Sequence Analysis, Antibiogram Profile, Virulence and Antibiotic Resistance Genes of XDR and MDR *Gallibacterium anatis* Isolated from Layer Chickens in Egypt

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**Background:** *Gallibacterium anatis* is incriminated frequently in severe economic losses and mortalities in the poultry industry. This study aimed to detect the prevalence of *G. anatis* in layer chickens, sequence analysis, the antibiogram profiles, and PCR screening of virulence determinants and antibiotic resistance genes.

**Methods:** Accordingly, 300 samples (tracheal swabs, ovari and oviduct, and lung) were randomly collected from 100 diseased layer chickens from private commercial layer farms at Elsharkia Governorate, Egypt. The bacteriological examination was carried out. The retrieved isolates were tested for 16S rRNA-23S rRNA gene sequencing, antibiogram profiling, PCR screening of virulence (*gtxA, fifA, and gyrB*), and antibiotic resistance genes (*bla*ROB, *aph*A1, *tet*B, and *tet*H).

**Results:** The prevalence of *G. anatis* was 25% in the examined diseased layer chickens. The sequence analyses emphasized that the tested strains derived from a common ancestor and exhibited a notable genetic similarity with other *G. anatis* strains from USA, China, and Denmark. The isolated *G. anatis* strains were highly resistant to sulfamethoxazole-trimethoprim, oxytetracycline, penicillin, ampicillin, kanamycin, neomycin, and erythromycin. The PCR revealed that the retrieved *G. anatis* strains carried *gtxA, gyrB*, and *fifA* virulence genes with a prevalence of 100%, 100%, and 38.3%, respectively. Approximately 30.1% of the retrieved *G. anatis* isolates were XDR to six antimicrobial classes and harbored *bla*ROB, *aph*A1, and *tet*B resistance genes. Moreover, 20.5% of the isolated *G. anatis* strains were MDR to three different classes and carried *bla*ROB and *tet*H resistance genes.

**Conclusion:** Briefly, this study emphasized the existence of XDR and MDR *G. anatis* strains in poultry. Florfenicol and norfloxacin displayed a promising antimicrobial effect against the emerging XDR and MDR *G. anatis* in poultry. The emergence of XDR and MDR *G. anatis* is considered a public health alarm.

**Keywords:** *G. anatis*, poultry, antibiogram, XDR, sequence analyses, virulence genes, antibiotic resistance genes

**Introduction**

Globally, there is an increased need for poultry meat and eggs as essential dietary components. Poultry diseases caused by resident microbiota are deleterious diseases that had severe losses in the poultry industry due to the marked decrease in growth and egg production, costs of treatment, and high mortality rates.1,2

Based on 16S rRNA gene sequencing, Genus *Gallibacterium* is categorized as a member of the *Pasteurellaceae* family.3 *Gallibacterium anatis* (G. anatis) is an opportunistic microorganism that normally inhabitant the genital and...
respiratory tracts of intensively reared chickens and other domestic birds. *G. anatis* is a Gram-negative coccobacillus frequently incriminated in mortalities in domestic birds, especially chickens, and sporadic human cases. Phenotypically, *G. anatis* is classified into two different biotypes: *G. anatis* biovar *haemolytica* (hemolytic biotype) and the *G. anatis* biovar *anatis* (non-hemolytic biotype). *G. anatis* is a multidrug-resistant (MDR) pathogen of poultry; causes serious diseases in poultry including salpingitis, decreased egg production, peritonitis, epididymitis, respiratory manifestations, and high mortalities. Moreover, infections caused by *G. anatis* in humans are rarely accompanied by abscessation of the lung, bacteremia, bronchitis, and mortalities.

It is crucial to understand the pathogenesis and the virulence determinants of *G. anatis* to avoid the adverse effects of this pathogen. The capability of *G. anatis* to adhere and invade the host epithelial cells is believed to induce a remarkable role in the pathogenesis of *G. anatis* infection in poultry. The most prevalent virulence determinants accompanying *G. anatis* are metalloproteases, capsule, fimbriae, hemagglutinin, and innovative elements such as the rtx-like toxin (*gtxA*). Cell-free filtrates of the hemolytic *G. anatis* strains are highly toxic against the avian-derived macrophage-like cells (HD11). The leukotoxic and hemolytic activities of *G.anatis* are attributed mainly to the *gtxA* toxin which is encoded by the *gtxA* gene. Moreover, the *gtxA* toxin has a cytotoxic effect on poultry macrophages in-vivo. Similarly, fimbriae are considered one of the vital virulence determinants of *G. anatis*. The fimbriae of *G. anatis* are categorized in the F17-like family. Mutant strains of *G. anatis* that lack the *flfA* fimbriae were noticed to be mild pathogenic to the experimentally infected birds. Other virulence determinants of *G. anatis* include the proteolytic proteases and the antiphagocytic capsules that initiate biofilm production.
Multidrug resistance has noticeably increased globally in the last decade, returning as a public health threat. Various modern surveys demonstrated the emergence of XDR and MDR bacterial pathogens from distinct sources such as poultry, fish, animals, food products, and humans.\textsuperscript{11–16} Despite that infections induced by \textit{G. anatis} could be treated with antibiotics, certain unresponsive cases were reported.\textsuperscript{17,18} Multidrug resistance patterns of \textit{G. anatis} to various antimicrobial classes (such as β-lactam antibiotics, sulfonamides, aminoglycosides, and tetracyclines) are frequently reported by several previous studies.\textsuperscript{3,6,19,20} This study aimed to detect the prevalence of \textit{G. anatis} in layer chickens, sequence analysis, the antibiogram profiles, and PCR screening of virulence determinants (\textit{gtxA, fifA, and gyrB}) and antibiotic resistance genes (\textit{bla}_{ROB}, \textit{aphA1}, \textit{tetB}, and \textit{tetH}) among the retrieved \textit{G. anatis} strains.

**Methods**

**Animal Ethics**

All procedures were carried out consistent with relevant regulations. All procedures and handling of birds were approved by the Animal Ethics Review Committee, Suez Canal University, Egypt.

**Sampling**

A total of 300 samples (tracheal swabs, ovary and oviduct, and lung; \textit{n}=100 for each) were randomly collected from 100 diseased layer chickens (3 types of samples from each bird) with an average age of 25–40 weeks from private commercial layer farms at Elsharkia Governorate, Egypt (from February to May 2020). The examined diseased layer chickens were suffering from depression, respiratory signs, occasionally head swelling, and decreased in egg production (5–10%). The post-mortem inspection of sacrificed and/or freshly dead birds displayed oophoritis, peritonitis, salpingitis, and tracheitis. All samples were gathered in sterile plastic bags, placed in an icebox and quickly transferred to the Microbiology laboratory for bacteriological examination.

**Isolation and Identification of \textit{G. anatis}**

Swabs from the obtained samples (tracheal swabs, ovary and oviduct, and lung) were directly streaked out on 5% Columbia blood agar and MacConkey agar plates (Difco, USA) and incubated aerobically at 37 °C for 24 h. The identification of \textit{G. anatis} was carried out according to Gram’s staining, culture characteristics, motility test, and the biochemical characteristics (oxidase, nitrate reduction, catalase, indole production, methyl red, Voges-Proskauer, citrate utilization, urease test, gelatinase, and sugar fermentation tests).\textsuperscript{5,21} Moreover, the identification of the retrieved \textit{G. anatis} isolates was ensured using PCR-based detection of the \textit{16S rRNA-23S rRNA} gene according to Bojesen,\textsuperscript{22} followed by gene sequencing.

**\textit{G. anatis} 16S rRNA-23S rRNA Gene Sequencing**

All the retrieved \textit{G. anatis} isolates displayed harmony in the biochemical and phenotypic features. Consequently, the PCR products of five indiscriminately selected \textit{G. anatis} strains were purified using the QIAquick PCR-Product extraction kit (QIAGEN GmbH, Hilden, D-40724, Germany), then were tested for sequencing in both directions through the Bigdye Terminator V3.1 cycle sequencing kit (Thermo Fisher Scientific GmbH, Dreieich 63,303, Germany). The recovered sequences were placed in the GenBank with accession numbers: OL549444, OL549445, OL549446, OL549447, and OL549460. The BLAST analysis was carried out to investigate the sequence identity. Moreover, the phylogenetic analysis was performed according to the neighbor-joining in MEGA6 as previously described.\textsuperscript{23}

**Antimicrobial Susceptibility Testing of the Recovered \textit{G. anatis}**

The recovered \textit{G. anatis} strains were examined for the susceptibility to several antimicrobial agents using the disc diffusion technique on Muller-Hinton agar (Oxoid, UK) was implemented consistently with the procedures of CLSI, 2018.\textsuperscript{24} Ten antimicrobial agents were involved, including; penicillin (PEN, 30μg), ampicillin (AMP, 30μg), amoxicillin-clavulanic acid (AMC, 30 μg), oxytetracycline (OX, 30μg), neomycin (NEO, 10 μg), kanamycin (KAN, 10 μg),
erythromycin (E, 15 μg), florfenicol (FFC, 30μg), sulphamethoxazole-trimethoprim (SXT, 30 μg), and norfloxacin (NOR, 10 μg) (ThermoFisher Scientific, USA). Moreover, E. coli -ATCC 25922 was involved as a control strain. The tested G. anatis isolates were categorized according to their resistance patterns into MDR (Multidrug-resistant: resistant to ≥ one antimicrobial agent in ≥ 3 classes) and XDR (Extensively drug-resistant: resistant to ≥ one agent in all tested antimicrobial classes except one or two) according to Magiorakos. Moreover, the multiple antibiotic resistance (MAR) index was determined as previously described.

PCR-Based Screening of Virulence and Antimicrobial Resistance Genes in the Isolated G. anatis

PCR was used to detect the virulence (gtxA: Cytolytic-hemolytic gene, fifA: Flageller gene, and gyrB: The gyrase subunit B gene) and the antimicrobial resistance genes (blaROB: β-lactam resistance gene, aphA1: aminoglycosides resistance gene, terB and terH: tetracycline resistance gene) in the retrieved G. anatis strains. DNA of the tested G. anatis strains was extracted following the manufacturer’s instructions of the QIAampDNA Mini Kit (Qiagen, GmbH, Germany/Cat. No.56304). The reaction volume was 25-μL, including 5 μL of extracted DNA, 12.5 μL of 2 × Master Mix, 20 pmol of tested primer, and distilled H2O. Negative control (reactions with no DNA template) and Positive controls (positive strains supplied by A.H.R.I, Egypt) were involved in every reaction. The used primers (Biobasic, Canada) and cycling conditions were demonstrated in Table 1. Lastly, the PCR products were separated using the agar gel electrophoresis (1.5% agarose stained using ethidium bromide 10 mg/mL), and then photographed the gel.

Statistical Analyses

The Chi-square test was used in data analyses (SAS software, 9.4 M6, SAS Institute, Cary, NC, USA) (The significance level was (p-value < 0.05). Besides, the correlation coefficient was estimated via the R-software (version 02.1; http://www.r-project.org/) using “corr” and “corrplot”.

Table 1 Primers Sequences and PCR Cycling Conditions

| Genes                                      | Oligonucleotides Sequences                  | Amplicon size (bp) | (35 Cycles) | References |
|--------------------------------------------|---------------------------------------------|--------------------|-------------|------------|
|                                            |                                             | Den.               | Annealing   | Ext.       |           |
| 16SrRNA (1133fgal)-23SrRNA (114r)          |                                             |                    |             |            |
| F: TATTCTTTGTACCACKGG                       |                                             | 1032               | 94°C        | 55°C       | 72°C 1 min | [22]       |
| R: GGTTCCTCCATCCGG                          |                                             |                    | 30 sec      | 50 sec     | 1 min    |           |
| gtxA (Cytolytic-hemolytic gene)            |                                             | 1257               | 94°C        | 51°C       | 72°C 1 min | [1]        |
| F: CAAACCTATTCAATCGGATG                     |                                             |                    | 30 sec      | 40 sec     | 1 min    |           |
| R: TGCTCAATATTTTCCATTTTC                    |                                             |                    |             |            |          |           |
| fifA (Flageller gene)                      |                                             | 538                | 94°C        | 55°C       | 72°C 45 sec | [27]       |
| F: CACCATGGGTGCAATGGCGATGACCC              |                                             |                    | 30 sec      | 40 sec     |          |           |
| R: TATCGTGATGCATGATGATTTC                   |                                             |                    |             |            |          |           |
| gyrB (The gyrase subunit B gene)           |                                             | 561                | 94°C        | 55°C       | 72°C 45 sec | [28]       |
| F: TGGCGGTTTCTGCGCAATGTC                   |                                             |                    | 30 sec      | 40 sec     |          |           |
| R: CGCTACCAAATGCGAGATTTC                    |                                             |                    |             |            |          |           |
| blaROB (Beta lactam resistance gene)        |                                             | 685                | 94°C        | 60°C       | 72°C 45 sec | [29]       |
| F: AATAACCCCTTGGCCCCAATTC                  |                                             |                    | 30 sec      | 40 sec     |          |           |
| R: TCCGTTATACGGTGTGCCG                      |                                             |                    |             |            |          |           |
| aphA1 (Aminoglycosides resistance gene)    |                                             | 489                | 94°C        | 54°C       | 72°C 40 sec | [30]       |
| F: TTATGCGCTTCCGCGACCATC                   |                                             |                    | 30 sec      | 40 sec     |          |           |
| R: GAGAAAACCTCACCGGACAG                     |                                             |                    |             |            |          |           |
| tetH (Tetracycline resistance gene)         |                                             | 1076               | 94°C        | 60°C       | 72°C 1 min | [30]       |
| F: ATACGTGCTGACGTCC                       |                                             |                    | 30 sec      | 40 sec     |          |           |
| R: TCCGATAGCGAGCT                          |                                             |                    |             |            |          |           |
| tetB (Tetracycline resistance gene)         |                                             | 774                | 94°C        | 50°C       | 72°C 1 min | [30]       |
| F: CCT TAT CATGCC AGT CTGTC                |                                             |                    | 30 sec      | 40 sec     |          |           |
| R: ACT GCCGTT TTT TCGCC                    |                                             |                    |             |            |          |           |
Table 2 The Prevalence of *G. anatis* Isolated from Examined Diseased Layer Chickens (n=73)

| No. of Examined Diseased Birds | Types of Organs | No. of Organs | No. of Positive Samples | Percentage of Positive Samples |
|-------------------------------|-----------------|---------------|-------------------------|--------------------------------|
| 100                           | Ovary and oviduct | 100           | 23                      | 23                             |
|                               | Tracheal swab    | 100           | 25                      | 25                             |
|                               | Lung             | 100           | 25                      | 25                             |
| Total                         |                 | 300           | 73                      | 24.3                           |

Abbreviation: NS, Non-significant.

Results

Phenotypic Characteristics of the Isolated *G. anatis* from Diseased Layers

The recovered *G. anatis* colonies were bright translucent, low convex, fine, circular, smooth-edged with greyish color, and mostly showed β-hemolysis on blood agar. Moreover, the colonies were small (pin point-like) and pink (lactose fermenter) on MacConkey agar. Gram’s staining displayed Gram-negative coccoid to small pleomorphic bacilli. The retrieved *G. anatis* isolates were positive for oxidase, catalase, nitrate reduction, sucrose, and mannitol fermentation tests. Conversely, the recovered isolates were negative for citrate utilization, indole, urease, gelatinase, motility, methyl red, and Voges-Proskauer tests.

Prevalence of *G. anatis* in the Examined Samples of Diseased Layer Chickens

A total of 73 *G. anatis* isolates were recovered from 300 bacteriologically examined samples obtained from 100 diseased layer chickens. Twenty-five isolates (25%) were obtained from tracheal swabs, 25 isolates (25%) from lung samples, and 23 isolates (23%) from ovary and oviduct samples. From the twenty-five infected birds with *G. anatis*, the pathogen was isolated from tracheal swab, lung, and ovary and oviduct samples of the same bird in 23 infected birds. Moreover, *G. anatis* was recovered from the lung and tracheal swabs of the same bird in two infected birds. There is no significant difference in the dissemination of *G. anatis* among the examined organs obtained from the diseased layer chickens (p > 0.05%), as illustrated in Table 2 and Figure 1. The prevalence of *G. anatis* was 25% (25/100) in the examined diseased layer chickens.

Phylogenetic Analyses of *G. anatis* 16S rRNA-23S rRNA Gene

Phylogenetic and sequence analyses of the 16S rRNA-23S rRNA gene emphasized that the tested *G. anatis* strains (n=5) derived from a common ancestor (Accession Numbers: OL549444, OL549445, OL549446, OL549447, and OL549460). In the present study, the tested *G. anatis* strains exhibited a notable genetic similarity (96.7–100%) with other *G. anatis* strains from various origins. For example, *G. anatis* strain G6_15 (99–100%) was isolated from a tracheal swab of

![Figure 1 Prevalence of G. anatis among different examined samples obtained from diseased layers.](https://doi.org/10.2147/IDR.S377797)
diseased layer chicken in Egypt (Accession No. KY274827). *G. anatis* strain UMN179 (99–100%) was isolated from an Iowa laying hen with peritonitis in the USA (Accession No. CP002667). *G. anatis* biovar hemolytica (98.3–98.7%) was isolated from poultry in Pennsylvania, USA (Accession No. MZ823357). *G. anatis* strain 202,004,302 (99.7–100%) was isolated from layer chicken in China (Accession No. MT445420), *G. anatis* strain GAC021 (99–100%) was isolated from poultry in China (Accession No. MH393187), *G. anatis* strain Yu-ZZ-XMZ-46-XZQ (99–100%) was isolated from a cloacal sample in China (Accession No. JN828473), *G. anatis* strain YT-1 (99–100%) isolated from oviduct in China (Accession No. OK582259), *G. anatis* strain 36,961/sv7 (99.4–99.7%) in Denmark (Accession No. AF228011), and *G. anatis* strain Gerl.4224 (99–100%) in Denmark (Accession No. AF228014) as shown in Figures 2 and 3.

**Figure 2** The phylogenetic analysis was carried out according to the 16SrRNA-23SrRNA gene sequencing. The phylogenetic tree clarifies the genetic relatedness between the recovered *G. anatis* strains and other strains deposited in the GenBank. The retrieved *G. anatis* strains in the present study were emphasized with red circles.

**Figure 3** Illustrates the percentage of *G. anatis* 16SrRNA-23SrRNA nucleotides sequences identity.
The in-vitro Antimicrobial Susceptibility of *G. anatis*

The antimicrobial susceptibility of the retrieved *G. anatis* isolates showed that the tested strains were resistant to sulfamethoxazole-trimethoprim (100%), oxytetracycline (97.3%), penicillin and ampicillin (95.9%), kanamycin and neomycin (64.4%), and erythromycin (46.6%). Moreover, the recovered isolates were sensitive to florfenicol (89%), norfloxacin (68.5%), and amoxicillin-clavulanic acid (43.8%) (As shown in Table 3 and Figure 4). Statistically, the recovered *G. anatis* strains displayed a significant difference in their susceptibility patterns to different tested antimicrobial classes (*p* < 0.05). Besides, the correlation coefficient was detected among the involved antimicrobial agents. Accordingly, strong positive correlations were detected between: KAN, NEO, P, AMP, OXY, and SXT (*r* = 0.99); FLO and NOR (*r* = 0.99); E, P, AMP, OXY, and SXT (*r* = 0.95); E, KAN, and NEO (*r* = 0.90). Moreover, moderate positive correlations were noticed between AMC and E (*r* = 0.66); AMC and FLO (*r* = 0.48); AMC and SXT (*r* = 0.42); AMC and OXY (*r* = 0.40); AMC, P, and AMP (*r* = 0.39) (Figure 5).

| Antimicrobial Class                        | Antimicrobial Agents                     | Sensitive | Intermediate | Resistant |
|-------------------------------------------|------------------------------------------|-----------|--------------|-----------|
|                                           |                                          | n | % | n | % | n | % |
| Penicillin                                | Penicillin                               | 0 | 0 | 3 | 4.1 | 70 | 95.9 |
|                                           | Ampicillin                               | 0 | 0 | 3 | 4.1 | 70 | 95.9 |
| β-lactam-β Lactamase inhibitor combination| Amoxicillin -clavulanic acid             | 32| 43.8| 11| 15.1| 30| 41.1|
| Tetracyclines                             | Oxytetracycline                          | 0 | 0 | 2 | 2.7 | 71 | 97.3 |
| Aminoglycosides                           | Neomycin                                 | 10| 13.7| 16| 21.9| 47| 64.4 |
|                                           | Kanamycin                                | 10| 13.7| 16| 21.9| 47| 64.4 |
| Macrolides                                | Erythromycin                             | 22| 30.1| 17| 23.3| 34| 46.6 |
| Phenicolis                                | Florfenicol                              | 65| 89 | 8 | 11 | 0 | 0 |
| Sulfonamides                              | Sulfamethoxazole-trimethoprim            | 0 | 0 | 0 | 0 | 73 | 100 |
| Fluroquinolones                           | Norfloxacin                              | 55| 68.5| 18| 24.6| 5 | 6.8 |
| Chi-square p value                        |                                          | 267.75   | 0.0001 | 47.702 | 0.0001 | 149.62 | 0.0001 |

Figure 4 Illustrates the antimicrobial susceptibility of the recovered *G. anatis* from diseased layer chickens.
Virulence Determinant and Antibiotic Resistance Genes of the Isolated G. anatis Strains

Using PCR, all the retrieved G. anatis isolates (100%) were positive for the confirmatory gene (16SrRNA-23SrRNA). Moreover, the recovered G. anatis strains commonly harbored the virulence genes gtxA1 (cytolytic-hemolytic gene) (100%) and gyrB (gyrase subunit B gene) (100%), followed by fifA gene (fimbrial gene) (38.3%). Furthermore, the tested G. anatis strains harbored the blaROB (β-lactam resistance), tetB (tetracycline resistance), aphA (aminoglycosides resistance gene), and tetH (tetracycline resistance) resistance genes with a prevalence of 95.9%, 76.7%, 64.4%, and 20.5%, respectively (Table 4 and Figure 6). The statistical analysis showed a significant difference (p < 0.05) in the distribution of antibiotic resistance and virulence genes in the isolated G. anatis strains.

Multidrug Resistance Patterns of the Retrieved G. anatis Strains

Our results evidenced that 30.1% (22/73) of the retrieved G. anatis isolates were XDR to six antimicrobial classes (Penicillins: PEN and AMP, β-lactam-β-Lactamase-inhibitor combination: AMC, Tetracyclines: OX, Aminoglycosides: NEO and KAN, Macrolides: E, and Sulfonamides: SXT) and harbored blaROB, aphA1, and tetB resistance genes. Moreover, 20.5% (15/73) of the isolated G. anatis strains were MDR to three different classes (Penicillins: PEN and AMP, Tetracyclines: OX, and Sulfonamides: SXT) and carried blaROB and tetH resistance genes. Furthermore, 17.8% (13/73) of the retrieved G. anatis strains were MDR to four different classes (Penicillins: PEN and AMP, Tetracyclines: OX, Aminoglycosides: NEO and KAN, and Sulfonamides: SXT) and possessed blaROB, aphA1, and tetB resistance genes. In addition, 10.9% (8/73) of the isolated G. anatis strains were MDR to
four different classes (Penicillins: PEN and AMP, Tetracyclines: OX, β-lactam-β-Lactamase-inhibitor combination: AMC, and Sulfonamides: SXT) and carried blaROB and tetB resistance genes. Besides, 9.6% (7/73) of the isolated G. anatis strains were MDR to five different classes (Penicillins: PEN and AMP, Tetracyclines: OX, Aminoglycosides: NEO and KAN, Macrolides: E, and Sulfonamides: SXT) and carried blaROB, aphA1, and tetB resistance genes as described in Table 5 and Figure 7. In the present study, the MAR index values (0.3–0.6) revealed multiple resistance patterns suggesting that the recovered G. anatis strains are derived from high-risk contamination. The correlation coefficient (r) was calculated among the demonstrated antimicrobial resistance genes in the recovered G. anatis strains and different involved antimicrobial agents. Our findings revealed positive correlations between: blaROB gene, P, and AMP (r=1); aphA1 gene, NEO, and KAN (r=1); tetB and OXY (r=0.97) as illustrated in Figure 8.

**Discussion**

This study aimed to investigate the prevalence of G. anatis in layer chickens, sequence analysis, the antibiogram profiles, and PCR screening of gtxA, fifA, and gyrB virulence genes and blaROB, aphA1, tetB, and tetH antibiotic resistance genes among the retrieved G. anatis strains.

| Types of Genes | n  | %     | Chi-Square | p value |
|----------------|----|-------|------------|---------|
| Confirmation gene | 16S rRNA-23S rRNA | 73 | 100 | 23.276 | 0.001 |
| Virulence-determinant genes | gtxA1 | 73 | 100 | 34.766 | 0.0001 |
| | gyrB | 73 | 100 |  |  |
| | fifA | 28 | 38.3 |  |  |
| Antimicrobial resistance genes | blaROB | 70 | 95.9 |  |  |
| | tetB | 56 | 76.7 |  |  |
| | tetH | 15 | 20.5 |  |  |
| | aphA1 | 47 | 64.4 |  |  |

*Figure 6* The distribution of antimicrobial resistance and virulence determinant genes in the retrieved G. anatis strains from diseased layer chickens.
In the current work, *G. anatis* was identified in layer chickens that suffered from respiratory manifestations and a drop in egg production. Besides, the PM inspection displayed oophoritis, peritonitis, salpingitis, and tracheitis. In the last decade, *G. anatis* was recovered from diseased chickens with tracheitis and salpingitis in different geographical areas all over the world. *G. anatis* is associated mainly with severe economic losses in the poultry industry.\(^{20,31,32}\) *G. anatis* is frequently retrieved from the genital and respiratory tracts of diseased poultry suffering from severe pathological lesions.\(^{33}\)

In the present study, the bacteriological examination proved that the prevalence of *G. anatis* was 25% in the examined diseased layer chickens, where the lung and trachea are the most predominant infected organs. Moreover, there is no inconsistency in the biochemical and phenotypic features of the isolated *G. anatis* strains that showed an obvious harmony. The recovered *G. anatis* colonies were circular, smooth-edged with greyish color, and mostly β-hemolytic on

| No. of Strains | %   | Type of Resistance | Multidrug Resistance Profiles | Antimicrobial-Resistance Genes | MAR-Index |
|---------------|-----|--------------------|-------------------------------|--------------------------------|-----------|
| 22            | 30.1| XDR                | - Six classes:                | *bla*<sub>ROB</sub>, *aph*A1, and tetB | 0.6       |
|               |     |                    | PEN and AMP AMC OX NEO and KANE SXT |                                |           |
| 15            | 20.5| MDR                | - Three classes:              | *bla*<sub>ROB</sub> and tetH | 0.3       |
|               |     |                    | PEN and AMP OX SXT            |                                |           |
| 13            | 17.8| MDR                | - Four classes:               | *bla*<sub>ROB</sub>, *aph*A1, and tetB | 0.4       |
|               |     |                    | PEN and AMP OX NEO and KANE SXT |                                |           |
| 8             | 10.9| MDR                | - Four classes:               | *bla*<sub>ROB</sub> and tetB | 0.4       |
|               |     |                    | PEN and AMP AMC OX SXT        |                                |           |
| 7             | 9.6 | MDR                | - Five classes:               | *bla*<sub>ROB</sub>, *aph*A1, and tetB | 0.5       |
|               |     |                    | PEN and AMP OX NEO and KANE SXT |                                |           |
| 5             | 6.8 | XDR                | - Six classes:                | *bla*<sub>ROB</sub>, *aph*A1, and tetB | 0.6       |
|               |     |                    | PEN and AMP OX NEO and KANE SXT NOR |                                |           |

### Table 5 The Prevalence of Multidrug-Resistance Profiles and the Resistance Genes Among the Recovered *G. anatis* Strains (n = 73)

In the present study, the bacteriological examination proved that the prevalence of *G. anatis* was 25% in the examined diseased layer chickens, where the lung and trachea are the most predominant infected organs. Moreover, there is no inconsistency in the biochemical and phenotypic features of the isolated *G. anatis* strains that showed an obvious harmony. The recovered *G. anatis* colonies were circular, smooth-edged with greyish color, and mostly β-hemolytic on
Figure 7 The emergence of XDR and MDR patterns between among the recovered *G. anatis* strains from diseased layer chickens.

Figure 8 The heat map illustrates the correlation coefficient (r) between the demonstrated antimicrobial resistance genes in the retrieved *G. anatis* strains and different involved antimicrobial agents.
blood agar. Moreover, the colonies were small (poor growth) and pink on MacConkey agar. Furthermore, the retrieved \textit{G. anatis} isolates were positive for oxidase, catalase, nitrate reduction, sucrose, and mannitol fermentation tests. On the other hand, the recovered isolates were negative for citrate utilization, indole, urease, gelatinase, and Voges-Proskauer tests. Our findings are consistent with those reported by Johnson\textsuperscript{34} and Van Driessche.\textsuperscript{4}

In the current study, the 16S rRNA-23S rRNA phylogenetic analyses highlighted that the tested \textit{G. anatis} strains have a common ancestor (Accession Numbers: OL549444, OL549445, OL549446, OL549447, and OL549460). Moreover, the tested \textit{G. anatis} strains showed high genetic similarity with other \textit{G. anatis} strains isolated from diseased poultry in different regions, such as \textit{G. anatis} strain G6.15 isolated by Elbestawy\textsuperscript{20} from a tracheal swab of diseased layer chicken in Egypt, \textit{G. anatis} strain UMN179 isolated from an Iowa laying hen with peritonitis in USA.\textsuperscript{34} \textit{G. anatis} strain Gerl.4224 was isolated from a chicken in Denmark,\textsuperscript{5} and \textit{G. anatis} strain GAC021 was isolated from a chicken in China.\textsuperscript{35} Our findings disagreed with the results of Paudel,\textsuperscript{4} who reported that strains of \textit{G. anatis} are divergent and usually exhibit genetic differences. Besides, these findings illustrated the epidemiological map and ensured the public health importance of \textit{G. anatis}.

Regarding the antimicrobial resistance patterns, the isolated \textit{G. anatis} strains showed remarkable resistance patterns to sulfonamides, tetracyclines, \(\beta\)-Lactam antibiotics, aminoglycosides, and macrolides. These findings nearly agreed with Bojesen\textsuperscript{17} and Elbestawy.\textsuperscript{36} The extensive uncontrolled use of antibiotics in the poultry farms, as well as the ability of \textit{G. anatis} to gain antibiotic resistance genes from other resistant bacteria, are the main factors that favor the existence of these superbugs.\textsuperscript{18}

In the present study, PCR evidenced that the tested \textit{G. anatis} strains are commonly harbored \textit{gtxA} and \textit{gyrB}, virulence genes, followed by the \textit{fifA} gene. Our results are nearly agreed with those reported by Krishnegowda,\textsuperscript{2} Sorour,\textsuperscript{37} and Nassik.\textsuperscript{38} The \textit{rtx}-like toxin (\textit{gtxA}) is one of the main virulence determinants of \textit{G. anatis} encoded by the \textit{gtxA} gene.\textsuperscript{27} The \textit{gtxA} toxin was demonstrated for the first time in a hemolytic \textit{G. anatis} strain isolated from diseased chicken in 2010 in Denmark. The toxin is accountable for hemolytic and leukotoxic activities of \textit{G. anatis}. Lacking the \textit{gtxA} gene indicates a reduced bacterial virulence.\textsuperscript{9} Besides, the \textit{gyrB} gene encodes the ATPase domain of DNA gyrase which is necessary for the replication of DNA in \textit{G. anatis}. The \textit{gyrB} gene is used frequently to identify \textit{G. anatis} infection in poultry.\textsuperscript{39} Fimbriae are a common virulence determinant of \textit{G. anatis} that plays a significant role in bacterial adhesion to the glycoprotein receptors in the host mucous membranes. Different F17-like fimbrial genes were recently determined in \textit{G. anatis} from different origins, where the \textit{fifA} gene is the most predominant one.\textsuperscript{27,28}

Regarding the multidrug resistance patterns in the isolated \textit{G. anatis} strains, a high proportion of the retrieved \textit{G. anatis} isolates were XDR to 6 antimicrobial classes and harbored \textit{bla}_{ROB}, \textit{aph}A1, and \textit{tetB} resistance genes. Moreover, a high percentage of the recovered \textit{G. anatis} strains were MDR to 3–5 different classes and carried \textit{bla}_{ROB}, \textit{aph}A, and \textit{tetB} or \textit{tetH} resistance genes. Antimicrobial resistance is considered one of the main threats to public health globally. It remains occurred due to the abuse of antibiotics in both veterinary and health practices and the bacterial acquirement of antibiotic resistance genes through mobile genetic components.\textsuperscript{40,41} The resistance to \(\beta\)-lactam antibiotics (such as amoxicillin, penicillin, and ampicillin) is mainly mediated by the \textit{bla}_{ROB-1} gene. Stimulatingly, the \textit{bla}_{ROB-1} gene is the most prevalent \(\beta\)-lactamase gene, frequently detected in the members of \textit{Pasteurellaceae}.\textsuperscript{42} The \textit{tetB} gene is the most prevalent tetracycline resistance gene in the present study, followed by the \textit{tetH} gene. These findings were supported by Bojesen, who reported the determination of the \textit{tetB} gene in 27 (27/49) tetracycline-resistant \textit{G. anatis} strains.\textsuperscript{17} Moreover, the acquired resistance to aminoglycosides antibiotics is mainly attributed to the enzymatic alteration mechanism, resulting in the inactivation of aminoglycosides in several bacterial pathogens, especially \textit{G. anatis}. The aminoglycosides phosphotransferases, encoded by the \textit{aph}A gene, are the most common aminoglycosides modifying enzymes.\textsuperscript{4,43}

Briefly, from what we know, this is the first report that emphasized the existence of XDR and MDR \textit{G. anatis} strains in diseased layers in Egypt, with particular reference to the sequence analyses and multidrug resistance profiles. The retrieved \textit{G. anatis} strains commonly harbor the \textit{gtxA} and \textit{gyrB} virulence genes, followed by the \textit{fifA} gene. The obtained \textit{G. anatis} strains are XDR or MDR to several antimicrobial classes (such as sulfonamides, tetracyclines, \(\beta\)-Lactam antibiotics, aminoglycosides, and macrolides) commonly harbored \textit{bla}_{ROB}, \textit{aph}A, and \textit{tetB} or \textit{tetH} resistance genes. Florfenicol and norfloxacin displayed a promising antimicrobial effect against the emerging
XDR and MDR *G. anatis* strains. Combining the conventional and molecular techniques is a consistent epidemiological tool used to diagnose *G. anatis* infection in poultry. Alarming, the emergence of XDR and MDR *G. anatis* strains establishes a public threat that specifies a lousy prognosis of diseases induced by these superbugs. Besides, it has an adverse impact on the poultry production. Consequently, it encourages the routine application of antimicrobial susceptibility testing along with the appropriate use of antimicrobial agents in the health sector and the veterinary practice.

**Author Contributions**

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

**Disclosure**

The authors declare no conflict of interest.

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