vaccines

Opinion

Summary of the Current Status of African Swine Fever Vaccine Development in China

Naijun Han [1,†], Hailong Qu [1,†], Tiangang Xu [1,2,†], Yongxin Hu [1], Yongqiang Zhang [1] and Shengqiang Ge [1,2,*]

[1] China Animal Health and Epidemiology Center, No. 369 Nanjing Road, Qingdao 266032, China
[2] Key Laboratory of Animal Biosafety Risk Prevention and Control (South), Ministry of Agriculture and Rural Affairs of the People's Republic of China, No. 369 Nanjing Road, Qingdao 266032, China
* Correspondence: geshengqiang@cahec.cn; Tel.: +86-53-2856-21552
† These authors contributed equally to this work.

Abstract: African swine fever (ASF) is a highly lethal and contagious disease of domestic pigs and wild boars. There is still no credible commercially available vaccine. The only existing one, issued in Vietnam, is actually used in limited quantities in limited areas, for large-scale clinical evaluation. ASF virus is a large complex virus, not inducing full neutralizing antibodies, with multiple genotypes and a lack of comprehensive research on virus infection and immunity. Since it was first reported in China in August 2018, ASF has spread rapidly across the country. To prevent, control, further purify and eradicate ASF, joint scientific and technological research on ASF vaccines has been carried out in China. In the past 4 years (2018–2022), several groups in China have been funded for the research and development of various types of ASF vaccines, achieving marked progress and reaching certain milestones. Here, we have provided a comprehensive and systematic summary of all of the relevant data regarding the current status of the development of ASF vaccines in China to provide a reference for further progress worldwide. At present, the further clinical application of the ASF vaccine still needs a lot of tests and research accumulation.

Keywords: African swine fever; live attenuated vaccine; subunit vaccine; live vector vaccine

check for updates

Citation: Han, N.; Qu, H.; Xu, T.; Hu, Y.; Zhang, Y.; Ge, S. Summary of the Current Status of African Swine Fever Vaccine Development in China. *Vaccines* **2023**, *11*, 762. https://doi.org/10.3390/vaccines11040762

Academic Editors: Marisa Arias and Carmina Gallardo

Received: 2 February 2023
Revised: 24 March 2023
Accepted: 27 March 2023
Published: 29 March 2023

1. Introduction

African swine fever (ASF) is an acute, febrile, highly contagious disease of pigs caused by the infection with African swine fever virus (ASFV). ASF is on the list of notifiable diseases of the World Organization for Animal Health (WOAH) and is classified as a Class I animal disease in the Chinese list of animal pathogenic microorganisms, which refers to diseases that pose a serious threat to humans and animals and require urgent, severe and compulsory measures for their prevention, control and eradication. ASFV can be transmitted over long distances through pork products, swill and other items, which has set the precedent for transcontinental outbreaks. In 2018, ASF appeared suddenly in China and the development of the African swine fever vaccine was initiated [1,2]. In the past 4 years (2018–2022), several groups in China have presided over/participated in the research and development of various types of ASF vaccines. More than 50 vaccine-related articles have been published (Figure 1), with some studies making marked progress and reaching certain milestones. To provide a reference for further progress worldwide, we have provided a comprehensive and systematic summary of all of the relevant data regarding the current status of the development of ASF vaccines in China.

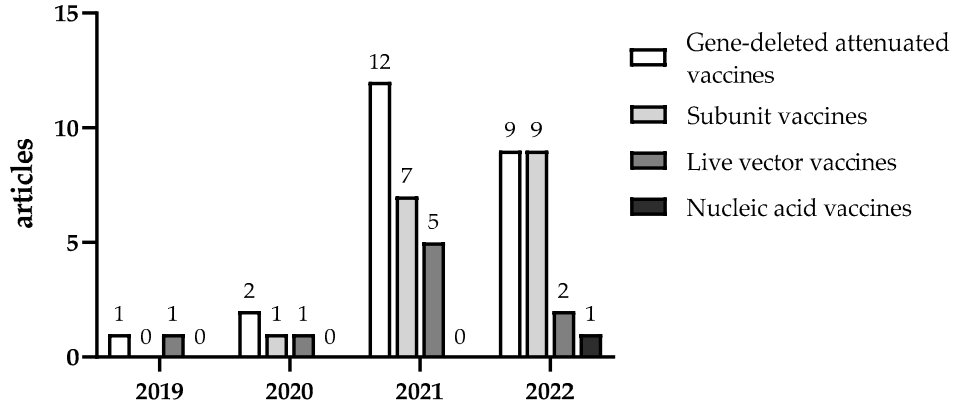

Figure 1. Publication of ASF vaccine articles in China.

2. Gene-Deleted Live Attenuated Vaccines (LAVs)

After ASF was first reported in China in 2018, the outbreak strains designated in China were 2018/1 [2], pig/HLJ/18 [3] and SY18 [1] and these were isolated by different research groups and used to conduct relevant vaccine studies. Foreign experience in ASF vaccine research has shown that inactivated vaccines have no reliable protection [4]; cell-passage-attenuated vaccine candidates is relatively difficult to determine the appropriate number of passages [5]; natural attenuated vaccine candidates are rare [6–8]; subunit vaccines/or vector vaccines have weak and unstable protection, etc.; so, these vaccine development methods are limited by a degree of uncertainty. In recent years, with the continuous development of gene editing technologies, artificial gene-deleted LAVs have become the most promising strategy for ASF vaccine development [9].

Among them, the MGF 360/505 gene (six genes) and CD2v gene have received wide attention from researchers. MGF360 and MGF505, located in the highly variable left terminal genomic region of ASFV, encode products with common structural similarities [10–12]. It was shown that MGF360 and MGF505 genes are involved in the inhibition of interferon (IFN) production [13] and are associated with viral virulence. The deletion of these genes can lead to the reduced virulence of ASFV and to the acquisition of gene-deleted live attenuated vaccines [14,15]. CD2v (EP402R) is an ASFV protein with a sequence homologous to the T lymphocyte surface adhesion receptor CD2, detected in the outer layer of the budding virus [16]. The extracellular structural domain causes the hemadsorption phenomenon [17]. The deletion of the CD2v (EP402R) gene highly attenuates the virulence of ASFV in vivo [14]. In China, several independent research groups have conducted knockout studies on the major genes of ASFV, and three of them have selected the combination of the deleted MGF 360/505 gene (six genes) and CD2v gene (one gene) as vaccine candidate strains for further evaluation [18,19].

2.1. Progress of Seven-Gene-(Dual-Gene)-Deleted LAV Research

Research on the HLJ/18-7GD strain has been highly comprehensive and has achieved the most rapid progress (see Table 1 for details). This gene-deleted live attenuated vaccine is based on the ASFV HLJ/18 virus as the backbone with the deletion of seven genes encoding MGF5051R, MGF505-2R, MGF505-3R, MGF360-12L, MGF36013L, MGF360-14L and CD2v. Safety evaluation and protective efficacy studies conducted on more than 1100 specific pathogen-free (SPF) pigs in the laboratory, as well as experiments on 14,487 commercial fattening pigs and 229 breeding sows in the field, have confirmed that the HLJ/18-7GD strain is genetically stable, does not cause disease or become virulent after inoculation and has no adverse effects on the growth, weight gain or mortality of fattening pigs. The survival protection rate for commercial pigs in the field exceeds 80% [19]. Other seven-gene-deleted strains, such as the ASFV CN2018 ΔMGF/ΔCD2v strain (unpublished data) and ASFV SY18 ΔMGF/ΔCD2v [20], have also had animal experiments conducted and have improved to be safe and effective. However, although the three strains have similar deletion

genes, the specific knockout sites are not identical, which, together with the differences in purification processes, culture systems and the number of passages, may lead to some differences in the deletion strains and the related test data.

Table 1. Advances in ASFV seven-gene-deleted attenuated vaccine (HLJ/18-7GD strain) development.

Period	Progress/Achievements	References
October–November 2018	Isolation and acquisition of endemic ASFV strains in China, completion of whole genome sequence determination and analysis and establishment of infection pathogenesis model	[3]
November 2018–May 2019	Screening out one safe and effective LAV candidate strain HLJ/18-7GD	[18]
December 2019	Approval of the gene-deleted LAV candidate strain for environmental release test after national review	[19]
June 2019–February 2020	Completion of vaccine laboratory product quality research, large-scale production process research and intermediate trial production, as well as biosafety evaluation intermediate test	[19]
March 2020	Approved for clinical trial of veterinary biological products by the Ministry of Agriculture and Rural Affairs	[19]
April–June 2020	Biosafety evaluation environmental release testing and Phase I clinical trial conducted in four independent pig farms	[19]
August–October 2020	Approved by the Ministry of Agriculture and Rural Affairs to enter the biological safety evaluation production test phase, and field biological safety production tests conducted at two enclosed test bases.	[19]
September–October 2020	Approved by the Ministry of Agriculture and Rural Affairs for conducting Phase II clinical trials at four clinical trial enclosed bases	[19]

As with ASFV-G-ΔI177L [21] (US vaccine strain), Lv17/WB/Rie1 [7] (European boar oral vaccine strain) and FK-32/13 [22] (Russian cell passage vaccine strain), HLJ/18-7GD [18] (Chinese vaccine strain) is still in the stage of clinical evaluation. The government has concerns about the safety of attenuated vaccines, the occurrence of post-viral shedding and post-vaccination complications and the inadequate protection of immunocompromised pigs [23], and is cautious about the large-scale promotion of an attenuated vaccine.

2.2. Research Progress of Other Gene-Deleted LAVs

During the clinical evaluation of the seven-gene-deleted live attenuated strains, research on gene-deleted live attenuated strains of ASF in China has not stopped, with increasing numbers of participating units and continuous updates of research results (Table 2). In addition to the above-mentioned seven-gene-deleted live attenuated strains, other ASFV gene-deleted strains have been constructed in recent years. Genes that can be knocked out include those related to innate immunity, such as MGF100-1R [24], MGF 110-9L [25], MGF 505-2R [26], MGF 505-7R(A528R) [27–29], QP509L/QP383R [30], E120R [31], F317 [32] and L7L-L11L [33], genes related to virus transcription, such as MGF360-9L [34], I226R [35], I215L [36,37] and I267 [38], and genes related to virus structure, such as A137R [39]. Strains with deletions of these genes or their combination with previously reported genes may provide new candidates for vaccine evaluation similar to the ASFV-Δ9L/Δ7R strain with the deletion of both MGF360-9L and MGF505-7R genes [40], and the ASFV-GZΔI177LΔCD2vΔMGF with simultaneous deletion of I177L, CD2v and virulence-associated MGF360-12L-MGF360-14L gene clusters [41]. Evaluations of most of the above vaccine candidates are currently limited to small-scale animal experiments (5–10 animals) in the laboratory, mainly to meet publication/patent requirements, and have not yet been studied on a large scale.

Table 2. Research progress of ASFV gene-deleted LAV candidate strains in China *.

Year	Targeted Genes	Immunizing Dose	Survival Rate	Challenge Timepoint (dpv)	Challenge Dose	Survival Rate	References
2019	MGF 360/505	10^3 $TCID_{50}$, 10^4 $TCID_{50}$	10/10	28	10^3 $TCID_{50}$	5/5	[20]
	MGF 360/505 + CD2v	10^3 $TCID_{50}$, 10^4 $TCID_{50}$	10/10	28	10^3 $TCID_{50}$	10/10	
2020	MGF 360/505 + CD2v	10^3 $TCID_{50}$, 10^5 $TCID_{50}$	8/8	21	200 PLD_{50}	8/8	[18]
	MGF 360/505	10^3 $TCID_{50}$, 10^5 $TCID_{50}$	8/8	21	200 PLD_{50}	8/8	
	9GL + UK	10^3 $TCID_{50}$, 10^5 $TCID_{50}$	12/12	21	200 PLD_{50}	0/12	
	CD2v	10^3 $TCID_{50}$, 10^5 $TCID_{50}$	3/8	21	/	/	
	CD2v + UK	10^3 $TCID_{50}$, 10^5 $TCID_{50}$	4/8	21	/	/	
	CD2v + UK	10^4 $TCID_{50}$	5/5	28	10^4 $TCID_{50}$	5/5	[42]
2021	I226R	10^4 $TCID_{50}$, 10^7 $TCID_{50}$	10/10	21	$10^{2.5}$ $TCID_{50}$/10^4 $TCID_{50}$	10/10	[35]
	MGF 505-7R	10 HAD_{50}	6/6	21	/	/	[27,28]
	MGF 110-9L	10 HAD_{50}	3/5	17	/	/	[25]
	QP509L/QP383R	10^4 HAD_{50}	6/6	17	10^2 HAD_{50}	0/6	[30]
2022	MGF360-9L	1HAD_{50}	4/5	17	/	/	[34]
	I267	10 HAD_{50}	1/6	21	/	/	[38]
	MGF360-9L + MGF505-7R	10^4 HAD_{50}	6/6	23	10^2 HAD_{50}	5/6	[40]
	EP153R/EP402R + MGF 360-12L/13L/14L	10^5 $TCID_{50}$	5/5	28	10^2 HAD_{50}	5/5	[43]

* Gene-deleted strains with reduced virulence after deletion; single-dose immunization and intramuscular route are primarily used.

3. Other Vaccines

The design and production of subunit or live vector vaccines do not involve the manipulation of the ASF live virus, and challenge protection data are not necessary in the submission content of patent applications. This has led to the emergence of a large number of ASF vaccine patents in China and as of December 2022, the number of ASF subunit and live vector vaccine patents publicly reported in China has reached 69 and 43, respectively, exceeding the number of patents for genetically attenuated live vaccines.

Based on previous experience in animal disease vaccine design and improved understanding based on previous research on the ASF subunit and live vector vaccines, Chinese researchers have adopted similar research strategies for the development of the ASF vaccine (Figure 2). For the subunit vaccine, the protein sequences were analyzed using bioinformatics methods [44–47] or by using monoclonal antibodies [48] to screen the antigenic epitopes. Once identified, the ASFV antigenic proteins were combined with other bacterial/viral proteins or functional proteins [49,50], so that the expressed ASFV antigenic proteins could self-assemble into a certain structure or improve the expression efficiency to improve the immunogenicity of the ASFV proteins. For the live vector vaccines, different vectors [51–55] and multiple gene expressions [56–58] were also evaluated.

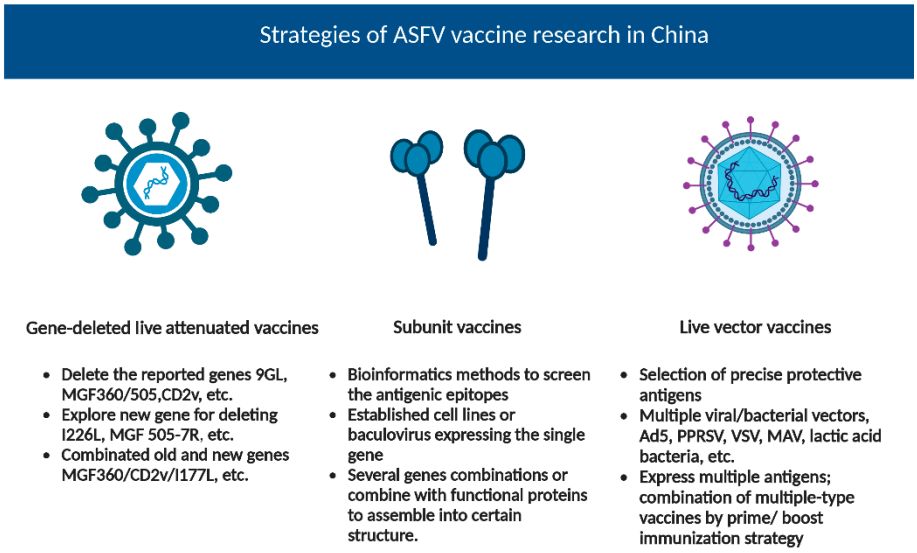

Figure 2. Created using BioRender.com.

However, the major challenges to the development of the ASF subunit or live vector vaccines in China remain, with most of the candidates awaiting protective immunity validation and patent authorization. Some patents relate only to the design concept of combining different genes without an in-depth discussion; so, it is impossible to judge their vaccine application potential.

4. Conclusions

Several ASF vaccines, all LAVs, that have entered the clinical trial phase have been urgently suspended due to safety concerns. ASF subunit vaccines are not associated with risks such as recombination, virulence reversion or virulence residues, and have unparalleled advantages in safety compared with LAVs; therefore, ASF subunit vaccines are now a focus of current research. However, further technological advances and basic research are required to successfully develop a safe and effective ASF vaccine.

Author Contributions: Conceptualization, N.H., H.Q. and T.X., investigation, N.H.; data curation, H.Q. and T.X.; writing—original draft preparation, N.H.; writing—review and editing, H.Q. and T.X.; visualization, Y.H. and Y.Z.; project administration, S.G.; funding acquisition, S.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Project for the Prevention and Control of major exotic animal diseases (grant no. 2022YFD1800500), and the National Key R&D Program for the 14th Five-Year Plan, the Ministry of Science and Technology, China.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors gratefully thank Zhiliang Wang, the expert of the WOAH reference laboratory for African swine fever, for the revision of parts of the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zhou, X.; Li, N.; Luo, Y.; Liu, Y.; Miao, F.; Chen, T.; Zhang, S.; Cao, P.; Li, X.; Tian, K.; et al. Emergence of African Swine Fever in China, 2018. *Transbound. Emerg. Dis.* **2018**, *65*, 1482–1484. [CrossRef] [PubMed]
2. Ge, S.; Li, J.; Fan, X.; Liu, F.; Li, L.; Wang, Q.; Ren, W.; Bao, J.; Liu, C.; Wang, H.; et al. Molecular Characterization of African Swine Fever Virus, China, 2018. *Emerg. Infect. Dis.* **2018**, *24*, 2131–2133. [CrossRef] [PubMed]

3. Zhao, D.; Liu, R.; Zhang, X.; Li, F.; Wang, J.; Zhang, J.; Liu, X.; Wang, L.; Zhang, J.; Wu, X.; et al. Replication and virulence in pigs of the first African swine fever virus isolated in China. *Emerg. Microbes Infect.* **2019**, *8*, 438–447. [CrossRef] [PubMed]
4. Urbano, A.C.; Ferreira, F. African swine fever control and prevention: An update on vaccine development. *Emerg. Microbes Infect.* **2022**, *11*, 2021–2033. [CrossRef]
5. Manso Ribeiro, J.; Nunes Petisca, J.L.; Lopes Frazao, F.; Sobral, M. Vaccination contre la peste porcine africaine. *Bull. De L'office Int. Des Epizoot.* **1963**, *60*, 921–937.
6. Boinas, F.S.; Hutchings, G.H.; Dixon, L.K.; Wilkinson, P.J. Characterization of pathogenic and non-pathogenic African swine fever virus isolates from Ornithodoros erraticus inhabiting pig premises in Portugal. *J. Gen. Virol.* **2004**, *85*, 2177–2187. [CrossRef]
7. Gallardo, C.; Soler, A.; Rodze, I.; Nieto, R.; Cano-Gómez, C.; Fernandez-Pinero, J.; Arias, M. Attenuated and non-haemadsorbing (non-HAD) genotype II African swine fever virus (ASFV) isolated in Europe, Latvia 2017. *Transbound. Emerg. Dis.* **2019**, *66*, 1399–1404. [CrossRef]
8. Sun, E.; Huang, L.; Zhang, X.; Zhang, J.; Shen, D.; Zhang, Z.; Wang, Z.; Huo, H.; Wang, W.; Huangfu, H.; et al. Genotype I African swine fever viruses emerged in domestic pigs in China and caused chronic infection. *Emerg. Microbes Infect.* **2021**, *10*, 2183–2193. [CrossRef]
9. Rock, D.L. Thoughts on African Swine Fever Vaccines. *Viruses* **2021**, *13*, 943. [CrossRef]
10. Gonzalez, A.; Calvo, V.; Almazan, F.; Almendral, J.M.; Ramirez, J.C.; Delavega, I.; Blasco, R.; Vinuela, E. MULTIGENE FAMILIES IN AFRICAN SWINE FEVER VIRUS-FAMILY-360. *J. Virol.* **1990**, *64*, 2073–2081. [CrossRef]
11. Rodriguez, J.M.; Yanez, R.J.; Pan, R.; Rodriguez, J.F.; Salas, M.L.; Vinuela, E. Multigene Families In African Swine Fever Virus-Family-505. *J. Virol.* **1994**, *68*, 2746–2751. [CrossRef]
12. Yozawa, T.; Kutish, G.F.; Afonso, C.L.; Lu, Z.; Rock, D.L. 2 Novel Multigene Families, 530 And 300, In The Terminal Variable Regions Of African-Swine-Fever Virus Genome. *Virology* **1994**, *202*, 997–1002. [CrossRef]
13. Afonso, C.L.; Piccone, M.E.; Zaffuto, K.M.; Neilan, J.; Kutish, G.F.; Lu, Z.; Balinsky, C.A.; Gibb, T.R.; Bean, T.J.; Zsak, L.; et al. African swine fever virus multigene family 360 and 530 genes affect host interferon response. *J. Virol.* **2004**, *78*, 1858–1864. [CrossRef]
14. Monteagudo, P.L.; Lacasta, A.; Lopez, E.; Bosch, L.; Collado, J.; Pina-Pedrero, S.; Correa-Fiz, F.; Accensi, F.; Navas, M.J.; Vidal, E.; et al. BA71DeltaCD2: A New Recombinant Live Attenuated African Swine Fever Virus with Cross-Protective Capabilities. *J. Virol.* **2017**, *91*, e01058-17. [CrossRef] [PubMed]
15. O'Donnell, V.; Holinka, L.G.; Gladue, D.P.; Sanford, B.; Krug, P.W.; Lu, X.Q.; Arzt, J.; Reese, B.; Carrillo, C.; Risatti, G.R.; et al. African Swine Fever Virus Georgia Isolate Harboring Deletions of MGF360 and MGF505 Genes Is Attenuated in Swine and Confers Protection against Challenge with Virulent Parental Virus. *J. Virol.* **2015**, *89*, 6048–6056. [CrossRef] [PubMed]
16. Alejo, A.; Matamoros, T.; Guerra, M.; Andres, G. A Proteomic Atlas of the African Swine Fever Virus Particle. *J. Virol.* **2018**, *92*, 18. [CrossRef] [PubMed]
17. Rodriguez, J.M.; Yanez, R.J.; Almazan, F.; Vinuela, E.; Rodriguez, J.F. African swine fever virus encodes a CD2 homolog responsible for the adhesion of erythrocytes to infected cells. *J. Virol.* **1993**, *67*, 5312–5320. [CrossRef]
18. Chen, W.; Zhao, D.; He, X.; Liu, R.; Wang, Z.; Zhang, X.; Li, F.; Shan, D.; Chen, H.; Zhang, J.; et al. A seven-gene-deleted African swine fever virus is safe and effective as a live attenuated vaccine in pigs. *Sci. China Life Sci.* **2020**, *63*, 623–634. [CrossRef]
19. Bu, Z. Latest progress in prevention and control of African swine fever and vaccine development. *Vet. Orientat.* **2021**, *371*, 6–7.
20. Zhang, Y.; Chen, T.; Zhang, J.; Qi, Y.; Miao, F.; Bo, Z.; Wang, L.; Guo, X.; Zhou, X.; Yang, J.; et al. Construction and immuno-protective properties of a gene-deleted vaccine strain of African swine fever virus. *Chin. J. Vet. Sci.* **2019**, *39*, 1421–1427. [CrossRef]
21. Borca, M.V.; Ramirez-Medina, E.; Silva, E.; Vuono, E.; Rai, A.; Pruitt, S.; Holinka, L.G.; Velazquez-Salinas, L.; Zhu, J.; Gladue, D.P. Development of a Highly Effective African Swine Fever Virus Vaccine by Deletion of the I177L Gene Results in Sterile Immunity against the Current Epidemic Eurasia Strain. *J. Virol.* **2020**, *94*, e02017-19. [CrossRef]
22. Sereda, A.D.; Balyshev, V.M.; Kazakova, A.S.; Imatdinov, A.R.; Kolbasov, D.V. Protective Properties of Attenuated Strains of African Swine Fever Virus Belonging to Seroimmunotypes I–VIII. *Pathogens* **2020**, *9*, 274. [CrossRef]
23. Wang, T.; Luo, R.; Sun, Y.; Qiu, H.J. Current efforts towards safe and effective live attenuated vaccines against African swine fever: Challenges and prospects. *Infect. Dis. Poverty* **2021**, *10*, 137. [CrossRef]
24. Liu, Y.; Li, Y.; Xie, Z.; Ao, Q.; Di, D.; Yu, W.; Lv, L.; Zhong, Q.; Song, Y.; Liao, X.; et al. Development and in vivo evaluation of MGF100-1R deletion mutant in an African swine fever virus Chinese strain. *Vet. Microbiol.* **2021**, *261*, 109208. [CrossRef]
25. Li, D.; Liu, Y.; Qi, X.; Wen, Y.; Li, P.; Ma, Z.; Liu, Y.; Zheng, H.; Liu, Z. African Swine Fever Virus MGF-110-9L-deficient Mutant Has Attenuated Virulence in Pigs. *Virol. Sin.* **2021**, *36*, 187–195. [CrossRef]
26. Huang, H.; Dang, W.; Shi, Z.; Ding, M.; Xu, F.; Li, T.; Feng, T.; Zheng, H.; Xiao, S. Identification of African swine fever virus MGF505-2R as a potent inhibitor of innate immunity in vitro. *Virol. Sin.* **2022**, *38*, 84–95. [CrossRef]
27. Li, D.; Yang, W.; Li, L.; Li, P.; Ma, Z.; Zhang, J.; Qi, X.; Ren, J.; Ru, Y.; Niu, Q.; et al. African Swine Fever Virus MGF-505-7R Negatively Regulates cGAS-STING-Mediated Signaling Pathway. *J. Immunol.* **2021**, *206*, 1844–1857. [CrossRef]
28. Li, D.; Zhang, J.; Yang, W.; Li, P.; Ru, Y.; Kang, W.; Li, L.; Ran, Y.; Zheng, H. African swine fever virus protein MGF-505-7R promotes virulence and pathogenesis by inhibiting JAK1- and JAK2-mediated signaling. *J. Biol. Chem.* **2021**, *297*, 101190. [CrossRef]

29. Liu, X.; Ao, D.; Jiang, S.; Xia, N.; Xu, Y.; Shao, Q.; Luo, J.; Wang, H.; Zheng, W.; Chen, N.; et al. African Swine Fever Virus A528R Inhibits TLR8 Mediated NF-κB Activity by Targeting p65 Activation and Nuclear Translocation. *Viruses* **2021**, *13*, 2046. [CrossRef]
30. Li, D.; Wu, P.; Liu, H.; Feng, T.; Yang, W.; Ru, Y.; Li, P.; Qi, X.; Shi, Z.; Zheng, H. A QP509L/QP383R-deleted African swine fever virus is highly attenuated in swine but does not confer protection against parental virus challenge. *J. Virol.* **2021**, *96*, Jvi0150021. [CrossRef]
31. Liu, H.; Zhu, Z.; Feng, T.; Ma, Z.; Xue, Q.; Wu, P.; Li, P.; Li, S.; Yang, F.; Cao, W.; et al. African Swine Fever Virus E120R Protein Inhibits Interferon Beta Production by Interacting with IRF3 To Block Its Activation. *J. Virol.* **2021**, *95*, e0082421. [CrossRef]
32. Yang, J.; Li, S.; Feng, T.; Zhang, X.; Yang, F.; Cao, W.; Chen, H.; Liu, H.; Zhang, K.; Zhu, Z.; et al. African Swine Fever Virus F317L Protein Inhibits NF-κB Activation to Evade Host Immune Response and Promote Viral Replication. *mSphere* **2021**, *6*, e00658-21. [CrossRef]
33. Zhang, J. Functional Identification of African Swine Fever Virus L7L-L11L Gene and Vaccine Candidate Strains. Ph.D. Thesis, Ningxia University, Yinchuan, China, 2021.
34. Zhang, K.; Yang, B.; Shen, C.; Zhang, T.; Hao, Y.; Zhang, D.; Liu, H.; Shi, X.; Li, G.; Yang, J.; et al. MGF360-9L Is a Major Virulence Factor Associated with the African Swine Fever Virus by Antagonizing the JAK/STAT Signaling Pathway. *mBio* **2022**, *13*, e02330-21. [CrossRef]
35. Zhang, Y.; Ke, J.; Zhang, J.; Yang, J.; Yue, H.; Zhou, X.; Qi, Y.; Zhu, R.; Miao, F.; Li, Q.; et al. African Swine Fever Virus Bearing an I226R Gene Deletion Elicits Robust Immunity in Pigs to African Swine Fever. *J. Virol.* **2021**, *95*, e0119921. [CrossRef]
36. Huang, L.; Xu, W.; Liu, H.; Xue, M.; Liu, X.; Zhang, K.; Hu, L.; Li, J.; Liu, X.; Xiang, Z.; et al. African Swine Fever Virus pI215L Negatively Regulates cGAS-STING Signaling Pathway through Recruiting RNF138 to Inhibit K63-Linked Ubiquitination of TBK1. *J. Immunol.* **2021**, *207*, 2754–2769. [CrossRef]
37. Li, L.; Fu, J.; Li, J.; Guo, S.; Chen, Q.; Zhang, Y.; Liu, Z.; Tan, C.; Chen, H.; Wang, X. African Swine Fever Virus pI215L Inhibits Type I Interferon Signaling by Targeting Interferon Regulatory Factor 9 for Autophagic Degradation. *J. Virol.* **2022**, *96*, e0094422. [CrossRef]
38. Ran, Y.; Li, D.; Xiong, M.G.; Liu, H.N.; Feng, T.; Shi, Z.W.; Li, Y.H.; Wu, H.N.; Wang, S.Y.; Zheng, H.X.; et al. African swine fever virus I267L acts as an important virulence factor by inhibiting RNA polymerase III-RIG-I-mediated innate immunity. *PLoS Pathog.* **2022**, *18*, e1010270. [CrossRef]
39. Sun, M.; Yu, S.; Ge, H.; Wang, T.; Li, Y.; Zhou, P.; Pan, L.; Han, Y.; Yang, Y.; Sun, Y.; et al. The A137R Protein of African Swine Fever Virus Inhibits Type I Interferon Production via the Autophagy-Mediated Lysosomal Degradation of TBK1. *J. Virol.* **2022**, *96*, e0195721. [CrossRef]
40. Ding, M.; Dang, W.; Liu, H.; Xu, F.; Huang, H.; Sunkang, Y.; Li, T.; Pei, J.; Liu, X.; Zhang, Y.; et al. Combinational Deletions of MGF360-9L and MGF505-7R Attenuated Highly Virulent African Swine Fever Virus and Conferred Protection against Homologous Challenge. *J. Virol.* **2022**, *96*, e0032922. [CrossRef]
41. Liu, Y.; Xie, Z.; Li, Y.; Song, Y.; Di, D.; Liu, J.; Gong, L.; Chen, Z.; Wu, J.; Ye, Z.; et al. Evaluation of An I177L gene-based five-gene-deleted African swine fever virus as a live attenuated vaccine in pigs. *Emerg. Microbes Infect.* **2022**, *12*, 2148560. [CrossRef]
42. Teklue, T.; Wang, T.; Luo, Y.; Hu, R.; Sun, Y.; Qiu, H.-J. Generation and Evaluation of an African Swine Fever Virus Mutant with Deletion of the CD2v and UK Genes. *Vaccines* **2020**, *8*, 763. [CrossRef]
43. Xie, Z.; Liu, Y.; Di, D.; Liu, J.; Gong, L.; Chen, Z.; Li, Y.; Yu, W.; Lv, L.; Zhong, Q.; et al. Protection Evaluation of a Five-Gene-Deleted African Swine Fever Virus Vaccine Candidate Against Homologous Challenge. *Front. Microbiol.* **2022**, *13*, 902932. [CrossRef]
44. Gao, Z.; Shao, J.; Chang, Y.; Zhang, G.; Kong, J.; Ge, S.; Chang, H. Predictive analysis of p72 protein antigenic epitopes of African swine fever virus and construction of multi-epitope vaccine. *Chin. J. Vet. Med.* **2020**, *56*, 13–17+142–144.
45. Zhou, X.; Mao, R.; Zhu, Z.; Sun, D.; Zhu, Y.; Wang, L.; Qi, M.; Zheng, H. Screening and antigenicity analysis of T-cell epitopes of African swine fever virus CP312R protein. *Chin. Vet. Sci.* **2022**, *52*, 410–416. [CrossRef]
46. Cai, J.; Cao, X.; Yang, Y.; Dai, B.; Cao, Q. Analysis of the dominant B and T cell antigenic epitopes of the MGF multigene family of African swine fever virus Pig/HLJ/2018 isolate. *Mod. Anim. Husb. Sci. Technol.* **2021**, *8*, 1–5. [CrossRef]
47. Cao, Q.; Dai, B.; Cao, X.; Yang, Y. Bioinformatics analysis of protein pp220 encoded by African swine fever virus Pig/HLJ/2018 strain CP2475L. *Swine Ind. Sci.* **2021**, *38*, 100–105.
48. Jia, R.; Zhang, G.; Bai, Y.; Liu, H.; Chen, Y.; Ding, P.; Zhou, J.; Feng, H.; Li, M.; Tian, Y.; et al. Identification of Linear B Cell Epitopes on CD2V Protein of African Swine Fever Virus by Monoclonal Antibodies. *Microbiol. Spectr.* **2022**, *10*, e0105221. [CrossRef]
49. Zhang, G.; Liu, W.; Gao, Z.; Chang, Y.; Yang, S.; Peng, Q.; Ge, S.; Kang, B.; Shao, J.; Chang, H. Antigenic and immunogenic properties of recombinant proteins consisting of two immunodominant African swine fever virus proteins fused with bacterial lipoprotein OprI. *Virol. J.* **2022**, *19*, 16. [CrossRef]
50. Zhang, G.L.; Liu, W.; Gao, Z.; Yang, S.C.; Zhou, G.Q.; Chang, Y.Y.; Ma, Y.Y.; Liang, X.X.; Shao, J.J.; Chang, H.Y. Antigenicity and immunogenicity of recombinant proteins comprising African swine fever virus proteins p30 and p54 fused to a cell-penetrating peptide. *Int. Immunopharmacol.* **2021**, *101*, 108251. [CrossRef]
51. Zhou, X.; Lu, H.; Wu, Z.; Zhang, X.; Zhang, Q.; Zhu, S.; Zhu, H.; Sun, H. Comparison of mucosal immune responses to African swine fever virus antigens intranasally delivered with two different viral vectors. *Res. Vet. Sci.* **2022**, *150*, 204–212. [CrossRef]
52. Fang, N.; Yang, B.; Xu, T.; Li, Y.; Li, H.; Zheng, H.; Zhang, A.; Chen, R. Expression and Immunogenicity of Recombinant African Swine Fever Virus Proteins Using the Semliki Forest Virus. *Front. Vet. Sci.* **2022**, *9*, 870009. [CrossRef] [PubMed]

53. Chen, L.; Zhang, X.; Shao, G.; Shao, Y.; Hu, Z.; Feng, K.; Xie, Z.; Li, H.; Chen, W.; Lin, W.; et al. Construction and Evaluation of Recombinant Pseudorabies Virus Expressing African Swine Fever Virus Antigen Genes. *Front. Vet. Sci.* **2022**, *9*, 832255. [CrossRef]
54. Lu, H.; Zhou, X.; Wu, Z.; Zhang, X.; Zhu, L.; Guo, X.; Zhang, Q.; Zhu, S.; Zhu, H.; Sun, H. Comparison of the mucosal adjuvanticities of two Toll-like receptor ligands for recombinant adenovirus-delivered African swine fever virus fusion antigens. *Vet. Immunol. Immunopathol.* **2021**, *239*, 110307. [CrossRef] [PubMed]
55. Chen, C.; Hua, D.; Shi, J.; Tan, Z.; Zhu, M.; Tan, K.; Zhang, L.; Huang, J. Porcine Immunoglobulin Fc Fused P30/P54 Protein of African Swine Fever Virus Displaying on Surface of S. cerevisiae Elicit Strong Antibody Production in Swine. *Virol. Sin.* **2021**, *36*, 207–219. [CrossRef] [PubMed]
56. Huang, M. Construction of Recombinant Adenoviral Vector Expressing ASFV Protective Antigen and Immunogenicity Study. Master's Thesis, Yangzhou University, Yangzhou, China, 2021.
57. Wu, B. Construction of African Swine Fever Virus Vector Vaccine Candidates Based on rAAV and Preliminary Evaluation. Master's Thesis, Huazhong Agricultural University, Wuhan, China, 2020.
58. Liang, W. Preliminary Study of a Recombinant Pseudorabies Vaccine Expressing the CD2v and P12 Proteins of African Swine Fever Virus. Master's Thesis, Fujian Normal University, Fuzhou, China, 2021.