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Original Research Article

Identifying the gaps in human and veterinary chlamydia vaccine development

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ABSTRACT

Background: Chlamydia infections in humans and animals pose a significant burden on health systems worldwide. While widespread screening, adequate treatment, and prevention programs are helpful to increase awareness and improve screening rates, infection rates are rising. A vaccine is necessary to slow increasing rates, manage negative consequences, and prevent possible antibiotic resistance. We present the current landscape regarding the innovations for commercial vaccine development in a “one-health” context.

Methods: We developed a unique dataset containing data of patent documents intended for human and veterinary use, and clinical trials in order to provide a detailed description of the global chlamydia vaccine developments.

Results: Analysis of patents and clinical trials intended for human use presented a vaccine field that is underdeveloped, with no commercial human chlamydia vaccine available, and two potential candidates in a phase 1 clinical trial. Comparing innovations concerning chlamydia vaccine developments for both human and veterinary patents, it was clear that these fields are very different and independent of each other. The field is small, and certain companies and researchers show repeated interest. Partnerships among applicants and those involved in chlamydia vaccine innovation would be an important step to take towards innovating and developing an effective vaccine.

Conclusions: We have shown that North America is considered, by patent application, to hold the most potential for a chlamydia vaccine, specifically against the *Chlamydia trachomatis* strain. A new vaccine is likely to be a subunit vaccine with components of the major outer membrane protein antigen.

Keywords: Chlamydia infections, Chlamydia vaccine development, Patents, Clinical trials

INTRODUCTION

Chlamydia trachomatis is the most common sexually transmitted bacterial infection (STI) in the world.¹ Being a gram-negative, obligate intracellular parasitic pathogen, three out of the nine existing strains infect humans (*C. trachomatis*, *C. pneumoniae*, and *C. psittaci*), of which *C. trachomatis* is the most prominent. With a global prevalence of 4.2% in women and 2.7% in men, *C. trachomatis* infections have tremendous health and societal impact.² With the bacterial STI being largely asymptomatic 70-90% of woman and 30-50% of men never display acute symptoms. However, infections can lead to substantial health damage before they are first

noticed. Especially women are unaware of their status, so a statement of global rates is likely to be an underestimation.³ The high and increasing infection rates of *C. trachomatis* are accompanied by increasing costs to both health systems and individuals. Previous cost-analysis studies have shown that the total direct lifetime cost of chlamydia is around half a billion US dollars in all those diagnosed and seeking treatment, representing about one-third of the \$15.6 billion global direct lifetime cost spent on all STIs.¹ Though widespread screening, adequate treatment, and various prevention programs have been helpful in increasing awareness and improving screening rates for chlamydia, these methods have not yet been able to reverse the rising trend of infections. Over

the years, rates of reported infections have increased almost tenfold, from 35 cases per 100,000 in 1986, to 332 per 100,000 in 2005.⁴ These numbers clearly show that something must be done to slow or ideally stop the growing rates, manage negative consequences, and prevent possible antibiotic resistance.

While persistence of the chlamydia bacterium has already been documented antibiotic resistance has not yet emerged in the pathogenesis of *C. trachomatis* to humans, but research does suggest that resistant phenotypes may arise in the future, especially with steadily increasing rates of infection.^{5,6}

In order to stop rising infection rates of a largely asymptomatic infection, and to control the potential of antibiotic resistance, vaccine development is essential.^{7,8} Indeed, the WHO, UNICEF and GAVI have identified *C. trachomatis* as one of four STIs with the greatest potential for the vaccine market.^{1,4,5} Computer modelling and prediction analysis showed that even a partially protective vaccine in a sub-optimal vaccination program would decrease infections, morbidity, and associated costs of the disease, and a fully protective vaccine has the potential to eradicate chlamydia within 20 years.^{1,9}

The need for a *C. trachomatis* vaccine has long been recognized but unsuccessful human trials, of a whole-cell vaccine in the 1960s, caused a pause in the research field for many years.³ Over the last decades vaccine innovations for men were unsuccessful in contrast to flourishing veterinary vaccine innovations. Currently there are multiple commercially available veterinary vaccines against certain veterinary strains of chlamydia. While veterinary vaccines have different characteristics and developmental requirements than human vaccines, such developments suggest that the production of a human vaccine is possible.¹⁰

To ensure a well-facilitated development process, a clearly defined market is considered crucial.¹¹ However, to date there is no clear understanding of where innovators perceive the largest market opportunities to lie.¹² Moreover, lack of a clear overview of vaccines and technologies in development hampers new innovators to join in a concerted effort to realize solutions to public health unmet needs.

The main objective of this study is therefore to present an overview of the current state of chlamydia vaccine development by constructing and analyzing a dataset containing data from patent documents, literature and clinical trials. Patent analysis as a tool is used to assess markets, can inform manufacturers of their abilities to participate in vaccine markets and elucidates concerns surrounding new patent claims.^{13,14}

This study provides an overview of the development of a human chlamydia vaccine over the past 20 years and an overview of the involvement of different stakeholders

(science, industry and government) in the vaccine development process.

METHODS

A comprehensive overview of chlamydia innovation efforts was obtained by studying patents and patent applications. Patent applications are measures of output of early-stage research. Most inventions in the pharmaceutical sector are covered by patents as they are the only way of offering solid intellectual property protection of new pharmaceutical compounds.¹⁵ Clinical trials represent late-stage drug development that all new inventions must pass before market entry, which make clinical trials a reliable indicator of the short-term market entry. However, a significant share of inventions disclosed in patents will not enter clinical testing due to disappointing research results, or due to strategic reasons.¹⁶ By combining patent data for insight into the medium to long-term interventions and clinical trial data for insight into the short-term market entry this study provides an overview of the process of vaccine development for chlamydia diseases.

Patents

Data collection and selection

The purpose of the patent analysis was to assess the trends and advances in chlamydia vaccine development in the last twenty years (1999-2019) in order to identify technologies and market changes that are supportive to the advancements in the field.

Data for the patent analysis were taken from the European Patent Office (EPO) Espacenet database, containing over 90 million patents and widely considered a comprehensive database.¹⁷ Data were extracted under the guidance of an expert from the Dutch (governmental) Patent Office (Dutch RVO). Search criteria were developed using the cooperative patent classification (CPC) system, a bilateral system developed together by the EPO and the United States Patent and Trademark Office (USPTO), combining classification terms used by both offices. Using the CPC system as a search tool, all technological fields related to chlamydia vaccine development could be identified and used to search relevant patents.

CPC codes were combined with specific search terms determined via expert guidance and initial database scoping. Based on the information desired, CPC code sets were chosen to find patents for two data sets - human vaccines and veterinary vaccines. After choosing relevant and comprehensive CPC codes, the advanced search option was used to combine codes with keywords retrieved from the literature to narrow our search. These were paired to codes through the use of Boolean operators, as visualized in Table 1.

Table 1: CPC codes and keyword combinations.

Human	Results	Animal	Results
A61K39/118 + chlamyd* + vaccin*/immun*	224	A61K2039/552 + chlamyd* + vaccin*/immun*	6
Chlamyd* + vaccin*/immun*	455	Y10S424 + chalmyd* + vaccin*/immun*	6
A61K39/00 + chlamyd* + vaccin*/immun*	176	C07K14/295 + chlamyd* + vaccin*/immun* + NOT human	152
C07K14/295 + chlamyd* + vaccin*/immun*	168	-	-
Total	1024	Total	404
Total after deduplication	484	Total after deduplication	359
Total animal + human	843	-	-
Total after deduplication	546	-	-
Total after all exclusion criteria applied	189	-	-

Data were exported as one comprehensive group to Microsoft Excel for deduplication and primary analysis. After deduplication and condensing based on priority numbers, 546 patents remained. Further exclusion criteria included exclusion of patents containing the words: “immunoassay”, “diagnosis”, “detection”, “treatment” in the title or abstract without also including “prevention”; exclusion of patents referring to *Chlamydomonas*, which is a genus of green algae; and exclusion of patents filed more than 20 years ago. Applying exclusion criteria resulted in 242 patents to analyze. Finally, after all remaining patents were imported into Atlas TI to be qualitatively analyzed, full text analysis of the patents led to a final exclusion of 53 additional patents and a final list of 189 patents for analysis.

The final list of 189 patents was further analyzed to visualize time and geographical trends. In line with criteria for assessing quantity over quality¹⁵, we also looked into high quality patents, here defined as being cited more times.

Through qualitative analysis of the patent text in Atlas TI, patents were placed in one of two categories: for veterinary use or for human use, based on the strain of chlamydia referred to and whether the patent text stated humans or animals to be the intended recipient of the innovation. Patents that mentioned both target groups were considered as human use.

Subjecting the primary patent documents to a full text analysis, factors including bacterial strain, technological innovation, and applicant type (e.g. academia, individuals, government or company) were identified. Applicants mentioned as inventors were classified as such, and when mentioned in combination with the institutions they were classified as type of the institution.

Specifically, for the timeline depictions a subset of data was created by excluding patents published in 2019 and 2018 since due to an 18-month delay that occurs between

patent filing and publication date this subset could not be considered complete. This resulted in excluding 10 patents for this analysis and a final count of 179 patents, of which 34 patents were intended for veterinary use, and 145 patents intended for human use.

Starting from the priority documents, kind codes from all published patent documents in the same family were analyzed to identify the geographical territories in which patent protection was applied for per invention. Countries were then categorized based on the region they belonged to, resulting in the total number of applied and granted patents for the following regions: USA, Canada, South America, Europe, Ukraine and Turkey, Africa, Middle East, Russia and Oceania. In addition, patents applied for at the EPO, the WIPO, or Eurasian patent applications were listed separately.

Clinical trial analysis

To gain a full picture of the current market of human chlamydia vaccines, a clinical trial analysis was conducted to reveal relevant vaccines that may soon reach the market. The WHO’s International Clinical Trial’s Registry Platform (ICTRP) database and the U.S. National Library of Medicine’s (NLM) database were used to search clinical trials. While the ICTRP database shows active clinical trials, the NLM’s database allows the search of completed clinical trials, painting a full picture of the research field. Two search queries were used, ‘chlamydia vaccine,’ and ‘chlamydia’, which, after excluding all trials not related to chlamydia vaccinology, resulted in a total of three human clinical trials to be assessed.

RESULTS

Patent analysis overview

From the 189 patents that were imported from Espacenet and analyzed in Excel and Atlas TI, 179 were used for

timelines to visualize trends in patent publication in the period 1999- 2017. The patent publication timeline (Figure 1) shows that the number of new patents for both

human and veterinary patents remains fairly constant, although more patents are applied for human than for veterinary purposes.

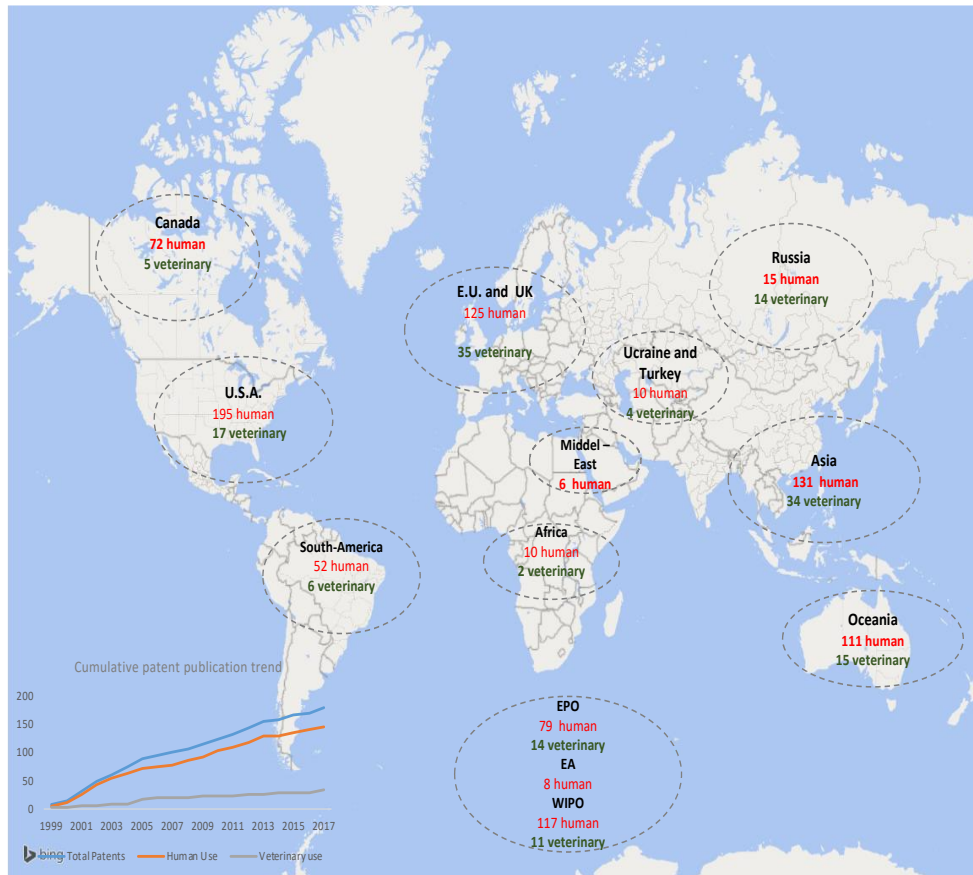


Figure 1: The US, Asia and Europe were considered most interesting ‘geographical’ territories for filing patent applications. Both human and veterinary patents show a modest but steady incline in number.

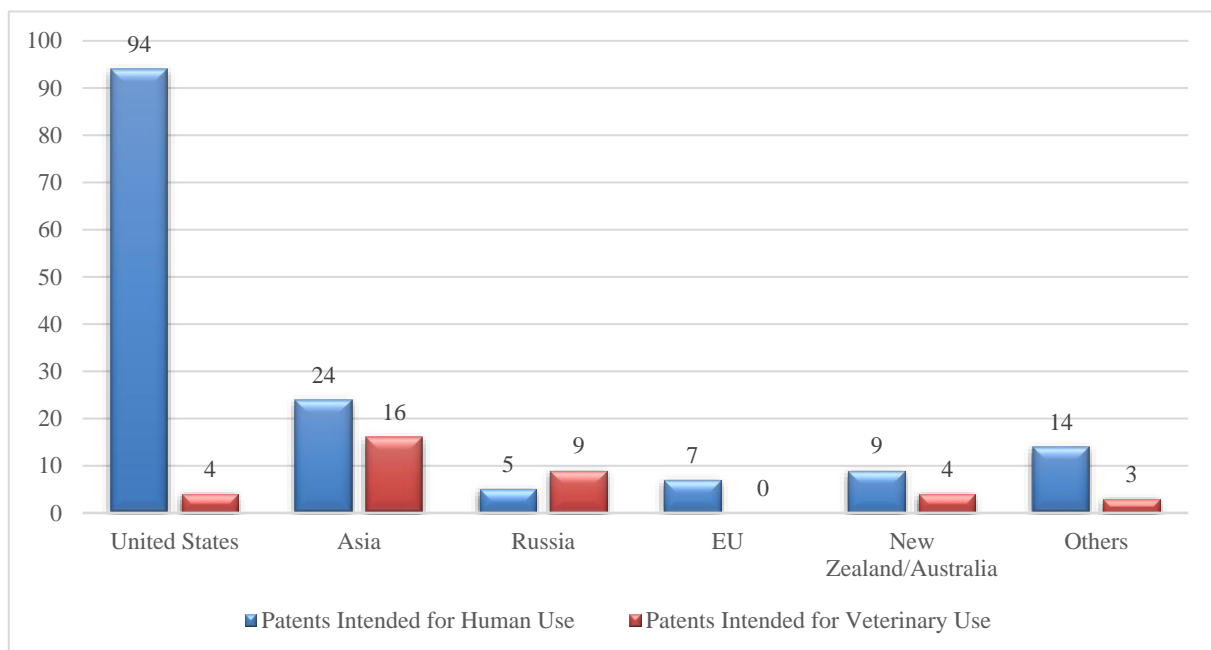


Figure 2: The US outperforms applicants from other regions by a factor 3 in patent applications. Patent applicants are shown per region or country (for total data set; 189 patents).

Between 1999 and 2017 most patents were applied for in the US, followed by Asia and Europe.

Applicants

The most patents were applied for by US applicants, followed by Asian and Russian applicants (Figure 2). These results suggest that North America is the most important player in new research towards the development of a chlamydia vaccine.

Further analysis of the patent applicants identified the institutes, companies and individuals that applied for the patents. After companies, academia claimed the next greatest number of patent applications, followed by individual inventors (Figure 3).

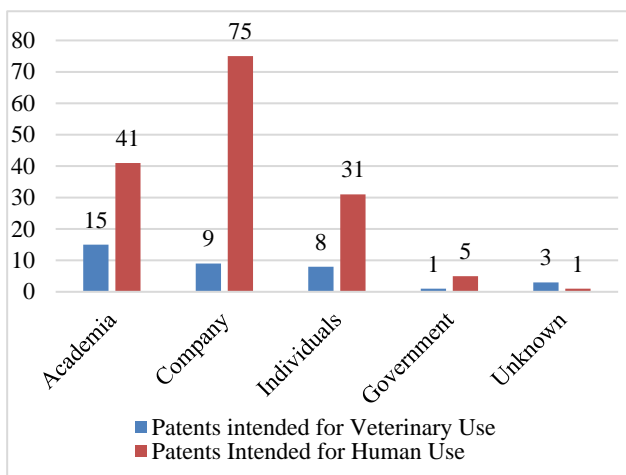


Figure 3: Companies form the largest group of applicants followed by academia. Patent applicants are shown per different applicant group (for total data set; 189 patents).

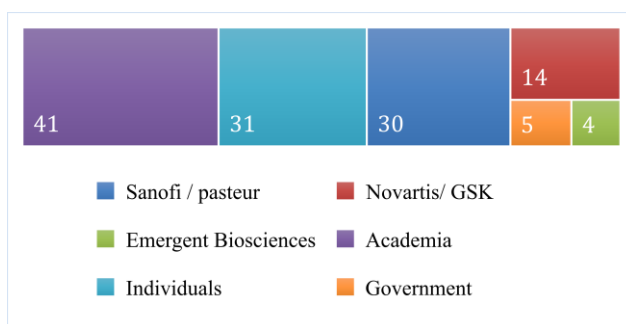


Figure 4: Sanofi and Novartis/GSK are the major companies filing one third of patents for human use followed by academia and individuals.

Major companies filed roughly one third of the total number of patents intended for human use, with Sanofi Pasteur owning the largest number of 30 patents, followed by Novartis/GlaxoSmithKline (GSK) owning 14 patents and Emergent Biosciences with 5 patents (Figure 4).

The qualitative analysis of patent content divided the patent documents into groups based on the strain of chlamydia they focused on (Figure 5). While a number of patent documents cited being pertinent to multiple chlamydia strains, the majority of patent documents intended for human use were only applicable to one of the two most relevant human strains: *C. pneumoniae* and *C. trachomatis*.

Patent applications specifically for *C. trachomatis* strain vaccines (Figure 5A) are the leading strain over the years, while patent applications for *C. pneumoniae* have slowed down. Since 2014, there have been no new applications for patents specifically intended for this strain.

Between 2001-2002 and 2004-2005 there was a small increase visible in patent filings intended for human use, applied for by Sanofi. Further analysis on these patents identified that primary scientists, with known collaborations to specific industry partners, have been prolific in these periods. The group of Murdin, in some instances collaborating with Sanofi, filed 22 patents in these periods and the group of Ratti, in some instances collaborating with Novartis, applied for 2 patents. An additional notable increase occurs in 2013, but very few of these patents are related to each other through inventors or applicants, suggesting distinct research efforts.

Of these two particular groups of scientists the group of Murdin, filed in total 42 patents in the field between the years of 2000 and 2010, 27 of which in partnership with Sanofi Pasteur. The other group of applicants being the group of Ratti, was found to hold 9 similar patents between 2001 and 2005, in partnership with GSK. No recorded intentions of vaccine trials based on these patents were found.

Of the 36 patent documents intended for veterinary use, the most common strains were *C. psittaci* and *C. felis*. (Figure 5B). In recent years, interest in patents for veterinary use declined significantly. Patent applications for *C. abortus* and *C. trachomatis* showed relatively large increases, though these were still small in absolute size.

Technology

Further qualitative analysis categorized technological features and vaccine components described in the patent documents. Most patent documents that were intended for human use described subunit vaccines (70 patents) and an additional 19 patent documents described subunit vaccines that made use of the major outer membrane protein (MOMP) antigen (Figure 6A). Only 2 patents referred to whole-cell vaccines, none of which were filed after 2005. Within the category ‘other’, we found patent documents using recombinant, chimeric and other vaccine preparation techniques. Only four patents were filed for adjuvants specific for a chlamydia vaccine for human use.

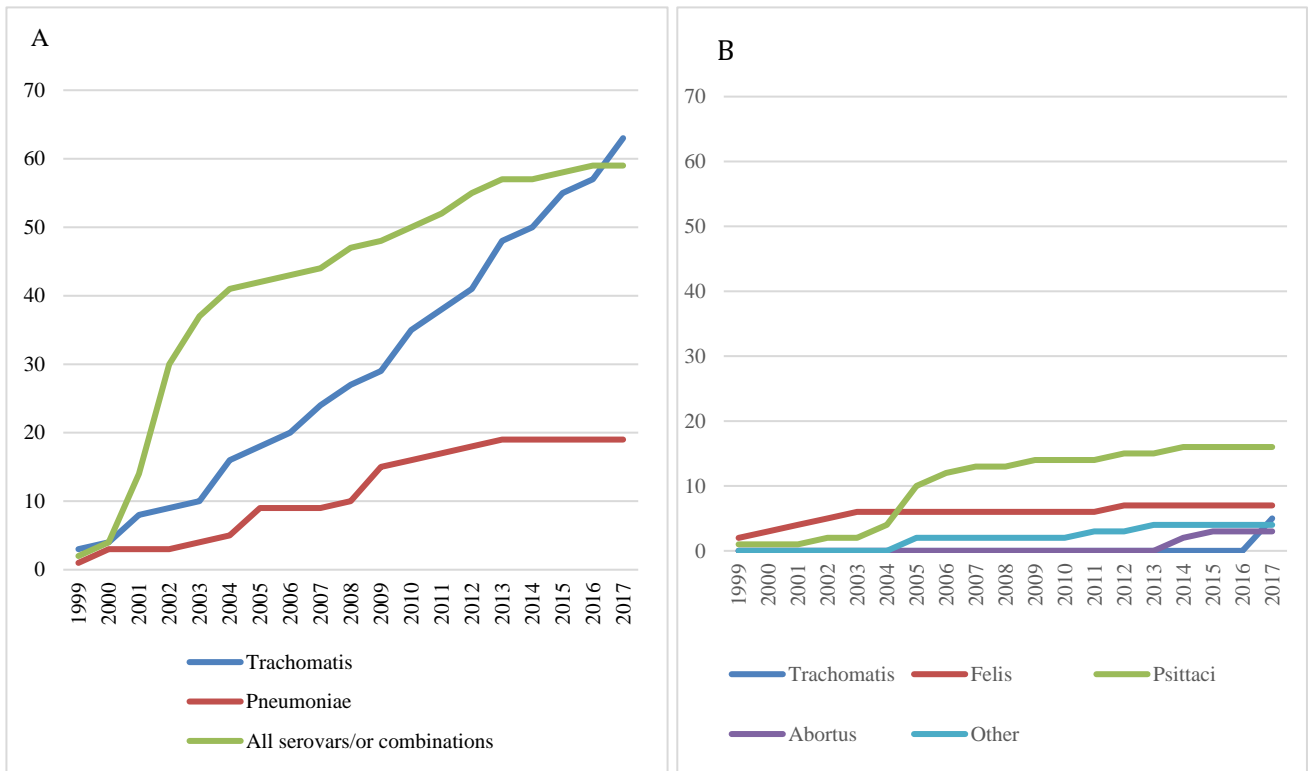


Figure 5: Most relevant strain in human patents is (A) *C. trachomatis* and for veterinary patents; (B) *C. psittaci* shown as cumulative publication trends for human and veterinary strains.

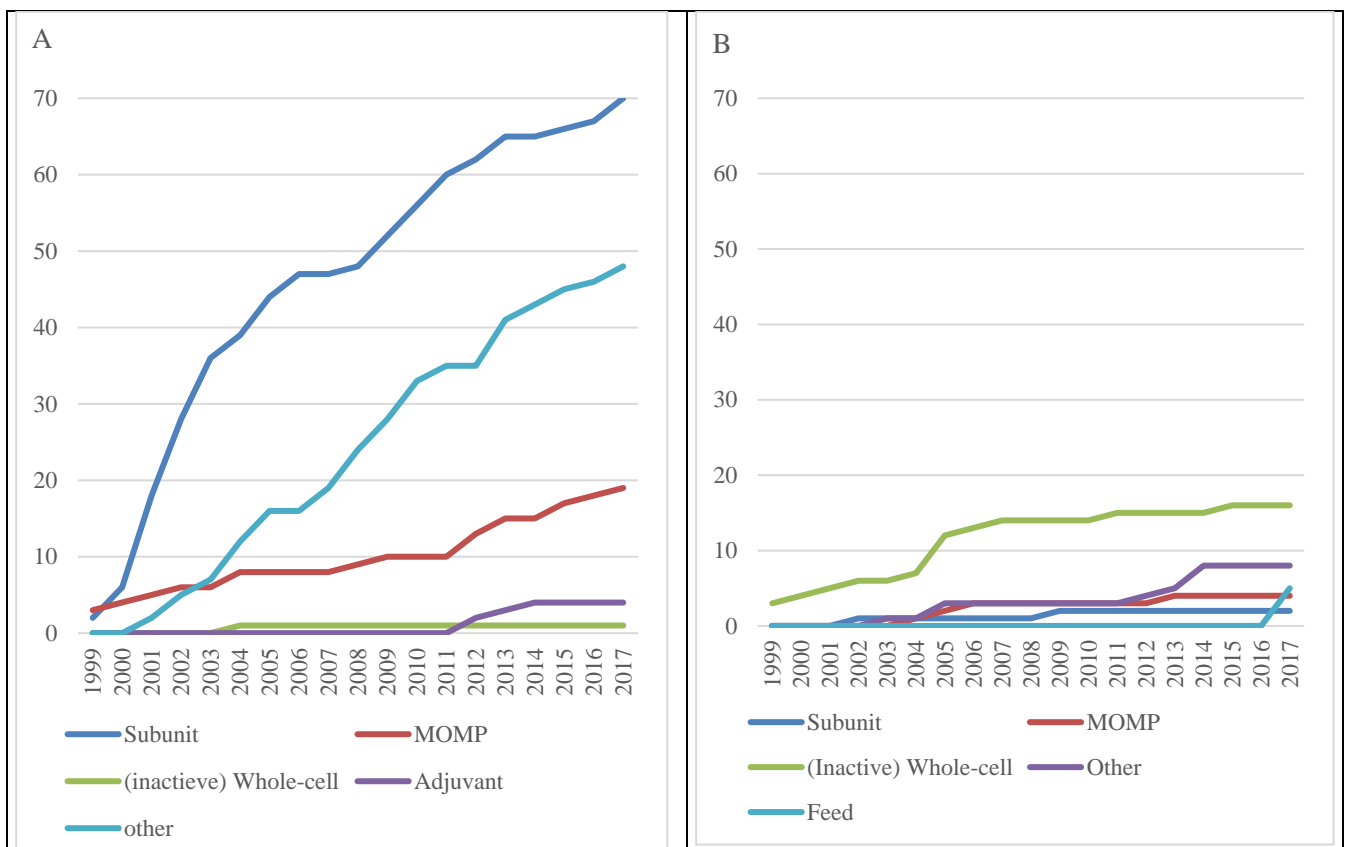


Figure 5 (A and B): Subunit and MOMP vaccines are the most prevalent technologies in patents for human use. In patents for veterinary most used technology is the (inactive) whole-cell. Most relevant technologies are shown in cumulative publication trends.

Table 2: Overview clinical trials in human.

Name of trial	Dates of activity	Sponsor	Collaborator	Status
Safety of chlamydia vaccine CTH522 in healthy women aged 18 to 45 years {NCT02787109} patent; Application DK2014000015W·2014-03-17 Publication WO2014146663A1·2014-09-25	July 2016 – July 31, 2017	Statens Serum Institute	Imperial College London	Reported in August 2019 (Phase1) ¹⁸
Safety and immunogenicity of a chlamydia vaccine CTH522 {NCT03926728}	September 2019 – December 2020	Statens Serum Institute	Imperial College London	Unknow
C. trachomatis immunology and vaccinology study {NCT01150747}	June 2010 – December 2015	Harold Weisenfeld, University of Pittsburgh	National Institute of Allergy and Infectious Disease	Completed ¹⁹

In the patent documents intended for veterinary use only 1 patent document from 2006 describes the use of a live antigen. Nearly half of all veterinary patent documents described the use of inactivated, whole-cell vaccines (Figure 6B).

Breakthroughs in patents

Two patents were cited more than 50 times. The first patent described a genomic sequence of *C. pneumoniae*, granted in 1999, and was cited in other patents 207 times since then. The other patent is for a MOMP vaccine, applied for by the US Department of Health in 1999.

Human clinical trials

Only three clinical trials were found for analysis. Two of the three trials focused on the same vaccine candidate and took place in the UK (Table 2). These trials made use of inventions described in patent documents applied for by the Statens Serum Institute, who is also the sponsor of the trials.

The third clinical trial was intended to determine the protective T cell response to incidental trachoma infections, so as to understand how the body deals with incidental infection, and how the body may respond upon secondary infection. This clinical trial took place in the US.

DISCUSSION

This study presents an overview of the current state of the global chlamydia vaccine developments. By comparing inventions for chlamydia vaccines for both human and veterinary indications, we demonstrate the difference between and independence of both fields. The extensive patenting in the US points to this territory as most interesting for the development of a human chlamydia vaccine, specifically for the *C. trachomatis* strain. We

conclude that chlamydia research is prolific but has to date been incapable of solving a significant unmet medical need. Recent breakthrough progressions, however, enabled by public-private partnerships, show promise for the future.

Chlamydia infections have been epidemic since the early 80's.²⁰ Despite the many efforts to lower the rate of (re)infections through e.g. early detection, treatment and prevention for repeat infections, *C. trachomatis* infections are rising.²¹ The ongoing unmet need and 'mounting pressure' to develop chlamydia vaccines is visible in the patent landscape and is especially reflected in patenting activity for interventions in humans.²²

This study found clear technical and clinical differences between innovation efforts in the human and veterinary field. For humans, the early days developed whole-cell vaccines with poor potential to enhance immune response or even resulted in disease enhancement, led to abandonment of this path.²⁰ In contrast, nowadays the veterinary field is still depending on this technology which is in line with earlier findings.^{6,23}

Although the global burden for humans infections of *C. trachomatis* and *C. pneumoniae* has not been well defined, 68 million chlamydia infections are estimated to occur globally each year.^{1,24} Our data show that half of the human patent documents are intended for the development of vaccines for *C. trachomatis* and for *C. pneumoniae* as attempt to solve the growing unmet need. Of the six chlamydial strains that are associated with high morbidities in animals we show that half of all veterinary patents are intended for the prevention of *C. psittaci* and *C. felis*. This difference in focus on different strains suggests no connection between the two fields. Some of these animal pathogens however have been recognized as zoonotic agents and the presence of animal *C. pneumoniae* genotypes in humans suggest a potential cross-species transmission to humans. One of the other genotypes, *C. psittaci*, is an important causative agent of

widespread zoonotic psittacosis or parrot fever.²⁵ Unmet needs will further extend when the veterinary chlamydia strains become a more global health problem in case of zoonoses and antibiotic resistance.

We show here that the US represents the country with the most patent applications for human use applied by academia and individual scientist, some in cooperation with the industry (SANOFI/Pasteur and GSK). All this indicates a high interest or high sense of urgency to solve the unmet need in the US.²¹ In contrast, most veterinary vaccines are applied for by Chinese and Russian applicants. This interest by Chinese applicants can be explained by the economic burden that veterinary chlamydia serovars pose on Chinese livestock. In contrast to Western countries, China often uses herbal medicine as prophylaxis or in conjunction with antibiotic treatment which is less likely to be accepted in the global market.^{26,27}

Looking at institutional background, the majority of applicants on veterinary patents are academic, indicating the existence of barriers hampering the realization and transition of an innovation into clinical and business development.²⁸

Overcoming these barrier will become of more interest if and when the zoonotic potential of different chlamydia strains is revealed, as was the case for avian *C. psittaci*.^{25,29} When it comes to preventing the widespread issue of antibiotic resistance, both possible and expected with the chlamydia bacterium, innovations in the veterinary domain are going to be highly relevant.^{26,27}

In contrast to the dominance of academia in patents for veterinary use, a large majority of patents for human use are filed by major pharmaceutical companies, especially ones known for the production of successful vaccines, namely Sanofi Pasteur and GSK. This supports the perceived commercial relevance of human veterinary vaccines.³⁰ Interestingly, the group of Murdin, affiliated with Sanofi Pasteur, is the applicant of the majority of patents intended for human use. With 42 patents in total, pertaining to *C. trachomatis*, *C. pneumoniae*, and to multiple strains, the group's presence demonstrates their leadership in the field. Additionally, their affiliation with Sanofi Pasteur underlines the importance of Sanofi Pasteur as an investor in the field. A second group of researchers surrounding Guilio and affiliated with GSK, also holds a large number of patents, again for both human *C. pneumoniae* and *C. trachomatis* strains. This ownership indicates the similar interest of GSK in the field. Considering these patents have been filed more recently, it is of interest to see whether these inventions will translate in new medical interventions that are to be tested in clinical trials in the coming years.

Over time, inventions on the two most important strains for human use, *C. trachomatis* and *C. pneumoniae*, have increased in number. The timelines overview in figure 5A however shows a plateau has been reached in the

innovation-curve for *C. pneumoniae* suggesting saturation or declining interest in contrast to the *C. trachomatis* research.^{31,32} Even though the high global antibody prevalence for *C. pneumoniae* is increasing proportionately and known to be associated with the onset of reactive arthritis and asthma.²⁵

Up to now a large number of preclinical chlamydia vaccine trials have taken place in mouse and non-human primate model systems.²² Recent progress in clinical development has been booked by a public-private partnership, although the first human clinical trials are still in phase I, suggesting a successful step in vaccine development. Interestingly, despite active patenting activity in the US, this clinical trial was conducted in Europe.¹⁸ The patents underlying the medical intervention were filed in different territories, including the US, Japan and China, supporting the global nature of this unmet need. Based on our analysis we conclude that this public-private partnership has been instrumental in establishing breakthrough progression; the Staten Serum Inst. working together with Imperial College London for the first human clinical trial in 2018.

The gap in the human chlamydia vaccine development process compared to veterinary vaccine development leads to the assumption that in human chlamydia vaccine development different barriers play a role limiting the innovation. One significant barrier was to generate an immune mechanism of protection against mucosal infections.³³ After the sequence of *C. pneumoniae* and the sequence for the MOMP vaccine were described in two – highly cited – patents, a large number of patent documents described subunit-vaccine technology including the MOMP technology solving the barrier of the induction of an immune reaction.³⁴ Being one of the first antigen molecules described, the MOMP subunit has been the subject of many innovation efforts.³⁵ More recent patenting developments primarily focus on subunit vaccines and may use MOMP immunogenic technology, even though vaccination attempts with MOMP subunits have delivered variable results.³⁴

Currently, there is debate in the academic literature whether it would be feasible to develop one vaccine that targets multiple serovars.³⁶ Since the MOMP technique is used to differentiate the chlamydia serovars, there are two specific serovars of interest in *C. trachomatis* for the development of a cross-serovar vaccine. The first causes genital chlamydia infection, and the second ocular infection, trachoma but are similar in pathology and affecting the immune system.³⁷⁻³⁹

An effective human chlamydial vaccine would have public health benefits in both HICs and LMICs. The greatest benefits will be in LMIC settings, where lack of medical infrastructure and resources preclude chlamydia screening programs and the disease burden is high.²⁴ Public-private partnerships with NGOs will be vital in introducing a vaccine that will be successful in reducing disease burden and preventing trachoma-related blindness

in LMICs. Especially because of the 10 patents applications for the region Africa, we suggest that partnerships should focus on the development of a vaccine that is applicable to both serovars preventing genital and ocular infections.

For the interpretation of the findings of this study several limitations need be taken into account. First, patent documents were retrieved from Espacenet by the use of a choice of several different CPC codes related to the development of a chlamydia vaccine. As patent applications only become public 18 months after filing our results don't contain the most recent patents documents next to the choice to put patents in two different patent groups, only for human or veterinary use. The design of a search query could have resulted in the inclusion- or exclusion of important data or non-relevant data, this was addressed by conducting full text analysis on all patents. To minimize the degree of affecting our data collection, we verified the search criteria with experts at the NVO patent offices and the ICTRP database and used both free search terms and CPC codes.

Looking from the perspective of the vaccine innovation cycle we show extensive efforts of solving the barriers for the chlamydia vaccine development.^{14,40} In the last 70 years medical unmet needs are prioritised extensively.²² Until recently the most difficult barrier to overcome was the lack of knowledge on the immune mechanism in response to infection with the chlamydia bacteria.²² Recent tools concerning the construction of the vaccine antigen and discovery of the double vaccination route, have led to a better understanding of the mechanism of immune system overcoming the barrier of transition into clinical and business development.^{6,10,33}

Overall, this study shows the underdeveloped chlamydia vaccine market, with no present commercially available vaccine for human use with recently one potential vaccine candidate for a *C. trachomatis* vaccine in stage 1 clinical trials.

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