



HAL
open science

Cancer and mosquitoes – An unsuspected close connection

Audrey Arnal, Benjamin Roche, Louis-Clément Gouagna, Antoine M Dujon, Beata Ujvari, Vincent Corbel, Franck Remoue, Anne Poinsignon, Julien Pompon, Mathieu Giraudeau, et al.

► **To cite this version:**

Audrey Arnal, Benjamin Roche, Louis-Clément Gouagna, Antoine M Dujon, Beata Ujvari, et al.. Cancer and mosquitoes – An unsuspected close connection. Science of the Total Environment, 2020, 743, pp.140631. 10.1016/j.scitotenv.2020.140631 . hal-02959074

HAL Id: hal-02959074

<https://hal.umontpellier.fr/hal-02959074>

Submitted on 22 Aug 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

Title

Cancer and mosquitoes – an unsuspected close connection

Authors

Audrey Arnal¹, Benjamin Roche^{1,2,3,4,5}, Louis-Clément Gouagna¹, Antoine Dujon^{2,6}, Beata Ujvari⁶, Vincent Corbel¹, Franck Remoue¹, Anne Poinson¹, Julien Pompon¹, Mathieu Giraudeau^{1,2,5}, Frédéric Simard^{1,5}, Dorothée Missé^{1,2}, Thierry Lefèvre^{1,5,7}, Frédéric Thomas^{1,2,5}

¹MIVEGEC, IRD, CNRS, Université Montpellier, Montpellier, France.

²Centre for Ecological and Evolutionary Research on Cancer (CREEC), Montpellier, France.

³IRD, Sorbonne Université, UMMISCO, F-93143, Bondy, France.

⁴Departamento de Etología, Fauna Silvestre y Animales de Laboratorio, Facultad de Medicina Veterinaria y Zootecnia, Universidad Nacional Autónoma de México (UNAM), Ciudad de México, México.

⁵Centre de Recherche en Écologie et Évolution de la Santé (CREES), Montpellier, France.

⁶School of Life and Environmental Sciences, Centre for Integrative Ecology, Deakin University, Waurn Ponds, VIC, Australia.

⁷Institut de Recherche en Sciences de la Santé, Bobo-Dioulasso, Burkina Faso.

* Corresponding author: au.arnal@gmail.com

1 **Introduction**

2 Cancer is a major public health problem, with an estimated 18.1 million new cases and 9.6
3 million deaths in 2018 (Bray et al., 2018). Moreover, high population growth, aging, and
4 increased exposure to pollutants are causing a rapid worldwide increase in cancer incidence
5 and mortality in countries with different levels of economic wealth (Bray et al., 2018; Torre et
6 al., 2015). The predicted burden is so high that cancer is thought to be the only important
7 obstacle to an increase of life expectancy during the 21st century (Torre et al., 2015), and it is
8 expected to become the leading cause of death worldwide.

9 Meanwhile, mosquitoes represent a global public health problem because they act as
10 vectors for viruses, bacteria and protozoa (Mehlhorn et al., 2012), including, among others,
11 agents of malaria, filariasis, encephalitis, yellow fever, dengue, West Nile fever, chikungunya,
12 and, more recently, Zika. Mosquito-borne infectious diseases cause significant morbidity and
13 mortality worldwide, with more than 700 million people infected and more than a million
14 deaths annually (Caraballo and King, 2014). They represent a growing problem, with
15 mosquito invasions occurring throughout the world and affecting every continent but
16 Antarctica (Masterson, 2019).

17 Regarding the dramatic global impacts of these two concerns for humans, it is crucial to
18 investigate whether they have a reciprocal connection. Indeed, cancers and mosquito-borne
19 pathogens are both globally distributed, therefore affecting the same populations and can co-
20 occur within the same individuals. Knowing whether there is a connection between cancers
21 and mosquito-borne pathogens could also be helpful not only for forecasting the net impact of
22 the different control strategies on human health, but also for envisioning integrative strategies
23 targeting the two problems at the same time. Unfortunately, very few studies (Benelli et al.,
24 2016) have examined the link between these two threats, and the existing ones have generally

25 focused only on the transmission of oncogenic pathogens through mosquitoes (Marcondes and
26 Benelli, 2019; Ward et al., 2016).

27 In this review, we provide an overview of the possible links between mosquitoes and
28 cancer. To do so, we focus on (i) the impact of mosquitoes on carcinogenesis in humans, (ii)
29 the impact of cancer development in humans on mosquito behaviour, and (iii) the
30 consequences of cancers in mosquitoes and on their disease transmission potential (see
31 Figure). We will then discuss the most promising research avenues on this topic and the
32 public health strategies that could be envisioned in this context.

33

34 **Impact of mosquitoes on carcinogenesis**

35 We first focus on how mosquitoes can promote the risk of developing cancer in humans. In
36 this part, we show that this risk could result from the (i) transmission of oncogenic pathogens,
37 (ii) inflammatory reactions following mosquito blood meals, (iii) non-inflammatory effects of
38 indirectly oncogenic mosquito-borne pathogens, and (iv) direct transmission of cancer cells.

39

40 *Oncogenic pathogen transmission.*

41 Over the last decades, an increasing number of infections have been linked to the
42 development of human and animal cancers (Ewald and Swain Ewald, 2015; McAloose and
43 Newton, 2009; Parkin, 2006; Zur Hausen, 2009). The frequency of cancers with an infectious
44 causation has certainly been underestimated because cancer symptoms generally occur after
45 years of development, therefore making the identification of a causal link extremely
46 challenging. Nevertheless, current estimates are that 20% of cancer cases have an infectious
47 causality (Parkin, 2006; Zur Hausen, 2009), and it has been suggested that underlying
48 infectious agents can only actually be strictly excluded in 5% of cancer cases (Ewald, 2009).
49 Epidemiological studies suggest that the current increase in emerging pathogen transmission

50 (Jones et al., 2008) could have a substantial effect on the future burden of cancer worldwide
51 (currently around two million cancer cases annually are known to be caused by an infectious
52 agent) (De Martel et al., 2012).

53 An infectious agent is considered as an oncogenic pathogen when the infection is a
54 prerequisite for the occurrence and/or the development of cancer (Zur Hausen, 2009).
55 Oncogenic pathogens may make a direct contribution to cancer development, most commonly
56 through integration of their DNA into the host genome (*e.g.* Epstein-Barr virus (Moormann et
57 al., 2011)). According to Ward et al. (2016), many of the pathogens that are likely to promote
58 cancer development (Ewald and Swain Ewald, 2012; Plummer et al., 2016) could possibly be
59 transmitted through mosquitoes because they can be found in blood (Ward et al., 2016). This
60 category of pathogens includes *Plasmodium* species, Epstein–Barr virus, Kaposi sarcoma
61 herpesvirus, Hepatitis B virus and Hepatitis C virus (Ward et al., 2016). Moreover, it has also
62 been suggested that mosquitoes may be able to transmit unknown viruses that could be linked
63 with cancer (Benelli et al., 2016; Lehrer, 2010a).

64 The International Agency for Research on Cancer has recently mentioned malaria, which is
65 caused by the mosquito-borne protozoan *Plasmodium* and produces 228 millions new
66 infections every year, as a probable oncogenic pathogen (WHO, 2019). This parasite can have
67 a direct action on carcinogenesis because analogies at the cellular level have been reported for
68 malaria and gastrointestinal tumours (Suresh et al., 2005). The association between malaria
69 and the risk of developing cancer could be explained by the ability of *Plasmodium* parasites to
70 induce the immune response towards the destruction of plasmodium-infected cells (Degarege
71 et al., 2009), which could decrease the immune system’s ability to target cancer cells. This
72 action could also be indirect, especially through reactivation of oncogenic viruses. For
73 instance, endemic Burkitt lymphoma occurs at higher incidences in areas where malaria is
74 endemic because *Plasmodium falciparum* fuels transmission of Epstein Barr virus that is

75 associated with more than 95% of cancer cases (Burkitt, 1961). Burkitt lymphoma is an
76 aggressive B-cell malignancy (Brady et al. 2007). The B-cells are the primary targets of
77 Epstein Barr virus (a known oncogenic pathogen) infection (Shannon-Lowe et al., 2017). By
78 stimulating the proliferation of B-cells, *Plasmodium falciparum* could enhance oncogenic
79 effects of the Epstein Barr virus on these target cells (Ewald and Swain Ewald 2014).
80 Knowing that mosquito-borne pathogens could stimulate antibody production (*e.g.*,
81 stimulating B-cell replication), there is good reason to think that other pathogens might
82 similarly contribute to amplified the oncogenic effect of Epstein Barr virus.

83 This connection is supported by the fact that several studies have found a significant
84 relationship between malaria cases and mortality across all cancers in all 50 states of the USA
85 (Lehrer, 2010a, 2010b). More specifically, relationships between malaria outbreaks in the
86 USA and reports of brain tumour incidence have also been observed (Lehrer, 2010a, 2010b).
87 While these results strongly suggest an association between malaria and cancer, they do not
88 provide a direct proof of causality between these two pathologies.

89 It is worth pointing out that other studies found that the stimulation of the host immune
90 system could also limit cancers development and progression. For example, malaria infection
91 can reduce the growth of lung tumours via the induction of innate and adaptive anti-tumour
92 responses in a mouse model (Chen et al., 2011; Faure, 2016). Therefore, the interaction
93 between *Plasmodium* parasites and cancer might be complex and needs much more
94 investigation.

95

96 *Immune reaction following the mosquito blood meal.*

97 Mosquito blood meals are characterised by an edema and an inflammatory influx of
98 neutrophils that yield localised innate immune reactions (Pingen et al., 2016). This
99 inflammation induces different immune responses, which are different for each mosquito

100 species (Donovan et al., 2007; Fontaine et al., 2011; Schneider et al., 2011, 2004), and
101 accompanied by tissue damage, which could increase the risk of developing cancer (Coussens
102 and Werb, 2002; Hanahan and Weinberg, 2011; Johansson and Ward, 2017). Moreover, it is
103 now becoming clear that the tumour's microenvironment, which is largely organised by
104 inflammatory cells, is driving the neoplastic process by fostering the proliferation, survival,
105 and migration of cancer cells (Coussens and Werb, 2002). Therefore, in areas where humans
106 are particularly exposed to mosquito bites, the risk of developing cancer should rise following
107 exposure to multiple mosquito blood meals. To the best of our knowledge, this has never been
108 investigated.

109

110 *Mosquito-borne transmission of indirectly oncogenic pathogens*

111 Each mosquito-borne pathogen can also indirectly contribute to carcinogenesis by inducing
112 changes in the microenvironment via inflammation or the immunomodulation they produce
113 (Dalton-Griffin and Kellam, 2009; Jacqueline et al., 2018; Zur Hausen, 2009). In this case,
114 their diversity of action ranges from chronic inflammation (*Helicobacter pylori*, which is
115 associated with 65% of stomach cancers (Sepulveda, 2013)) to immunosuppression (HIV
116 (Gopal et al., 2014)). Moreover, pathogen persistence within the host induces successive
117 genetic, epigenetic, and/or immune changes that facilitate cancerous development (Ewald and
118 Swain Ewald, 2012; Ewald and Swain Ewald, 2013).

119

120 *Direct transmission of cancer cells.*

121 While not observed in natural conditions, a study has shown that a hamster reticulum cell
122 sarcoma, named TM, can be transmitted by the mosquito species *Aedes aegypti* through a
123 direct transfer of cancer cells (Banfield et al., 1966, 1965). When passed by subcutaneous
124 transplantation within the hamsters, cancer cells appear in their blood after five days and

125 increase constantly until reaching a high density just before host death (greater than 100,000
126 per mm³). TM cancer cells remained viable for up to eight hours after ingestion by the adult
127 mosquito, and only 1 to 2% of the mosquitoes tested had viable cancer cells after several
128 days, which could be due to the digestion processes in the mosquito gut. Mosquitoes carrying
129 cancer cells were able to implant these cells into 5 to 10% of other hamsters (Banfield et al.,
130 1966, 1965).

131

132 **Consequences of cancers in humans on mosquitoes**

133 A variety of changes in mosquito behaviour have been reported when they are exposed to
134 people infected with pathogens (Busula et al., 2017; Emami et al., 2017; Lacroix et al., 2005;
135 Robinson et al., 2018). Infection induces a change in host odour, CO₂ blood concentration,
136 and many other physiological factors (Cummins et al., 2014; Shirasu and Touhara, 2011),
137 which could impact the attractiveness of mosquitoes for infected hosts. Since cancer can
138 influence many aspects of host physiology, it could similarly influence attraction of
139 mosquitoes.

140 Malignant cancers are often associated with a higher iron level in blood (Kwok, 2002).
141 This surplus of iron is needed during early steps of tumour development, *i.e.*, enhanced
142 survival (Bauckman et al., 2015) and proliferation of transformed cells (Steedmann-
143 Olmedillas, 2011), as well as during late stages to promote the metastatic cascade (Jung et al.,
144 2019). Moreover, iron is required for optimal egg development and viable offspring in
145 mosquitoes (Zhou et al., 2007), suggesting that blood meal with higher iron concentration
146 may impact mosquito behaviour and reproduction (hence vector population dynamics and
147 infectious disease transmission intensity).

148 Some cancers can change human odour (Shirasu and Touhara, 2011). For example,
149 patients with gynaecological tumours also complain of heavy vaginal discharge with an

150 offensive odour resulting from the production of acetic, isovaleric, and/or butyric acids (Kuge
151 et al., 1996). Matsumura et al. have shown that the urine from mice with artificially induced
152 cancerous lung tumours could be clearly discriminated from non-affected (control) mice by
153 the detection of volatile biomarkers in their urine (Matsumura et al., 2010). Dogs are also able
154 to detect these odour modifications and so can be used as potential detectors of different
155 cancers, such as melanoma, bladder cancer, ovarian cancer, and colorectal cancer (Horvath et
156 al., 2008; McCulloch et al., 2006; Pickel et al., 2004; Sonoda et al., 2011; Willis et al., 2004).
157 Other study have investigated the potential of using the *Drosophila*'s olfactory system to
158 recognise cancer cells by their scent (Strauch et al., 2014).

159 Cancer can also change the CO₂ concentration in the blood (major driver of mosquito host
160 seeking behaviour). Lung cancer is often associated with dyspnea (shortness of breath) or
161 previous respiratory disease including chronic bronchitis, emphysema, or pneumonia, all of
162 which can alter the CO₂ concentration in the blood (Brenner et al., 2012). Dyspnea was also
163 observed for other cancers (e.g., breast cancer, lymphoma) but could be linked to risk factors
164 such as a history of smoking, asthma, or chronic obstructive pulmonary disease or a history of
165 exposure to asbestos (Dudgeon et al., 2001).

166 Since cancer can modify many physiological factors in humans, we would expect that their
167 attractiveness to mosquitoes could also be altered. This suggests that individuals with cancer
168 could be more or less actively targeted for the transmission of mosquito-borne pathogens.

169

170 **Consequences of cancers in mosquitoes on humans**

171 No study has yet detected natural cancer in mosquitoes, so the impact of cancer on
172 mosquito life history traits is highly speculative at the moment. Nevertheless, several types of
173 tumours occurring naturally (Robert, 2010; Salomon and Rob Jackson, 2008; Scharrer and
174 Lochhead, 1950) or triggered by genetic engineering (Mirzoyan et al., 2019), including

175 neuroblastoma, ovarian, and imaginal disk tumours, have been reported in different insect
176 species, especially in *D. melanogaster* (Mirzoyan et al., 2019; Salomon and Rob Jackson,
177 2008). It is therefore possible that natural cancers exist in mosquitoes and have significant
178 effect on traits such as longevity, fecundity, or feeding-behaviour.

179 Changes in an organism's life-history traits may be an adaptive response to a parasitic
180 infection (Adamo, 1999; Minchella and Loverde, 1981; Polak and Starmer, 1998). One
181 solution developed by many animal species against biotic aggressors (such as parasites) is the
182 adjustment of life-history traits to compensate for their negative effects on fitness (Forbes,
183 1993; Hochberg et al., 1992; Michalakis and Hochberg, 1994; Thomas et al., 2000). An
184 example is the work by Vézilier and colleagues, which shows that mosquitoes infected by
185 *Plasmodium* species lay their eggs two days earlier than non-infected ones (Vézilier et al.,
186 2015) to compensate for the rapid decrease in egg quality observed in infected mosquitoes.
187 This type of adaptive response can have consequences on mosquito communities and
188 indirectly on the evolution of pathogen communities.

189 Because malignancies usually also reduce survival, and hence potentially host fitness, a
190 similar process could also exist in this context. Indeed, it has been shown that *Drosophila*
191 *melanogaster* harbouring an early gut cancer adjust their life-history traits by having their
192 egg-laying period peak two days earlier than normal, which would maximise their immediate
193 reproductive effort and therefore compensate for the reduced survival (Arnal et al., 2017).

194

195 **Conclusion and perspectives**

196 Despite the significant impact of cancers and mosquito-borne diseases on human health,
197 there is little documented evidence of a relationship between these two concerns for humans.
198 Briefly, we know that the direct transmission of cancer cells is mechanistically possible based
199 on a single experimental model and that mosquitoes can transmit oncogenic pathogens or

200 induce immune reactions, which could favour carcinogenesis. In addition, we have seen
201 evidence that cancer in humans or in insect can alter the insect's life history traits, hence
202 pathogen transmission dynamics. Nevertheless, the impact of these connections *in natura*
203 needs to be quantified, especially in populations affected by these two threats.

204 First, we need to determine if there are more oncogenic pathogens transmitted by
205 mosquitoes than are currently observed, especially by refining our knowledge on the
206 oncogenic capacities of malaria. Identifying such connections between pathogens and cancer
207 could have a strong impact on prevention strategies, as exemplified by the papillomavirus
208 vaccine that avoids cases of cervical cancer by protecting against its infectious causation.
209 Moreover, this interaction could be more complicated because mosquito bites can create
210 immunosuppression, which can favor proliferation of oncogenic pathogens but also directly
211 cancer development (so called "promoter arthropods" hypothesis (Coluzzi et al., 2003, 2002)).
212 In the case of mosquito-borne pathogens, identifying such connections could create an
213 unprecedented synergy between vector control programs and the prevention of numerous
214 cancer cases, with paying much attention on using insecticides to avoid increasing cancer risk.

215 It is worth pointing out that the vast majority of blood feeding events will be by
216 mosquitoes engaging in their first (*i.e.* mosquitoes are non-infectious) blood meal or by
217 mosquitoes that do not carry infectious agents from previous blood meals. Thus, while all
218 feeding events will cause inflammatory reactions and possibly impact cancer dynamics, only a
219 small proportion of feeding events will involve the vectoring of infectious agents.

220 Regarding the huge number of people living in areas affected by mosquitoes, investigating
221 the link between the rate of mosquito bites and the probability of developing cancer through
222 local inflammation could also be very informative. Experimental studies are first required to
223 evaluate the immunomodulation effect after exposure to mosquito saliva (therefore mosquito
224 blood meal) on cancer development and to characterise interactions between the inflammatory

225 process involved following mosquito blood meals and the one involved in cancer initiation.
226 Second, large-scale statistical analyses are now possible due to improved both cancer
227 surveillance in tropical countries and mosquito surveillance in the North hemisphere
228 (Sankaranarayanan, 2014).

229 Importantly, experiments on mosquito transmission of cancer cells must be repeated with
230 different host species, different mosquito species, and different types of cancer cells. While
231 very promising, these experiments cannot conclusively prove the existence of such
232 transmission in the field, and most importantly to humans. Once mosquito transmission has
233 been quantified experimentally in a more robust way, the question of the importance of this
234 transmission route *in natura* can be addressed.

235 Experiments on odour modification in people affected by cancer and its correlation with
236 mosquito attractiveness can quantify the impact of human cancer development on mosquito
237 behaviour. The technical tools are available today (Vantaux et al., 2018) to perform such
238 experiments, and the integration of such information to epidemiological models could provide
239 a first estimation of the impact of human cancers on the epidemiology of mosquito-borne
240 pathogens (Roux et al., 2015).

241 Finally, the potential consequences of natural cancers in mosquitoes on human health
242 could be also important. We first need to identify natural cases of cancer in mosquitoes, even
243 if the prevalence is low. Once this has been quantified, we can expose mosquitoes to
244 radiation, pesticides or other xenobiotic agents. We can also use genetic engineering to create
245 cancerous mosquitoes in order to design experiments to study the evolution of mosquito life
246 history traits when a cancer affects them.

247 To conclude, it is essential to develop integrative strategies considering both cancers and
248 mosquito-borne pathogens. Such a research avenue will require inter-disciplinary
249 collaborations from evolutionary biologists, entomologists, experts in chemical ecology,

250 oncologists, immunologist, epidemiologists, and public health experts. Considering the
251 potentially huge impact of such connections, quantifying them to forecast the impact of
252 different control strategies for human health should lead to promising benefits.

253

254 **Figure list**

255 **Figure 1.** Schematic representation of the possible connections between mosquitoes,
256 mosquito-borne diseases, and cancer. (A) The impact of mosquitoes on carcinogenesis in
257 humans, including the mosquito transmission of oncogenic pathogens (symbolized here by a
258 human herpesvirus 8), the mosquito transmission of cancer cells from a cancerous person to
259 another susceptible person, and the possible immune reactions following mosquito blood
260 meals. All these processes could increase the risk of developing cancer in the human
261 population. (B) The possible negative or positive impact of cancer on human attractiveness to
262 mosquitoes, and therefore on the transmission intensity of mosquito-borne diseases, and (C)
263 the possible negative or positive impacts that natural cancers could have on mosquito
264 phenotype (lifespan, fecundity, feeding behaviour) and therefore on their vector capacity.

265

266 **References**

- 267 Adamo, S., 1999. Evidence for adaptive changes in egg laying in crickets exposed to bacteria
268 and parasites. *Anim. Behav.* 57, 117–124. <https://doi.org/10.1006/anbe.1998.0999>
- 269 Arnal, A., Jacqueline, C., Ujvari, B., Leger, L., Moreno, C., Faugere, D., Tasiemski, A.,
270 Boidin-Wichlacz, C., Misse, D., Renaud, F., Montagne, J., Casali, A., Roche, B., Mery,
271 F., Thomas, F., 2017. Cancer brings forward oviposition in the fly *Drosophila*
272 *melanogaster*. *Ecol. Evol.* 7, 272–276. <https://doi.org/10.1002/ece3.2571>
- 273 Banfield, W., Woke, P., MacKay, C., 1966. Mosquito transmission of lymphomas. *Cancer* 19,
274 1333–1336. [https://doi.org/10.1002/1097-0142\(196610\)19:10<1333::AID-](https://doi.org/10.1002/1097-0142(196610)19:10<1333::AID-CNCR2820191002>3.0.CO;2-I)
275 [CNCR2820191002>3.0.CO;2-I](https://doi.org/10.1002/1097-0142(196610)19:10<1333::AID-CNCR2820191002>3.0.CO;2-I)
- 276 Banfield, W.G., Woke, P.A., Mackay, C.M., Cooper, H.L., 1965. Mosquito transmission of a
277 reticulum cell sarcoma of hamsters. *Science.* 148, 1239–1240.
278 <https://doi.org/10.1126/science.148.3674.1239>
- 279 Bauckman, K., Haller, E., Taran, N., Rockfield, S., Ruiz-Rivera, A., Nanjundan, M., 2015.
280 Iron alters cell survival in a mitochondria-dependent pathway in ovarian cancer cells.
281 *Biochem. J.* 466, 401–413. <https://doi.org/10.1042/BJ20140878>
- 282 Benelli, G., Lo Iacono, A., Canale, A., Mehlhorn, H., 2016. Mosquito vectors and the spread
283 of cancer: an overlooked connection? *Parasitol. Res.* 115, 2131–2137.
284 <https://doi.org/10.1007/s00436-016-5037-y>
- 285 Brady, G., MacArthur, G.J., Farrell, P.J., 2007. Epstein-Barr virus and Burkitt lymphoma. *J.*
286 *Clin. Pathol.* 60, 1397–1402. <https://doi.org/10.1136/jcp.2007.047977>
- 287 Bray, F., Ferlay, J., Soerjomataram, I., Siegel, R.L., Torre, L.A., Jemal, A., 2018. Global
288 cancer statistics 2018: GLOBOCAN estimates of incidence and mortality worldwide for
289 36 cancers in 185 countries. *CA. Cancer J. Clin.* 68, 394–424.
290 <https://doi.org/10.3322/caac.21492>

291 Brenner, D.R., Boffetta, P., Duell, E.J., Bickebölller, H., Rosenberger, A., McCormack, V.,
292 Muscat, J.E., Yang, P., Wichmann, H.E., Brueske-Hohlfeld, I., Schwartz, A.G., Cote,
293 M.L., Tjonneland, A., Friis, S., Le Marchand, L., Zhang, Z.F., Morgenstern, H.,
294 Szeszenia-Dabrowska, N., Lissowska, J., Zaridze, D., Rudnai, P., Fabianova, E.,
295 Foretova, L., Janout, V., Bencko, V., Schejbalova, M., Brennan, P., Mates, I.N., Lazarus,
296 P., Field, J.K., Raji, O., McLaughlin, J.R., Liu, G., Wiencke, J., Neri, M., Ugolini, D.,
297 Andrew, A.S., Lan, Q., Hu, W., Orlov, I., Park, B.J., Hung, R.J., 2012. Previous lung
298 diseases and lung cancer risk: A pooled analysis from the international lung cancer
299 consortium. *Am. J. Epidemiol.* 176, 573–585. <https://doi.org/10.1093/aje/kws151>

300 Burkitt, D.P., 1961. Observations on the geography of malignant lymphoma. *East Afr. Med. J.*
301 38, 511–514.

302 Busula, A.O., Verhulst, N.O., Bousema, T., Takken, W., de Boer, J.G., 2017. Mechanisms of
303 *Plasmodium*-enhanced attraction of mosquito vectors. *Trends Parasitol.* 33, 961–973.
304 <https://doi.org/10.1016/j.pt.2017.08.010>

305 Caraballo, H., King, K., 2014. Emergency department management of mosquito-borne illness:
306 malaria, dengue, and West Nile virus. *Emerg. Med. Pract.* 16, 1–23.

307 Chen, Lili, He, Z., Qin, L., Li, Q., Shi, X., Zhao, S., Chen, Ling, Zhong, N., Chen, X., 2011.
308 Antitumor effect of malaria parasite infection in a murine lewis lung cancer model
309 through induction of innate and adaptive immunity. *PLoS One* 6, e24407.
310 <https://doi.org/10.1371/journal.pone.0024407>

311 Coluzzi, M., Calabrò, M.L., Manno, D., Chieco-Bianchi, L., Schulz, T.F., Ascoli, V., 2003.
312 Reduced seroprevalence of Kaposi's sarcoma-associated herpesvirus (KSHV), human
313 herpesvirus 8 (HHV8), related to suppression of *Anopheles* density in Italy. *Med. Vet.*
314 *Entomol.* 17, 461–464. <https://doi.org/10.1111/j.1365-2915.2003.00465.x>

315 Coluzzi, M., Manno, D., Guzzinati, S., Tognazzo, S., Zambon, P., Arcà, B., Costantini, C.,

316 Ascoli, V., 2002. The bloodsucking arthropod bite as possible cofactor in the
317 transmission of human herpesvirus-8 infection and in the expression of Kaposi's sarcoma
318 disease. *Parassitologia* 44, 123–129.

319 Coussens, L.M., Werb, Z., 2002. Inflammation and cancer. *Nature* 420, 860-867.
320 <https://doi.org/10.1038/nature01322>

321 Cummins, E.P., Selfridge, A.C., Sporn, P.H., Sznajder, J.I., Taylor, C.T., 2014. Carbon
322 dioxide-sensing in organisms and its implications for human disease. *Cell. Mol. Life Sci.*
323 71, 831–845. <https://doi.org/10.1007/s00018-013-1470-6>

324 Dalton-Griffin, L., Kellam, P., 2009. Infectious causes of cancer and their detection. *J. Biol.* 8,
325 67. <https://doi.org/10.1186/jbiol168>

326 De Martel, C., Ferlay, J., Franceschi, S., Vignat, J., Bray, F., Forman, D., Plummer, M., 2012.
327 Global burden of cancers attributable to infections in 2008: A review and synthetic
328 analysis. *Lancet Oncol.* 13, 607–615. [https://doi.org/10.1016/S1470-2045\(12\)70137-7](https://doi.org/10.1016/S1470-2045(12)70137-7)

329 Degarege, A., Anmut, A., Legesse, M., Erko, B., 2009. Malaria severity status in patients
330 with soil-transmitted helminth infections. *Acta Trop.* 112, 8–11.
331 <https://doi.org/10.1016/j.actatropica.2009.05.019>

332 Donovan, M.J., Messmore, A.S., Scrafford, D.A., Sacks, D.L., Kamhawi, S., McDowell,
333 M.A., 2007. Uninfected mosquito bites confer protection against infection with malaria
334 parasites. *Infect. Immun.* 75, 2523–2530. <https://doi.org/10.1128/IAI.01928-06>

335 Dudgeon, D.J., Kristjanson, L., Sloan, J.A., Lertzman, M., Clement, K., 2001. Dyspnea in
336 cancer patients: Prevalence and associated factors. *J. Pain Symptom Manage.* 21, 95–
337 102. [https://doi.org/10.1016/S0885-3924\(00\)00258-X](https://doi.org/10.1016/S0885-3924(00)00258-X)

338 Emami, S.N., Lindberg, B.G., Hua, S., Hill, S.R., Mozuraitis, R., Lehmann, P., Birgersson,
339 G., Borg-Karlson, A.K., Ignell, R., Faye, I., 2017. A key malaria metabolite modulates
340 vector blood seeking, feeding, and susceptibility to infection. *Science.* 355, 1076–1080.

341 <https://doi.org/10.1126/science.aah4563>

342 Ewald, P.W., 2009. Chapter 2 An evolutionary perspective on parasitism as a cause of cancer,
343 in: *Advances in Parasitology*. pp. 21–43.

344 Ewald, P.W., Swain Ewald, H.A., 2012. Infection, mutation, and cancer evolution. *J. Mol.*
345 *Med.* 90, 535–541. <https://doi.org/10.1007/s00109-012-0891-2>

346 Ewald, P.W., Swain Ewald, H.A., 2013. Toward a general evolutionary theory of
347 oncogenesis. *Evol. Appl.* 6, 70–81. <https://doi.org/10.1111/eva.12023>

348 Ewald, P.W., Swain Ewald, H.A., 2014. Joint infectious causation of human cancers, in:
349 *Advances in Parasitology*. pp. 1–26. [https://doi.org/10.1016/B978-0-12-800099-1.00001-](https://doi.org/10.1016/B978-0-12-800099-1.00001-6)
350 6

351 Ewald, P.W., Swain Ewald, H.A., 2015. Infection and cancer in multicellular organisms.
352 *Philos. Trans. R. Soc. B Biol. Sci.* 370, 20140224.
353 <https://doi.org/10.1098/rstb.2014.0224>

354 Faure, E., 2016. Puzzling and ambivalent roles of malarial infections in cancer development
355 and progression. *Parasitology* 143, 1811–1823.
356 <https://doi.org/10.1017/S0031182016001591>

357 Fontaine, A., Diouf, I., Bakkali, N., Missé, D., Pagès, F., Fusai, T., Rogier, C., Almeras, L.,
358 2011. Implication of haematophagous arthropod salivary proteins in host-vector
359 interactions. *Parasites and Vectors* 4, 187. <https://doi.org/10.1186/1756-3305-4-187>

360 Forbes, M.R.L., 1993. Parasitism and host reproductive effort. *Oikos* 67, 444–450.
361 <https://doi.org/10.2307/3545356>

362 Gopal, S., Achenbach, C.J., Yanik, E.L., Dittmer, D.P., Eron, J.J., Engels, E.A., 2014.
363 Moving forward in HIV-associated cancer. *J. Clin. Oncol.* 32, 876–878.
364 <https://doi.org/10.1200/JCO.2013.53.1376>

365 Hanahan, D., Weinberg, R.A., 2011. Hallmarks of cancer: The next generation. *Cell* 144,

366 646–674. <https://doi.org/10.1016/j.cell.2011.02.013>

367 Hochberg, M.E., Michalakis, Y., de Meeus, T., 1992. Parasitism as a constraint on the rate of
368 life-history evolution. *J. Evol. Biol.* 5, 491–504. <https://doi.org/10.1046/j.1420->
369 9101.1992.5030491.x

370 Horvath, G., Järverud, G.A.K., Järverud, S., Horváth, I., 2008. Human ovarian carcinomas
371 detected by specific odor. *Integr. Cancer Ther.* 7, 76–80.
372 <https://doi.org/10.1177/1534735408319058>

373 Jacqueline, C., Bonnefoy, N., Charrière, G.M., Thomas, F., Roche, B., 2018. Personal history
374 of infections and immunotherapy: Unexpected links and possible therapeutic
375 opportunities. *Oncoimmunology* 7, e1466019.
376 <https://doi.org/10.1080/2162402X.2018.1466019>

377 Johansson, O., Ward, M., 2017. The human immune system’s response to carcinogenic and
378 other infectious agents transmitted by mosquito vectors. *Parasitol. Res.* 116, 1–9.
379 <https://doi.org/10.1007/s00436-016-5272-2>

380 Jones, K.E., Patel, N.G., Levy, M.A., Storeygard, A., Balk, D., Gittleman, J.L., Daszak, P.,
381 2008. Global trends in emerging infectious diseases. *Nature* 451, 990–994.
382 <https://doi.org/10.1038/nature06536>

383 Jung, M., Mertens, C., Tomat, E., Brüne, B., 2019. Iron as a central player and promising
384 target in cancer progression. *Int. J. Mol. Sci.* 20, E273.
385 <https://doi.org/10.3390/ijms20020273>

386 Kuge, S., Tokuda, Y., Ohta, M., Okumura, A., Kubota, M., Ninomiya, S., Sawamura, S.,
387 Makuuchi, H., Tajima, T., Mitomi, T., 1996. Use of metronidazole gel to control
388 malodor in advanced and recurrent breast cancer. *Jpn. J. Clin. Oncol.* 26, 207–210.
389 <https://doi.org/10.1093/oxfordjournals.jjco.a023215>

390 Kwok, J.C., 2002. The iron metabolism of neoplastic cells: Alterations that facilitate

391 proliferation? *Crit. Rev. Oncol. Hematol.* 42, 65–78. <https://doi.org/10.1016/S1040->
392 8428(01)00213-X

393 Lacroix, R., Mukabana, W.R., Gouagna, L.C., Koella, J.C., 2005. Malaria infection increases
394 attractiveness of humans to mosquitoes. *PLoS Biol.* 3, e298.
395 <https://doi.org/10.1371/journal.pbio.0030298>

396 Lehrer, S., 2010a. Anopheles mosquito transmission of brain tumor. *Med. Hypotheses* 74,
397 167–168. <https://doi.org/10.1016/j.mehy.2009.07.005>

398 Lehrer, S., 2010b. Association between malaria incidence and all cancer mortality in fifty
399 U.S. states and the District of Columbia. *Anticancer Res.* 30, 1371–1373.

400 Marcondes, C.B., Benelli, G., 2019. Mosquitoes, infectious diseases, and cancer: A
401 connection to study? *Int. J. Environ. Res. Public Health* 16, 4859.
402 <https://doi.org/10.3390/ijerph16234859>

403 Masterson, K., 2019. Mosquitoes, war and power. *Nature* 572, 310–311.
404 <https://doi.org/10.1038/d41586-019-02418-6>

405 Matsumura, K., Opiekun, M., Oka, H., Vachani, A., Albelda, S.M., Yamazaki, K.,
406 Beauchamp, G.K., 2010. Urinary volatile compounds as biomarkers for lung cancer: A
407 proof of principle study using odor signatures in mouse models of lung cancer. *PLoS*
408 *One* 5, e8819. <https://doi.org/10.1371/journal.pone.0008819>

409 McAloose, D., Newton, A.L., 2009. Wildlife cancer: a conservation perspective. *Nat. Rev.*
410 *cancer* 9, 517–526.

411 McCulloch, M., Jezierski, T., Broffman, M., Hubbard, A., Turner, K., Janecki, T., 2006.
412 Diagnostic accuracy of canine scent detection in early- and late-stage lung and breast
413 cancers. *Integr. Cancer Ther.* 5, 30–39. <https://doi.org/10.1177/1534735405285096>

414 Mehlhorn, H., Al-Rasheid, K.A.S., Al-Quraishy, S., Abdel-Ghaffar, F., 2012. Research and
415 increase of expertise in arachno-entomology are urgently needed. *Parasitol. Res.* 110,

416 259–265. <https://doi.org/10.1007/s00436-011-2480-7>

417 Michalakis, Y., Hochberg, M.E., 1994. Parasitic effects on host life-history traits: A review of
418 recent studies. *Parasite* 1, 291–294. <https://doi.org/10.1051/parasite/1994014291>

419 Minchella, D.J., Loverde, P.T., 1981. A cost of increased early reproductive effort in the snail
420 *Biomphalaria glabrata*. *Am. Nat.* 118, 876–881.

421 Mirzoyan, Z., Sollazzo, M., Allocca, M., Valenza, A.M., Grifoni, D., Bellosta, P., 2019.
422 *Drosophila melanogaster*: A model organism to study cancer. *Front. Genet.* 10, 1–16.
423 <https://doi.org/10.3389/fgene.2019.00051>

424 Moormann, A.M., Snider, C.J., Chelimo, K., 2011. The company malaria keeps: How co-
425 infection with Epstein-Barr virus leads to endemic Burkitt lymphoma. *Curr. Opin. Infect.*
426 *Dis.* 24, 435–441. <https://doi.org/10.1097/QCO.0b013e328349ac4f>

427 Parkin, D.M., 2006. The global health burden of infection-associated cancers in the year 2002.
428 *Int. J. Cancer* 118, 3030–3044. <https://doi.org/10.1002/ijc.21731>

429 Pickel, D., Manucy, G.P., Walker, D.B., Hall, S.B., Walker, J.C., 2004. Evidence for canine
430 olfactory detection of melanoma. *Appl. Anim. Behav. Sci.* 89, 107–116.
431 <https://doi.org/10.1016/j.applanim.2004.04.008>

432 Pingen, M., Bryden, S.R., Pondeville, E., Schnettler, E., Kohl, A., Merits, A., Fazakerley,
433 J.K., Graham, G.J., McKimmie, C.S., 2016. Host inflammatory response to mosquito
434 bites enhances the severity of arbovirus infection. *Immunity* 44, 1455–1469.
435 <https://doi.org/10.1016/j.immuni.2016.06.002>

436 Plummer, M., de Martel, C., Vignat, J., Ferlay, J., Bray, F., Franceschi, S., 2016. Global
437 burden of cancers attributable to infections in 2012: a synthetic analysis. *Lancet Glob.*
438 *Heal.* 4, e609-616. [https://doi.org/10.1016/S2214-109X\(16\)30143-7](https://doi.org/10.1016/S2214-109X(16)30143-7)

439 Polak, M., Starmer, W.T., 1998. Parasite-induced risk of mortality elevates reproductive effort
440 in male *Drosophila*. *Proc. Biol. Sci.* 265, 2197–2201.

441 <https://doi.org/10.1098/rspb.1998.0559>

442 Robert, J., 2010. Comparative study of tumorigenesis and tumor immunity in invertebrates
443 and nonmammalian vertebrates. *Dev. Comp. Immunol.* 34, 915–925.
444 <https://doi.org/10.1016/j.dci.2010.05.011>

445 Robinson, A., Busula, A.O., Voets, M.A., Beshir, K.B., Caulfield, J.C., Powers, S.J.,
446 Verhulst, N.O., Winskill, P., Muwanguzi, J., Birkett, M.A., Smallegange, R.C., Masiga,
447 D.K., Richard Mukabana, W., Sauerwein, R.W., Sutherland, C.J., Bousema, T., Pickett,
448 J.A., Takken, W., Logan, J.G., De Boer, J.G., 2018. *Plasmodium*-associated changes in
449 human odor attract mosquitoes. *Proc. Natl. Acad. Sci. U. S. A.* 115, E4209–E4218.
450 <https://doi.org/10.1073/pnas.1721610115>

451 Roux, O., Vantaux, A., Roche, B., Yameogo, K.B., Dabiré, K.R., Diabaté, A., Simard, F.,
452 Lefèvre, T., 2015. Evidence for carry-over effects of predator exposure on pathogen
453 transmission potential. *Proc. R. Soc. B Biol. Sci.* 282, 20152430.
454 <https://doi.org/10.1098/rspb.2015.2430>

455 Salomon, R.N., Rob Jackson, F., 2008. Tumors of testis and midgut in aging flies. 2, 265–
456 268. <https://doi.org/10.4161/fly.7396>

457 Sankaranarayanan, R., 2014. Screening for cancer in low- and middle-income countries. *Ann.*
458 *Glob. Heal.* 80, 412–417. <https://doi.org/10.1016/j.aogh.2014.09.014>

459 Scharrer, B., Lochhead, M.S., 1950. Tumors in the invertebrates: *A review*. *Cancer Res.* 10,
460 403–419.

461 Schneider, B.S., Mathieu, C., Peronet, R., Mécheri, S., 2011. *Anopheles stephensi* saliva
462 enhances progression of cerebral malaria in a murine model. *Vector-Borne Zoonotic Dis.*
463 11, 423–432. <https://doi.org/10.1089/vbz.2010.0120>

464 Schneider, B.S., Soong, L., Zeidner, N.S., Higgs, S., 2004. *Aedes aegypti* salivary gland
465 extracts modulate anti-viral and TH1/TH2 cytokine responses to sindbis virus infection.

466 Viral Immunol. 17, 565–573. <https://doi.org/10.1089/vim.2004.17.565>

467 Sepulveda, A.R., 2013. Helicobacter, inflammation, and gastric cancer. *Curr. Pathobiol. Rep.*
468 1, 9–18. <https://doi.org/10.1007/s40139-013-0009-8>

469 Shannon-Lowe, C., Rickinson, A.B., Bell, A.I., 2017. Epstein-barr virus-associated
470 lymphomas. *Philos. Trans. R. Soc. B Biol. Sci.* 372, 20160271.
471 <https://doi.org/10.1098/rstb.2016.0271>

472 Shirasu, M., Touhara, K., 2011. The scent of disease: Volatile organic compounds of the
473 human body related to disease and disorder. *J. Biochem.* 150, 257–266.
474 <https://doi.org/10.1093/jb/mvr090>

475 Sonoda, H., Kohnoe, S., Yamazato, T., Satoh, Y., Morizono, G., Shikata, K., Morita, Makoto,
476 Watanabe, A., Morita, Masaru, Kakeji, Y., Inoue, F., Maehara, Y., 2011. Colorectal
477 cancer screening with odour material by canine scent detection. *Gut* 60, 814–819.
478 <https://doi.org/10.1136/gut.2010.218305>

479 Steegmann-Olmedillas, J.L., 2011. The role of iron in tumour cell proliferation. *Clin. Transl.*
480 *Oncol.* 13, 71–76. <https://doi.org/10.1007/s12094-011-0621-1>

481 Strauch, M., Lüdke, A., Münch, D., Laudes, T., Giovanni Galizia, C., Martinelli, E., Lavra,
482 L., Paolesse, R., Ulivieri, A., Catini, A., Capuano, R., Di Natale, C., 2014. More than
483 apples and oranges - Detecting cancer with a fruit fly's antenna. *Sci. Rep.* 4, 3576.
484 <https://doi.org/10.1038/srep03576>

485 Suresh, S., Spatz, J., Mills, J.P., Micoulet, A., Dao, M., Lim, C.T., Beil, M., Seufferlein, T.,
486 2005. Connections between single-cell biomechanics and human disease states:
487 Gastrointestinal cancer and malaria. *Acta Biomater.* 1, 15–30.
488 <https://doi.org/10.1016/j.actbio.2004.09.001>

489 Thomas, F., Guégan, J., Michalakis, Y., Renaud, F., 2000. Parasites and host life-history
490 traits: implications for community ecology and species co-existence. *Int. J. Parasitol.* 30,

491 669–674. [https://doi.org/10.1016/S0020-7519\(00\)00040-0](https://doi.org/10.1016/S0020-7519(00)00040-0)

492 Torre, L.A., Bray, F., Siegel, R.L., Ferlay, J., Lortet-Tieulent, J., Jemal, A., 2015. Global
493 cancer statistics, 2012. *CA. Cancer J. Clin.* 65, 87–108.
494 <https://doi.org/10.3322/caac.21262>

495 Vantaux, A., Yao, F., Hien, D.F., Guissou, E., Yameogo, B.K., Gouagna, L.-C., Fontenille,
496 D., Renaud, F., Simard, F., Constantini, C., Thomas, F., Mouline, K., Roche, B., Cohuet,
497 A., Dabire, K.R., Lefevre, T., 2018. Field evidence for manipulation of mosquito host
498 selection by the human malaria parasite, *Plasmodium falciparum*. *bioRxiv* 207183.
499 <https://doi.org/10.1101/207183>

500 Vézilier, J., Nicot, A., Gandon, S., Rivero, A., 2015. Plasmodium infection brings forward
501 mosquito oviposition. *Biol. Lett.* 11, 20140840. <https://doi.org/10.1098/rsbl.2014.0840>

502 Ward, M., Ward, A., Johansson, O., 2016. Does the mosquito have more of a role in certain
503 cancers than is currently appreciated? – The mosquito cocktail hypothesis. *Med.*
504 *Hypotheses* 86, 85–91. <https://doi.org/10.1016/j.mehy.2015.12.005>

505 WHO, 2019. World malaria report 2019 Available from: [https://www.who.int/news-](https://www.who.int/news-room/feat)
506 [room/feat](https://www.who.int/news-room/feat).

507 Willis, C.M., Church, S.M., Guest, C.M., Cook, W.A., McCarthy, N., Bransbury, A.J.,
508 Church, M.R.T., Church, J.C.T., 2004. Olfactory detection of human bladder cancer by
509 dogs: Proof of principle study. *Br. Med. J.* 329, 712.
510 <https://doi.org/10.1136/bmj.329.7468.712>

511 Zhou, G., Kohlhepp, P., Geiser, D., Frasquillo, M. del C., Vazquez-Moreno, L., Winzerling,
512 J.J., 2007. Fate of blood meal iron in mosquitoes. *J. Insect Physiol.* 53, 1169–1178.
513 <https://doi.org/10.1016/j.jinsphys.2007.06.009>

514 Zur Hausen, H., 2009. The search for infectious causes of human cancers: Where and why.
515 *Virology* 392, 1–10. <https://doi.org/10.1002/anie.200901917>



