (Table 2). Our data establish a positive correlation between uracil supply and production of capsule in $S. \text{pneumoniae}$ serotype 2. Under the conditions studied, we showed that uracil is the factor limiting growth of strain D39, while the acapsular strain R6 is unresponsive to the uracil concentration in the medium. The bioenergetic parameters fully support this view.

Figure 5. Effect of nucleobases concentration on growth profiles. Growth of strains D39 (A) and R6 (B) in CDM containing 1% (wt/vol) glucose, under controlled conditions of pH (6.5), temperature (37 °C), and atmosphere (semi-aerobiosis), in a 2-l bioreactor. The nucleobases were added to the medium as follows: (■), G, A, X, U 10 mg l$^{-1}$ each; (▲), G, A, X, U 30 mg l$^{-1}$ each; (●), G, A, X 10 mg l$^{-1}$ each plus 30 mg l$^{-1}$ U. G = guanine; A = Adenine; X = Xanthine; U = Uracil. doi:10.1371/journal.pone.0058492.g005

Figure 6. Effect of varying uracil concentration on growth of strain D39. (A) Growth of strain D39 in CDM containing 1% (wt/vol) glucose with different concentrations of uracil (U), as specified below. Growth was performed at 37 °C, without pH control (initial pH 6.5), under semi-aerobic conditions. Uracil concentrations in mg l$^{-1}$: (□), 0; (▲), 0.67; (○), 1; (◇), 3.3; (▲), 5; (■), 10; (●), 30; (◇), 40. The other three nucleobases (G, X, A) were always present in the medium at a concentration of 10 mg l$^{-1}$. G = guanine; X, xanthine; A, adenine. (B) Linear correlation between the maximal D39 biomass ($\text{OD}_{\text{Max}}$) and the medium uracil concentration (from 0.67 to 10 mg l$^{-1}$).

$y = 0.1494x + 0.1182$
$R^2 = 0.9968$

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In summary, we developed a CDM and growth conditions that support high yield of strains D39 and R6. For strain D39, a better growth performance was observed in CDM (Table 1) containing 1% (wt/vol) glucose and supplemented with uracil to a final concentration of 30 mg m⁻¹, under controlled conditions of temperature (37°C), pH (6.5) and gas atmosphere (semi-aerobic, initial air tension of 50–60%). For strain R6, the best growth was observed in CDM containing 1% (wt/vol) glucose, under controlled conditions of temperature (37°C), pH (6.5) and gas atmosphere (strictly anaerobic). The optimized conditions for strain R6 were used to perform in vivo NMR studies.

**Glucose Metabolism Monitored by in vivo NMR**

The use of the in vivo NMR technique to study bacterial metabolism has been reported before [20]. However, due to the low sensitivity of this technique, dense cell suspensions are usually required. Thus, we sought to prepare dense cell suspensions of strains D39 and R6. To our disappointment, only small volumes of D39 cultures could be pelletted, which effectively prevented the preparation of dense cell suspensions (13–14 mg protein m⁻¹) required for NMR studies. In contrast, compact pellets were obtained upon centrifugation of R6 cultures. Glucose metabolism of R6 resting cells was monitored under controlled conditions of pH (6.5), temperature (37°C) and gas atmosphere (anaerobic) using the on-line NMR system developed by Neves et al. (1999) [20].

(i) **Pools of metabolites by in vivo ¹³C-NMR.** The time course for glucose consumption and product formation under anaerobic conditions is shown in Fig. 7A. The end-products of [¹³C]glucose (20 mM) metabolism were lactate (35.8±2.04 mM), acetate (2.6±0.4 mM) and glycerol (0.36±0.04 mM). As expected lactate was the major end-product accounting for 89% of the glucose consumed. Interestingly, a 2 min delay for glucose consumption was observed after the pulse of glucose, which was then consumed at a maximal rate of 0.32 μmol min⁻¹ mg⁻¹ of protein (Fig. 7A). The pool of fructose 1,6-bisphosphate (FBP) increased to a steady concentration of about 30 mM, and declined to undetectable levels at the onset of glucose exhaustion (Fig. 7A). FBP was the only glycolytic metabolite detected. The glycolytic dynamics in S. pneumoniae are considerably different from those reported for the closely related organism L. lactis (reviewed in [19]). In L. lactis, at the onset of glucose depletion the pool of FBP declines to an intermediate level, and thereafter decreases slowly to undetectable concentrations (reviewed in [19]). Moreover, in L. lactis, 3-phosphoglycerate (3-PGA) and phosphoenolpyruvate (PEP) accumulate after glucose depletion (reviewed in [19]). In the dairy bacterium, slow depletion of FBP and accumulation of 3-PGA and PEP were rationalized as resulting from progressive obstruction at the level of pyruvate kinase (PK), a glycolytic enzyme regulated at the metabolic level by FBP (activator) and inorganic phosphate (inhibitor) (reviewed in [19]). Based on the established differences between the metabolic profiles in L. lactis and S. pneumoniae, a different regulatory mechanism at the level of pyruvate kinase can be envisaged for the pathogen.

(ii) **Pools of NTP and Pi by in vivo ³¹P-NMR.** To obtain information on the energetic status of the cells, in vivo ³¹P-NMR spectra were obtained during the metabolism of glucose by resting cells of strain R6. Glucose (20 mM) was supplied at a time designated zero (0 min) and the time course for formation of NTP and total Pi is shown in Fig. 7B. Upon glucose addition, the pool of inorganic phosphate (Pi) decreased from about 60 to 2 mM, in 7 min, consistent with glycolytic usage. In accordance, this was also the time required for total consumption of glucose in the in vivo ¹³C-NMR experiment of strain R6. During glucose consumption the NTP pools reached values of about 2.2 mM, which were maintained until the time-point 10 min, and disappeared afterwards. The pool of Pi became visible well after NTP depletion (after glucose disappearance) reaching values of approximately 60 mM. The build-up of the Pi pool in S. pneumoniae differs from that in L. lactis, for which Pi accumulates soon after glucose depletion. Moreover, the NTP pools in L. lactis are 3-fold higher than in S. pneumoniae R6, and remain high beyond glucose depletion [19,20]. It should be noted that L. lactis was grown in similar conditions as S. pneumoniae [20]. The levels of NTP detected in vivo in S. pneumoniae are similar to the concentrations measured in vivo [12]. In S. pneumoniae, the dynamics of glycolytic intermediates at the onset of glucose exhaustion (Fig. 7A) could in part be explained by the delay in Pi accumulation, and thus lack of inhibition of PK. However, our own preliminary results indicate that the pneumococcal PK is less sensitive to Pi than its lactococcal homologue (data not shown). The effects of FBP and Pi on PK activity are currently under investigation in our laboratory.

**Conclusions**

A chemically defined medium and growth conditions supporting high biomass yields of S. pneumoniae strains D39 and R6 have been developed. Importantly, during this process an extensive comparative metabolic characterization between these strains under controlled conditions of pH, temperature and gas atmosphere has been accomplished. The results of these studies showed that strains D39 and R6 display a better growth performance under different environmental and nutritional conditions. In strain D39 the growth rate was stimulated under semi-aerobic conditions, whereas in strain R6 strictly anaerobic conditions rendered optimal growth. The better performance of D39 in semi-aerobic conditions was attributed to the lower activity of pyruvate oxidase and higher activity of NADH oxidase as compared to R6. Furthermore, the maximal biomass achieved by strain D39 was substantially enhanced when a supplement of uracil was added to the culture medium, whereas R6 was unresponsive to this nucleobase. Our metabolic data showed that, more than an energetic burden capsule is a cost in nutritional terms and uracil is the limiting nutrient, indicating a direct link between capsule production and the requirement for uracil. Pyrimidine nucleobases and nucleosides are often unavailable as exogenous nutrients (reviewed in [49]). However, in blood, where capsule of S. pneumoniae is an absolute requirement, uridine was detected at a homeostatic concentration of about 3–4 μmol m⁻¹ [50]. Replacement of uracil by uridine in CDM (Table 1) did not change the growth profile of strain D39 (data not shown), suggesting that these compounds are redundant. We hypothesize that uracil and/or its nucleoside derivatives may be an important signal for capsule synthesis.

The surprisingly marked physiological differences between strains D39 and R6 substantiate the view that findings in strain R6 cannot be generalized to D39, at least when growth physiology is concerned [4]. Finally, the chemically defined medium optimized in this study was suitable for the application of in vivo NMR to the study of pneumococcal sugar metabolism. We are the first to obtain time series data on concentrations of metabolite pools online and non-invasively for S. pneumoniae. Our data suggest a unique regulation of glycolysis in S. pneumoniae as compared to other Streptococci.
Materials and Methods

Bacterial Strains, Stocks Preparation and Storage

The S. pneumoniae strains used in this study were the serotype 2 D39 and its unencapsulated derivative R6 obtained from the Department of Molecular Biology of the University of Groningen. This strain D39 displays characteristics of the D39 Lilly isolate [4,28]. Long-term storage of strains D39 and R6. Permanent stock cultures (1 ml) were prepared in cryogenic vials from cells grown in M17 broth (Difco) supplemented with 0.5% (wt/vol) glucose (Glc-M17), harvested in exponential phase, and were maintained at −80°C in 25% (vol/vol) glycerol. Preparation of stocks. D39 and R6 cells scraped from the permanent frozen stocks were grown overnight (~14 h) in 5 ml Glc-M17, at 37°C and stored as 1 ml aliquots in 10% (vol/vol) glycerol at −80°C. Working stocks preparation. Strains D39 and R6 were cultured by transferring 1 ml aliquot of the frozen stock cultures into 50 ml of Glc-M17, followed by incubation at 37°C until late-exponential phase (OD600 0.8–1.0). Cultures were then centrifuged (5750 g, 7 min, 4°C), the supernatants discarded and the pellets were concentrated 2-fold in fresh M17. Aliquots of 1 ml were stored in 10% (vol/vol) glycerol at −80°C.

S. pneumoniae Growth Studies

S. pneumoniae was grown in the CDM described in Table 1 prepared in bi-distilled water (Millipore E-POD), except when stated otherwise. Growth was monitored hourly by measuring the optical density at 600 nm (OD600). Batch cultivations were initiated at an OD600 of 0.05–0.06 by the addition of a preculture (3–4% vol/vol). The precultures were prepared as follows: 1 ml working stock (D39 or R6) was used to inoculate 80 ml of CDM containing 0.25% (wt/vol) glucose and each nitrogenous base was added individually to a final concentration of 30 mg l⁻¹. Two independent experiments were performed. The error in each point of the growth curves was always below 10%.

The uracil-dependency on growth of strain D39 was assessed by cultivating cells in semi-aerobic conditions as above, except that uracil was omitted or added to the medium in the following concentrations: 0.67, 1, 3.3, 5, 10, 30 and 40 mg l⁻¹. Two independent experiments were performed at least for each growth condition. The error in each point of the growth curves was always below 10%.

Factors That Affect Growth of S. pneumoniae

Figure 7. Glucose metabolism in resting cell suspensions of S. pneumoniae R6 under anaerobic conditions monitored by in vivo NMR. (A) Kinetics of 20 mM [1,13C]glucose consumption, end-products formation and build-up of glycolytic intermediate pools by R6 resting cells as monitored in vivo by 13C-NMR (B) Time course for the concentration of NTP (▲) and total inorganic phosphate, P_i (●) monitored in vivo by 31P-NMR during glucose (20 mM) metabolism of R6 resting cells. Symbols: (●), glucose; (□), lactic acid; (○), acetate; (◇), glycerol; (△), fructose 1,6-bisphosphate.

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Batch cultivations in bioreactors with pH control. D39 and R6 strains were grown in CDM in a 24 bioreactor (Bartorius Biostar® B plus) with the pH-controlled at 6.5, and under anaerobic (argon atmosphere), semi-aerobic (initial specific air tension of 50–60%) or aerobic (continuous specific air tension of 40%) conditions. For anaerobic growth, the medium was degassed by flushing argon overnight preceding inoculation, and the headspace was continuously sparged with argon at a rate of 50 ml min⁻¹ during growth. For the semi-aerobic conditions and aerobic growth, dissolved oxygen was monitored with a polarographic oxygen electrode (Mettler-Toledo International). The electrode was calibrated to zero or 100% by bubbling sterile argon or air through the medium, respectively. The continuous specific air tension of 40% in the culture medium was maintained by automatic control of the airflow and agitation. Specific air tension consumption over time in growth under semi-aerobic conditions was registered in the MFCS/DA software (B. Braun Biotech International) coupled to the fermentation unit. Independently of the growth condition, glucose was used as carbon source at a final concentration of about 60 mM, except when the effect of glucose concentration on growth was tested. For these experiments, glucose was added to the medium at concentrations of 0.5%, 1% and 5% (wt/vol). To investigate the effect of nucleobases (Table 1) on growth, their concentrations were raised from 10 to 30 mg l⁻¹ in the culture medium. To test the effect of uracil per se on growth of strains D39 and R6 the concentration of this nucleobase was increased from 10 to 30 mg l⁻¹. The pH was kept at 6.5 by the automatic addition of 10 M NaOH, and the temperature was set to 37°C. Under anaerobic and semi-aerobic conditions culture homogenization was achieved by maintaining an agitation speed of 70 rpm. For each growth condition at least two independent experiments were performed. The error in each point of the plotted growth curves was always below 20%.

Kinetics of Oxygen Consumption

Oxygen concentration in the culture medium was calculated using the equation of Henry’s Law: X_{O2} (mol O₂ mol⁻¹ H₂O) = P_{O2}/H. The partial pressure of oxygen (P_{O2}, atm) in the culture medium was calculated by multiplying the percentage of air in the culture medium by the percentage of O₂ in an atmosphere saturated with air (20.95% (vol/vol) of O₂). The Henry’s Law constant (H) for O₂ at 37°C was 5.18 × 10⁻⁵ atm mol⁻¹ O₂ mol⁻¹ H₂O. Water concentration (mol H₂O 1⁻¹ H₂O) is 55.5 M. The oxygen consumption rate (µmol O₂ min⁻¹) from Fig. S1) was estimated from a first-order derivative of a polynomial fit of the observed O₂ consumption time series. Dry weight (DW) was used as a measure of cell mass.

Quantification of Glucose and Fermentation Products

Strains were grown in CDM supplemented with glucose, and with pH control. Culture samples (2 ml) were taken at different time-points of growth, centrifuged (16,000 × g, 2 min, 4°C), filtered (Millex-GN 0.22 µm filters) and the supernatant solutions were stored at −20°C until analysis by high performance liquid chromatography (HPLC). Substrates and end-products were quantified as before [12], in an HPLC apparatus equipped with a refractive index detector (Shodex RI-101, Showa Denko K. K.) using an HPX-87H anion exchange column (Bio-Rad Laboratories Inc.) at 60°C, with 5 mM H₂SO₄ as the elution fluid and a flow rate of 0.5 ml min⁻¹. Alternatively, quantification of metabolites in the supernatant solutions was performed by H-NMR in a Bruker AMX300 spectrometer (Bruker BioSpin GmbH). Formic acid (sodium salt) was added to the samples and used as an internal concentration standard. The ATP yield was calculated as the ratio of ATP produced to glucose consumed. The global yields of ATP were calculated from the fermentation products determined at the time-point of growth arrest assuming that all ATP was synthesized by substrate-level phosphorylation. A factor of 0.39, determined from a DW (mg ml⁻¹) versus OD₆₀₀ curve, was used to convert OD₆₀₀ into dry weight (mg biomass ml⁻¹). For the aerobic samples, hydrogen peroxide was quantified in fresh supernatant solutions as described below.

Determination of Hydrogen Peroxide (H₂O₂)

Hydrogen peroxide was determined in supernatants of cultures grown under semi-aerobic and aerobic conditions and with pH set to 6.5. Culture samples of 1 ml were harvested at different time-points of the growth curves, centrifuged (16,000 × g, 2 min, 4°C) and filtered (Millex-GN 0.22 µm filters). The Amplex® Red Hydrogen Peroxide/Peroxidase assay kit (Invitrogen) was used to quantify H₂O₂ contents below 10 µM. Determinations of H₂O₂ up to 300 µM were performed as described elsewhere [51]. Briefly, 1.25 ml of peroxide reagent (192 mM phosphate, 14.8 mM azide, 0.96 ml⁻¹ Triton X-100, 2 KU l⁻¹ horseradish peroxidase (Roche), 0.48 mM 4-aminophenazone and 9.6 mM chromotrope acid) was added to 50 µl of supernatant, mixed and allowed to stand for 5 minutes at room temperature. In the presence of H₂O₂, the chromotrope acid was converted by the peroxidase into a blue coloured compound with maximal absorbance at 600 nm. Absorbance was read at 600 nm. Water was used as the blank and standard curves were performed with fresh dilutions of a stabilized solution of 30% (wt/vol) H₂O₂. The absorbance of the samples was compared to that of the standard solutions.

Enzymatic Activities

(i) Pyruvate oxidase activity. Cell lysates and pyruvate oxidase activity were performed as described in [35] with minor modifications. Cells grown aerobically with pH control were harvested in late-exponential phase of growth (R6, OD₆₀₀ 0.16 ± 0.00; D39, OD₆₀₀ 0.29 ± 0.06), centrifuged (5750 × g, 5 min, 4°C), and the pellets washed twice in one volume of 50 mM KPO₄, pH 7.4. Cells were re-suspended in 0.1 volume of the same buffer containing 0.1% Triton X-100, and incubated for 10 min at 37°C. Reactions for determination of pyruvate oxidase activity contained 50 mM potassium phosphate (pH 6.0), 5 mM MgSO₄, 0.5 mM thiamine pyrophosphate, 0.1 mM FAD, 15 mM sodium pyruvate, 0.2 U ml⁻¹ horseradish peroxidase, 100 µM Amplex® Red Reagent (Invitrogen) and 10 µl of cell lysate. Standard curves were performed with fresh dilutions of a stabilized solution of 30% (wt/vol) H₂O₂. The assays were incubated at 37°C and the absorbance of the reaction was read in a SmartSpec™ Plus spectrophotometer (BioRad) at 563 nm every 5 min for 1 h.

(ii) NADH oxidase activity. NADH oxidase activity was determined in cells grown without pH control under semi-aerobic and aerobic conditions. Cells were harvested in late-exponential phase of growth (Fig. 1A and Fig. S1), and cells lysates prepared as above. NADH oxidase activity was assayed spectrophotometrically (Beckman DU70) at 37°C in a total volume of 1 ml containing 100 mM Tris-HCl buffer, pH 7.2, 5 mM MgCl₂, and 0.29 mM NADH. The reaction was initiated by the addition of an adequate amount of cell lysate and monitored by the decrease in absorbance at 340 nm. One unit of enzyme activity was defined as the amount of enzyme catalyzing the conversion of 1 µmol of substrate per minute under the experimental conditions used.

(iii) Lactate dehydrogenase activity. Lactate dehydrogenase (LDH) activity was determined in cells grown without pH...
control under semi-aerobic conditions. Cells were grown until late-exponential phase, centrifuged (5750 × g, 5 min, 4°C), washed with KP, 10 mM (pH 7.0) and suspended in the same buffer. The cell suspensions were disrupted in a French Press (SLM Amino Instrum., Golden Valley, MN, USA) at 36 MPa. LDH activity was assayed spectrophotometrically by NADH measurement, as described elsewhere [52], except that the temperature was kept at 37°C.

**In vivo 13C-NMR Experiments**

*S. pneumoniae* R6 cells (21) were grown under anaerobic conditions with pH control as described above, harvested in the late-exponential phase of growth (OD600 1.9, as in Fig. 1C), centrifuged (5750 × g, 7 min, 4°C), washed twice with 5 mM KP, buffer with 2% (wt/vol) choline, pH 6.5 (5750 × g, 5 min, 4°C) and suspended to a protein concentration of 13–14 mg ml⁻¹ in 50 mM KP, with 2% (wt/vol) choline, pH 6.5. Choline was added to prevent cell lysis [53–55]. In buffer containing choline, lysis was marginal during the time span of 13C-NMR experiments (30 min). The OD600 value of the suspension decreased by less than 3% in 30 min and 6.5% in 1 h, while in the absence of choline the optical density values had decreased by 40% and 85% after 30 and 60 min, respectively (Fig S5). Deuterium oxide (D2O) was added to a final concentration of 6% (vol/vol) to provide a lock signal. NMR experiments were performed using the on-line system described elsewhere, which consists of a mini-bioreactor (50 ml working volume) coupled to NMR detection with a circulating fluid of 20% (vol/vol) deuterated water. The working volume) coupled to NMR detection with a circulating fluid of 20% (vol/vol) deuterated water. NMR and 13C-NMR spectra was performed as described by Neves et al. (2002) [39], except that the temperature was kept at 37°C. The quantitative kinetic data for intracellular metabolites were monitored in vivo. At the end of the in vivo NMR experiment the cell suspension was passed through a French press: the resulting cell extract was incubated at 80–90°C (10 min) in a stopped tube, cooled down on ice and cell debris and denatured macromolecules were removed by centrifugation. The supernatant (NMR-extract) was used for quantification of end-products and minor metabolites as below. Due to the fast pulsing conditions used for acquiring 13C-spectra, correction factors for resonances due to C1 and C6 of FBP were obtained in real time non-invasively.

**Supporting Information**

**Figure S1** Kinetics of oxygen consumption of strains D39 and R6 grown under semi-aerobic conditions. Strains D39 (□) and R6 (■) were grown under semi-aerobic conditions as described elsewhere [20]. Acquisition of 31P-NMR and 13C-NMR spectra was performed as described by Neves et al. (1999) [20]. For calculation of the correction factors 13C-NMR spectra were acquired with a 60° flip angle and a recycle delay of 1.5 s (saturating conditions) or 60.5 s (relaxed conditions). Carbon and phosphorus chemical shifts are referenced to the resonance of external methanol and H3PO4 (85% vol/vol) designated at 49.3 and 0.0 ppm, respectively.

**Figure S2** Effect on growth of increasing a single nucleobase. Growth profile of strain D39 in CDM containing 0.25% (wt/vol) glucose with 30 mg l⁻¹ of the specified nucleobase. Cultures were performed in 250 ml in 96-well microtiter plates and growth monitored at 395 nm and 37°C. Symbols: (□), G, A, X, U 10 mg l⁻¹ each; (□), G, A, X 10 mg l⁻¹ each plus 30 mg l⁻¹ U; (△), G, A, U 10 mg l⁻¹ each plus 30 mg l⁻¹ X; (○), G, X, U 10 mg l⁻¹ each plus 30 mg l⁻¹ A; (■), A, X, U 10 mg l⁻¹ each plus 30 mg l⁻¹ G. G = guanine; A = adenine; X = xanthine; U = uracil.

**Figure S3** Growth profiles of D39 and R6 cultures started with precultures of different ages. (A) Growth of precultures of strains D39 (□) and R6 (■) in CDM containing 60 mM glucose, without pH control (initial pH 6.5), at 37°C, under semi-aerobic conditions. Growth of strain R6 in CDM containing 60 mM glucose, under controlled conditions of pH (6.5), temperature (37°C) and atmosphere (anaerobiosis), in a 24-bioreactor. Symbols: (○), inoculation with a preculture in late-exponential phase (LExp, 6–7 hours of incubation at 37°C, OD600=0.8–1.0); (□), inoculation with a preculture in early-stationary phase (EStat, 8–9 hours of incubation at 37°C, OD600=1.4–1.6); (△), inoculation with a preculture in late-stationary phase (LStat, 18 hours of incubation at 37°C, OD600=1).
of strains D39 (□) and R6 (■) in CDM containing 60 mM glucose, without pH control (initial pH of 6.5), at 37°C, under aerobic conditions. The arrows indicate the time-points at which cells were harvested for measurement of NADH oxidase activities. The growth rate for each culture is also indicated and the values are averages ± SD. (TIF)

**Figure S5 Pneumococcal lysis in resting cell suspensions.** Optical density variation during glucose (20 mM) metabolism of resting cells of strain R6, grown as in vivo.

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**Author Contributions**

Conceived and designed the experiments: SMC ARN. Performed the experiments: SMC. Analyzed the data: SMC OPK ARN. Contributed reagents/materials/analysis tools: OPK ARN. Wrote the paper: SMC OPK ARN.

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